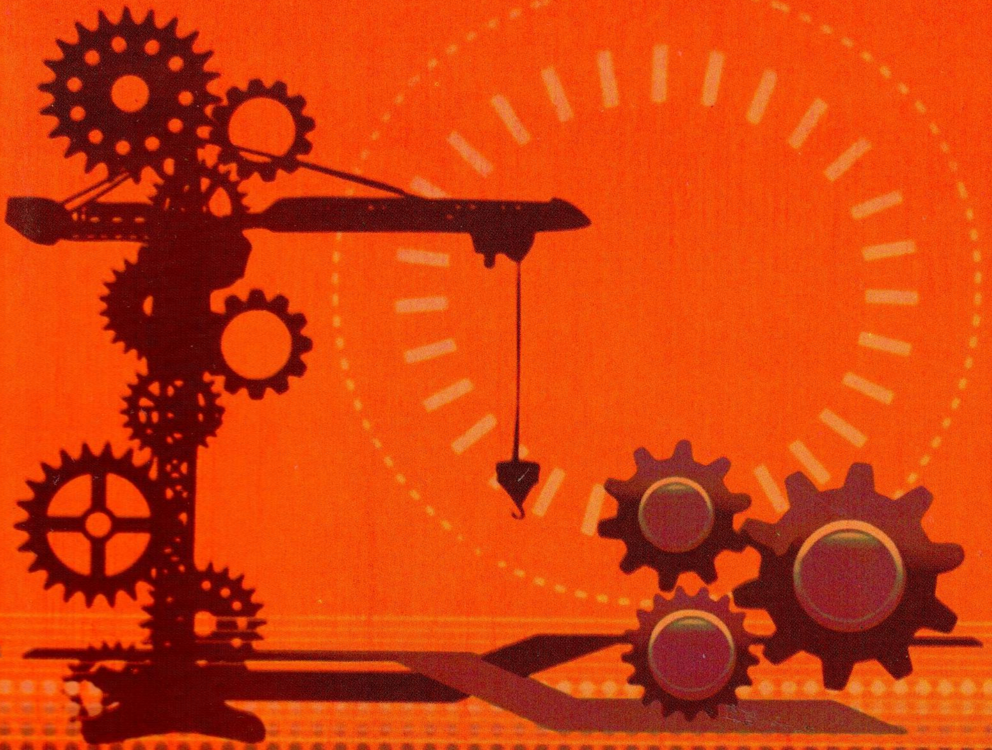

CURRENT TRENDS IN ENGINEERING PRACTICE

Volume III

Editor
Sneh Anand

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All India Council for Technical Education

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Current Trends in Engineering Practice

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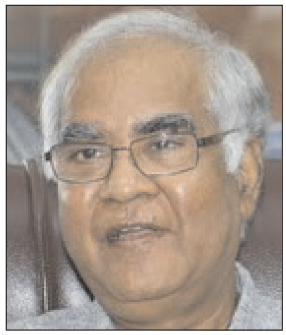
FROM THE PRESIDENT'S DESK



The world is experiencing technology and policy paradigm changes to match the challenges of sustainability. There is a growing awareness that engineering graduates need mentorship to excel in soft and engineering skills to compete in the present scenario and meet the demands of the country and the world. The role of the industry and the academia has always been understood to be complementary and crucial Industry is responsible for producing; the products and wealth; the academia supplies the necessary back up in terms of the technocrats and the professionals who run the industry. Recent times, have seen renewed efforts to enhance industry-academia-research interactions. Indeed, there is a great need for these specialists to interact with each other; build up synergies and address the complementary issues through strengthening interfaces and mechanisms of implementation. Academic institutes have realized to place priority on closer interactions with industry and R&D organizations. Cohesive approach to harness Academia-Research-Industry expertise, is key to imparting relevant and right knowledge to young minds; essential for sustainability in the changing eco-system. It is also realized that during the course of teaching engineering at under graduate and postgraduate levels, it is an essential prerequisite to correlate theoretical knowledge with 'real life' practical problems experienced by industry as well opportunities in fertile research domains. This approach makes the teaching relevant to the industrial and research realms and adds realism to the courses taught in engineering institutions.

INAE together with All India Council for Technical Education (AICTE) launched "AICTE-INAE. Distinguished Visiting Professorship Scheme" in 1999. Under this scheme, Industry experts are encouraged to give series of lectures at educational institutions for a specific time period. This scheme has gained motivation among industry experts as well as educational institutions. The scheme has narrowed the gap between academia and industry. Through this scheme, the engineering students get an opportunity to be exposed to the industrial ambiance and R&D needs of the industry. It also creates a liaison between institutions and industry and students are motivated and enabled to do their project work or thesis based on industry oriented real-time problems, in frontier areas of interest and utility.

The first volume of "Current Trends in Engineering Practice" a compilation of papers based on the lectures delivered by industry experts in engineering colleges under the AICTE-INAE Distinguished Visiting Professorship scheme was brought out in the year 2006. The second volume of this series-"Current Trends in Engineering Practice Volume II" was published in the year

2010. Both the volumes dealt with engineering approaches, contents based on solving challenges and practices pursued by our distinguished colleagues in different engineering disciplines and specializations. The volumes have been appreciated by persons from academia, research and industry.

I am delighted to note that the third volume is ready for publication. The contents have improved in quality and quantity since the first publication in the year 2006. I express my gratitude to AICTE and industry experts. Eminent experts deserve all our praise for making contributions to this volume as well as their efforts in making the scheme an outstanding success. This scheme has indeed enriched the cause of strengthening academia-research-industry interfaces: in the current India and the world. I am confident that this book will be valuable to the engineering institutions, research organizations and industry. I sincerely hope that sincere efforts, in this direction, shall continue, to be enhanced and improved by all concerned for the success of the scheme in the year to come.

I wish you enrichment and empowerment, in serving the nation; INDIA

Baldev Raj
President, INAE

PREFACE

It has long been felt that there is a need for active linkages between industry and engineering institutions which enrich the curriculum content. Closer interactions among industry, R&D institutions and the academia through institutionalized mechanisms are now finding greater importance. Under the AICTE-INAE Distinguished Visiting Professorship scheme, industry experts are encouraged to give series of lectures at an educational institution in their proximity for a specific time period. This scheme has become popular among industry experts as well as educational institutions. Thirteen Industry Experts were selected during the year 2000; eighteen each in 2001 and 2002; fourteen in 2003; ten in 2004; thirteen in 2005; fourteen during the year 2006; fifteen during 2007; eleven during 2008; eighteen during the year 2009; nine during the year 2010, seven during the year 2011; twelve during the year 2012 and fourteen during the year 2013 by a high level selection committee of experts from Academia, Industry and representatives from All India Council for Technical Education (AICTE) and Confederation of Indian Industry (CII).

The scheme has undoubtedly been a great success and has been running effectively during the last thirteen years. During their visits, the visiting professors besides delivering lectures on the state-of-art industrial practices and sharing their industrial experience with the faculty/students of the affiliated engineering institutions are also assisting in updating the curriculum. They also have made significant contributions in guiding and evaluating UG and PG projects, and formulating certain useful collaboration projects between the concerned industry and institution. The feedback received from the engineering colleges/institutions has been positive and encouraging. The concerned Heads of Department of the affiliated engineering institutions have unanimously expressed that this scheme helps the budding engineers to know more about the industrial requirements and helps them understand the concepts more easily as they gain exposure to practical aspects. The interaction with captains of the industry has led to bringing new and innovative ideas, thereby enhancing credibility of the teaching imparted at the institution.

The first volume of “Current Trends in Engineering Practice” - a compilation of papers based on the lectures delivered by industry experts in engineering colleges under this scheme was brought out in the year 2006 and was sent to the concerned industry experts, engineering colleges/institutions and professional bodies/other organizations. The second volume of this series – “Current Trends in Engineering Practice Volume II” was brought out in the year 2010. Both the volumes dealt with certain engineering practices adopted in various projects in different engineering disciplines and specializations. They were well received by persons from academia and industry. We are happy that the third volume is being brought out.

I am grateful to all the Distinguished Visiting Professors who have devoted their valuable time in contributing to this book. I also express my thanks to the Heads of Departments & Programme Coordinators of the concerned engineering institutions who have helped in the successful implementation of the scheme.

Sneh Anand
Project Coordinator
AICTE-INAE Distinguished
Visiting Professorship Scheme

FOREWORD

Universities in developed countries have a fairly long history of contributing to industrial growth through active participation in their technology development activities. University research always has a fundamental value perse and it gets value added in applied terms through sustained academic-industry joint initiatives. Though, a few Indian engineering institutions have made significant contributions to the growth of industrial research, the overall situation related to academic – industry collaboration continue to remain weak in India. Realising its adverse impact on the future growth of Indian university research in applied terms if the ground situation remains unchanged, the Indian National Academy of Engineering (INAE) launched the Distinguished Visiting Professorship (DVP) scheme in 1999 in association with the All India Council of Technical Education (AICTE). The DVP scheme has several unique features viz., engineering curriculum enrichment, continuing education of engineering faculty, product/process development and information exchange achieved through cooperative R&D programmes and guided student projects and direct dissemination of industrial knowledge to academic institutions by the visiting professors from the industry. Over the years, the DVP scheme has gained high level of acceptance by both industry and academic communities. This is evident by its attracting more than 150 visiting professors from industry and industrial R&D institutions till 2010. The INAE is constantly making efforts to strengthen this scheme further.

One of the major highlights of the DVP scheme has been the publication of the lectures delivered by the visiting professors at various institutions. The INAE has brought out two volumes in 2006 and 2010 respectively. Both of them have been very well received. This document contains the third volume of DVP lectures delivered subsequent to 2010. I am very positive that this volume will also receive the same level of patronage as the first two volumes. I express my deep sense of appreciation to the efforts made by the INAE Secretariat and the visiting Professors for promotion of this wonderful initiative. I wish the programme all success.

K V Raghavan

Vice President, INAE

Chairman, Steering Committee on
AICTE-INAE Distinguished Visiting
Professorship Scheme

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CIVIL ENGINEERING

Current Trends in Engineering Practice Vol. III
Editor: Sneh Anand

ADVANCED FINITE ELEMENT STRUCTURAL ANALYSIS

P. KANNAN[1], T. CHRISTOPHER[1] AND B. NAGESWARA RAO[2*]

Structural design provides the shape, size and material of a product under the specified service conditions. Structural analysis and testing are being employed to assess the adequacy of the design. The derivation of classical (analytical) solutions to obtain design formulae for complex structural configurations involves considerable mathematical difficulties. The finite element method has become one of the most popular and general numerical methods of structural analysis. Application of finite element method to other areas of engineering includes Fluid Flows, Heat Transfer, Electromagnetism, etc. Brief historical reviews of the finite element method are given in two articles [1, 2]. Mackerle [3] provides a guide to information sources on finite element methods.

Computing technology is the technological foundation of **Computational Structures Technology (CST)**. The advance made in computer hardware and software has impacted all aspects of CST development significantly. Current CST activities include computational material modeling; computational methods for predicting the response, performance, failure and life of structures and their components; and automated methods of structural synthesis and optimization.

Application of CST to contemporary structures problems typically involves a sequence of five steps: observation of the response phenomena of interest; development of computational models for the numerical simulation of these phenomena; development and assembly of software and/or hardware to implement the computational models; post-processing and interpretation of the predictions of the computational models; and utilization of the computational models in the analysis and design of structures.

Development of a computational model includes selection of the mathematical model that describes the phenomena; mathematical analysis of the model to ensure that the problem is properly formulated; testing the range of validity of the model; and development of a discrete

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model, computational strategy, and numerical algorithms to approximate the mathematical model. Successful computational models for structures are those based on thorough familiarity with the response phenomena being simulated and a good understanding of the mathematical models available to describe them.

1. STRUCTURAL COMPONENTS IN A LAUNCH VEHICLE

The structural components of a launch vehicle can be broadly classified into: **primary structures** (viz., motor cases, inter-stages, propellant tanks, thrust frame/structure, nose fairings, etc.), which are intended to provide a load transfer path during the actual service; and **secondary/appendage structures** (viz., solar panel backup deck plates/antenna dishes, cover panels, etc.), which are primarily functional designs which need to bear self-weight. These are further classified into pressurized and non-pressurized structures, and depending on service environment, these could be either heated/hot or cold structures.

Structural components/critical areas needing detailed investigation are: Pressure vessels (metallic/composite motor casing, tanks in liquid propulsion systems); Segmented joints in solid propellant rocket motors; Junctions of cylindrical shell and ends; Solid propellant rocket motor grain configurations; Rocket motor nozzles (high temperature, pressure, multi-layered dissimilar materials); Inter-stage structures: truncated conical shell/cylindrical shell (semi-monocoque); Heat-shield structures; Final stage motor casings and satellite interface; and Satellite structures.

The performance of a space-vehicle structure depends upon its strength, stiffness and compatibility with propulsion and guidance. Probability of a successful space flight is increased by simplicity of design and analysis, avoidance of discontinuities and high thermal gradients, minimization of dynamic effects, and use of stable materials and structural configurations. A higher local safety factor greatly improves the reliability of connections, attachments, fittings, and other load-concentration areas, with only a very small over-all weight increase. A smooth flow of stress is important. Therefore machine-welded, milled, forged, extruded or cast parts with continuous contours and gradual cross-sectional changes are preferable to built-up hand-welded, spot-welded, bolted or riveted parts.

2. FAILURE MODES

The causes of failures in structural components may be generally classified into three groups: faulty design, including improper selection of materials; faulty manufacturing; and deterioration with time in service conditions may deviate from the designer's expectations. The generally identified modes of structural failure are: brittle fracture, fatigue, yielding due to overload of the cross-section, leakage of containment vessels, corrosion, erosion, corrosion fatigue and stress corrosion, instability (buckling) and creep or creep-fatigue interaction. Two types of failure criteria recognized by rocket industry are yielding and fracture.

Failure due to yielding is applied to a criterion in which some functional of the stress or strain is exceeded, and fracture is applied to a criterion in which an already existing crack extends according to energy balance hypothesis. Experimentation with a variety of materials would show that the theory works well for certain materials but not very well for others. Designer has to use/establish a suitable failure theory for the intended materials.

3. FINITE ELEMENT ANALYSIS

The finite element method has the capability to deal with complex loading conditions, material behaviour and practical geometries. The finite element methods for analyzing the stress and displacement distributions of an elastic continuum have long been interpreted as approximate methods associated with different variational principles in elasticity. These displacement and/or stress fields are then assumed in each element and the resulting equations from the application of the variational principles are simultaneous algebraic equations, which may have: generalized displacements; generalized internal forces or stresses; or both displacements and forces at the nodal points as unknowns to be evaluated.

Based on the nature of the final matrix equations, the above three categories of finite element methods are often referred to as: displacement method; force method; and mixed method. The hybrid model involves either assumed equilibrating stresses only within each element and compatible displacements along the inter-element boundary or assumed continuous displacement distribution within each element and equilibrating surface tractions along the inter-element boundary. There is no definite relation between the finite element models and the types of resulting matrix equation. For example, the equilibrium model may lead to both a displacement method and a force method and it turns out that all four of the models just described may be formulated such that only the nodal displacements remain as the unknowns of the final matrix equations. The derivation of an element stiffness matrix involves the evaluation of the strain energy content in the element with prescribed boundary displacements that are interpolated in terms of a finite number of nodal displacements and are compatible with those of the neighboring elements. An approximate solution to such a problem can be accomplished by the use of the principle of minimum complementary energy.

Commercial codes (*viz.,* MARC, NASTRAN, NISA, ANSYS, etc.) and user's guides are currently available to solve structural problems. Based on the geometry and application, the most commonly used finite elements can be classified as: One-dimensional elements (Viz., cable elements, which take only tensile load; Truss elements, which take tensile and compressive loads; and beam elements, which take tensile, compressive, bending, shear and torsional loads), Two-dimensional elements (*viz.,* plane stress elements; plane strain elements; plate/shell bending elements; and axisymmetric elements), and Three-dimensional elements. However, selection of suitable elements for modeling, specification of boundary conditions for the intended structural analysis under the specified loading conditions and interpretation of finite element analysis results need experience. Let us review the basic ideas and trends in the development of the finite element method using the approach known as displacement formulation.

3.1 Displacement Formulation

The basis of the method is the assumption that every body may be represented as an assemblage of finite elements. For each element an analytic relationship may be obtained between nodal forces and displacements, which involve the stiffness matrix. The stiffness matrices of the individual elements are assembled into the matrix of the system of linear algebraic equations, which express the conditions of equilibrium of the body. The input data for the finite element computer program consist of a geometrical description of the structure, the material properties, the specification of load and temperature and the definition of elements by which the given body may be represented. The formulation of analytic relationships between nodal forces and displacements for various types of element is the corner stone of the finite element method. This is a very important aspect of the method since the resulting solution and the potentialities of the method depend very much on the structural elements used. The formulation of force-displacement relationships is based on the methods of elasticity theory, which define these relationships fairly accurately, but, in spite of this, the error involved in the solution is sometimes very large. This may occur, for example, because of the application of too coarse a network or due to the elements being excessively long and narrow. The use of isoparametric elements permits curved boundaries to be represented by a small number of elements. It should be noted that an interpolation function or a shape function in the formulation of isoparametric element has unit value at one nodal point and zero value at all other nodal points. The geometry and displacements of the element are described in terms of the same parameters and are of the same order. The accuracy of computations can be improved by introducing additional nodes. In constructing the stiffness matrix of each element it is necessary to use numerical integration (because of the complexity of the expressions).

The basic steps involved in the finite element method are:

Step 1: Discretization of the body into finite elements.

Step 2: Evaluation of element stiffness by deriving nodal force-displacement relationships.

Step 3: Assemblage of the stiffness and force matrices for the system of elements and nodes.

Step 4: Introduction of boundary conditions.

Step 5: Solution of the resulting equations for nodal displacements.

Step 6: Calculation of strains and stresses based on nodal displacements.

The discrepancy between the results of finite element analysis and the actual behavior of the structure, if any, may be due to improper selection of the elements, improper specification of boundary conditions and inadequate modeling of the structure.

3.2 LIMITATIONS OF STANDARD FINITE ELEMENT ANALYSIS

Figures 1 and 2 illustrate the variation of the stress component parallel to the direction of the uniform tension applied to a wide panel containing a circular or elliptic hole, according to the theory of elasticity [7]. The presence of a circular hole raises the stress level at the edge of the hole to three times the applied stress level, while for elliptic hole, the stress concentration at the edge with small radius of curvature increases in proportion to the ratio of the major to minor axis.

A crack or flaw of finite proportions can be thought of as the limiting case of an elliptical hole as the ratio b/a approaches zero, as illustrated in Fig. 3. According to the theory of elasticity, the maximum stress parallel to the direction of the applied load at the edge of the crack increases

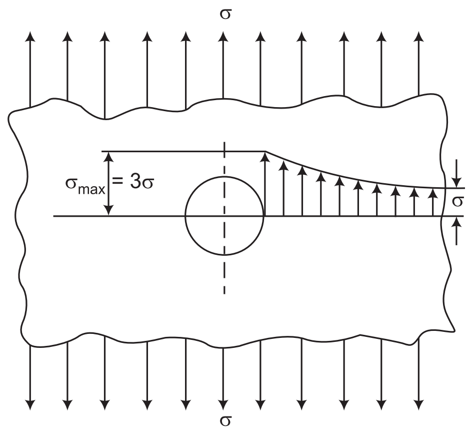

FIG. 1 CIRCULAR HOLE IN AN INFINITE PLATE

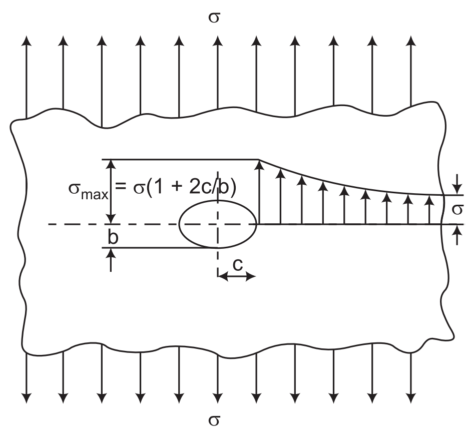

FIG. 2 ELLIPTICAL HOLE IN AN INFINITE PLATE

without limit. However, the material at the edge of a sharp crack obviously cannot support infinitely large stresses. In real metals, state of plastic yield develops over a small region bordering the edge of the crack (see Fig. 4). Under these circumstances, continuum mechanics principles cannot be directly applied to the structural components, which contain flaws.

3.2.1 Usage of fracture mechanics concepts

Failure assessment of cracked configurations can be made through the evaluation of the stress intensity factor (K) at the crack-tip, which has to be compared with the fracture toughness (Kc) of the material. For a given cracked configuration, K can be evaluated from any one of the following methods: The displacement method [8]; Energy method such as strain energy release rate, G [9];

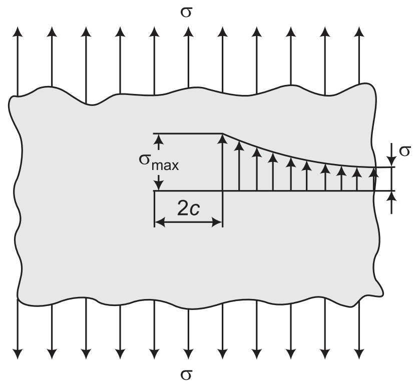

FIG. 3 CRACK IN AN INFINITE PLATE

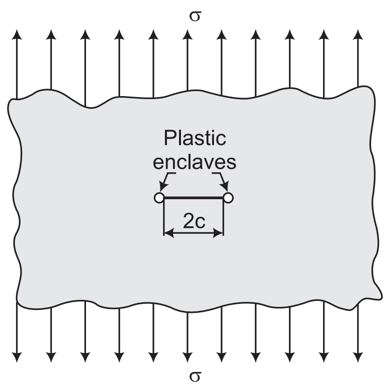

FIG. 4 PLASTIC REGION AROUND CRACK-TIP

Line integral method (J-integral) [10, 11]; Crack Closure Integral [12, 13]; and The superposition method [14, 15].

3.2.2 Finite element modeling of bonded joints

Joints in components or structures incur a weight penalty, are a source of failure and cause manufacturing problems; whenever possible, therefore, a designer will avoid using them. Unfortunately, it is rarely possible to produce a construction without joints owing to limitations on material size, convenience in manufacture or transportation and the need for access in order to inspect or repair the structure. Basically, there are two types of joint commonly employed with composite materials: adhesively bonded joints and mechanically fastened joints. Welding is also a possibility for thermoplastic composites, but this technique is not well developed for load-carrying joints.

Adhesive bonding is being used extensively in several spacecraft structures. This is made possible by the development of adhesive capable of withstanding the extreme environmental conditions encountered in space flight. The application of adhesive bonding can also be found in solid propellant rocket motors (see Fig. 5). In this case there are several layers of bonding. The propellant is bonded to the liner, the liner is bonded to insulation and the insulation is bonded to the casing.

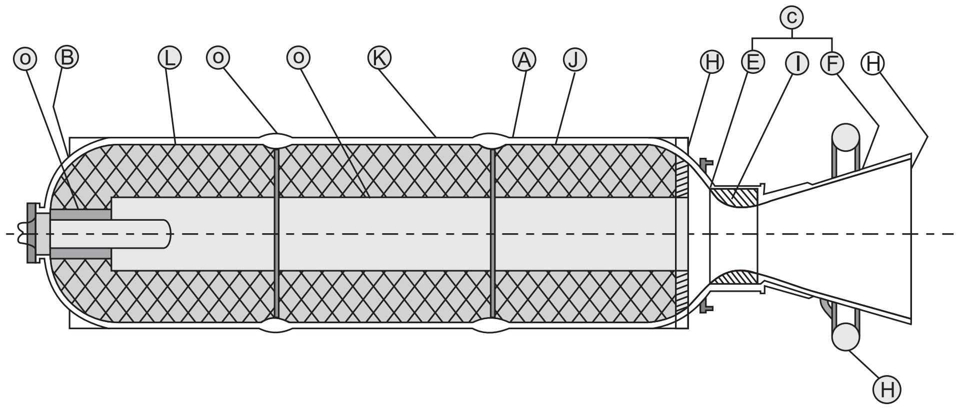

FIG. 5 CROSS-SECTION OF A TYPICAL CASE-BONDED SOLID ROCKET MOTOR

(A) Chamber; (B) Head end dome; (C) Nozzle; (D) Igniter; (E) Nozzle convergent portion; (F) Nozzle divergent portion; (G) Port; (H) Inhibitor; (I) Nozzle throat insert; (J) Lining; (K) Insulation; (L) Propellant; (M) Nozzle exit plane; (N) SITVC system; (O) Segment joint.

Standard finite elements may not always be well suited for the analysis of adhesive layers. It is normally observed that the adhesive layer is extremely thin compared with other dimensions of the bonded structure. It is also known that most elements give best results when the ratio of the width of the element (a) to the height of the element (b) is approximately unity. Distorted elements have poor properties. It has been found that an element having a large a/b ratio becomes much stiffer in the transverse direction and much weaker in the axial direction. A special 6-node isoparametric element for the adhesive layer is formulated [16] following the procedure described by Barker and Hatt [17]. The element properties for the 6-node special element are given below. Since the adhesive layer is relatively thin, the special element used to idealize it assumes identical coordinates for the top and bottom nodes. In addition, the longitudinal direct stress and the variation of the other two stresses along the thickness of the adhesive layer are neglected for this element.

Lap joint, which consists of two sheets of the substrates joined by a simple overlay, is one of the most common joint designs employed in industry. It is simple and convenient test geometry for evaluating adhesive joints. However, the stresses in the adhesive layer are not, in practice uniform, and stress concentrations arise from the differential straining of the bonded substrates and form the eccentricity of the loading path (see Fig. 6).

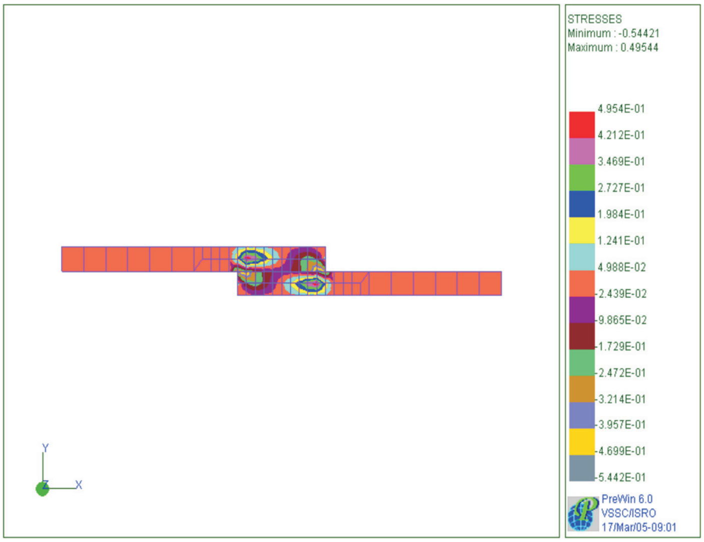

FIG. 6(a) SHEAR STRESS DISTRIBUTION OF THE LAP JOINT

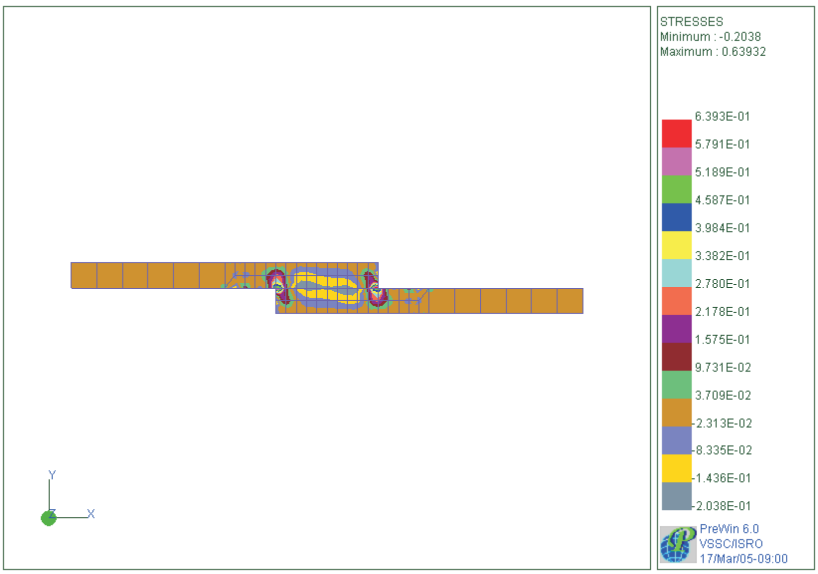

FIG. 6(b) NORMAL STRESS DISTRIBUTION OF THE LAP JOINT

4. HYBRID-STRESS-DISPLACEMENT FORMULATION

Based on Spilker's concept [18, 19], three efficient hybrid–stress- displacement finite elements were developed for mechanical, thermal and body force loads suitable for modeling the propellant grains in a rocket motor [20, 21]. These are, 4-node quadrilateral plane strain, axi-symmetric, and 8-node brick elements. These elements have several advantages compared to the familiar displacement formulation for studying the structural behavior of compressible/nearly incompressible solid rocket motor propellant and insulation materials, under various loading environments. This formulation involves independent interpolations of intra-element equilibrating stresses and compatible (boundary or intra-element) displacements. As the stresses are independent in each element, the stress parameters are eliminated at the element level and a conventional stiffness matrix results.

An infinitely long thick cylindrical shell having propellant grain, insulation and casing as interior, middle and outer layers respectively is analyzed for three loading conditions. These are: case a) an internal pressure of 4.905 N/mm^2, case b) thermal load due to temperature change from 68°C to 30°C (cooling) and case c) 1-g gravity load. The grain inner radius is 500 mm and outer radius is 1389 mm. The insulation thickness is 5 mm and casing thickness is 7.8 mm. The length of the thick cylindrical shell is considered as 1800 mm. For thermal and pressure loading conditions, the axial displacement is constrained at both ends of the cylindrical shell, where as in the case of storage condition (gravity loading), displacements are constrained at the bottom portion of the casing. Cyclic symmetric conditions are imposed in the plane strain and 3-D finite element model.

The material properties considered are as in Table 1 below. The results obtained with the three types of elements are presented in Table 2 along with analytical results and results obtained from MARC software, demonstrating the accuracy of the present elements. Figure 8 shows contours for all load cases obtained with 3-D brick elements. Table 2 gives good comparison of finite element analysis results. The present linear elements can be used for modelling with compressible and incompressible materials, where as in the MARC software quadratic Herman elements only can be used for modelling incompressible materials. Further tying option is required at the interface while using the MARC elements.

Table 1. *Material properties*

Material	*Young's modulus (N/mm^2)*	*Poisson's ratio*	*Weight density N/mm^3*	*Coefficient of thermal expansion (/°C)*
Casing	186390	0.3	7.6518e-5	0.000011
Insulation	1.962	0.499	1.74618e-5	0.0003
Propellant	4.905*	0.499	1.74618e-5	0.0001

* Young's modulus corresponding to ignition peak pressure, whereas it is 1.962 for thermal and gravity loads.

Table 2. *Comparison of results with closed form solution and MARC*

Loads	*Analytical [22, 23]*	*Finite Element Analysis [21]*			*Marc*	
		Plane strain	*Axisym metric*	*Brick*	*Plane strain*	*Axisym-metric*
(a) Pressure						
(1) Radial displacement at inner port (mm)	26.086	26.064	26.09	26.064	25.580	26.086
(2) Hoop strain at inner port (%)	5.2170	5.095	5.149	5.180	5.5060	5.1810
(b) Thermal load						
(i) Maximum radial Stress at the interface of propellant and insulation (N/mm^2)	0.04458	0.04532	0.04529	0.04477	0.04573	0.04460
(ii) Maximum Hoop strain at inner port (%)	3.350	3.3296	3.3650	3.3260	3.260	3.327
(c) Axial Inertia i.e., Gravity load Maximum slump displacement, w (mm)	7.875	–	7.895	7.845	–	7.892

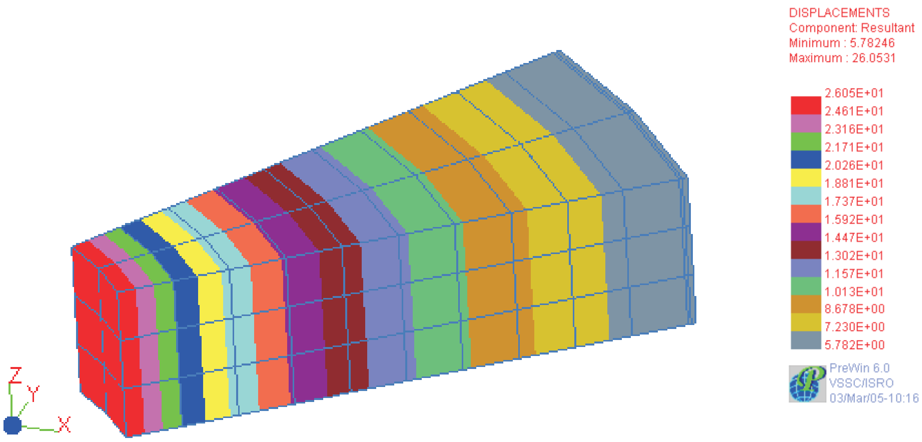

FIG. 7(a) RESULTANT DISPLACEMENT CONTOUR UNDER PRESSURE LOAD

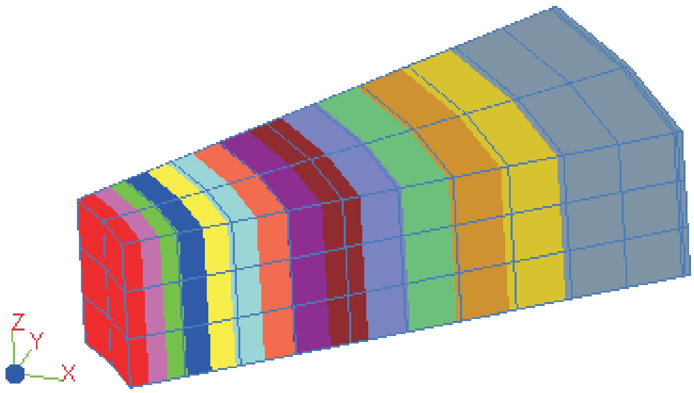

FIG. 7(b) RESULTANT DISPLACEMENT CONTOUR UNDER THERMAL LOAD

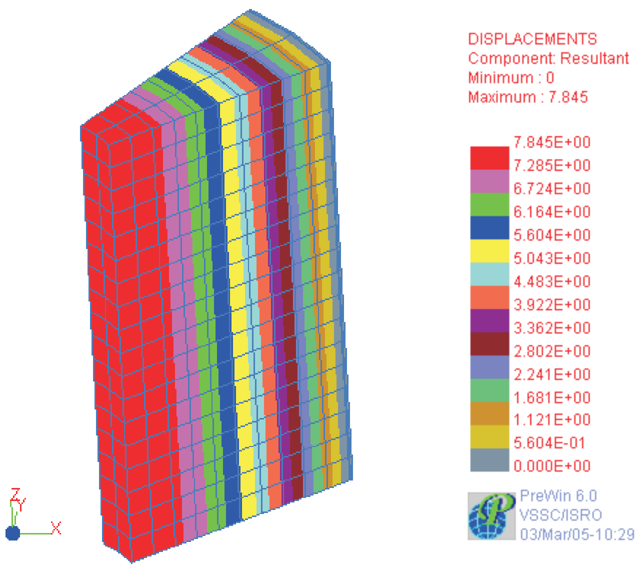

FIG. 7(c) RESULTANT DISPLACEMENT CONTOUR UNDER GRAVITY LOAD

5. STRUCTURAL NON-LINEARITY

In the linear structural analysis, displacements and strains are assumed to be small; the stress-strain relation is linear (material behaviour is linear elastic); and the nature of boundary conditions, remain same throughout the analysis. It is essential to carryout non-linear structural analysis for the following situations: The stress-strain relation is non-linear (material non-linearity); large displacements under the specified loading conditions (geometric non-linearity); change in the boundary conditions during deformation (contact non-linearity). By loading the structure in increments and through the use of an iterative procedure, it is possible to extend the linear solution of elasticity problems into the plastic range.

5.1 Rocket Motor Cases/Pressure Vessels

Finite element analysis (FEA) has been carried out utilizing the ANSYS software package to assess the failure of thick and thin-walled steel cylindrical pressure vessels. An axisymmetric finite element (Element type: 2D PLANE 42) available in ANSYS software package is utilized to model the cylindrical pressure vessel. Axial displacement is suppressed at both ends of the cylindrical shell to have no-axial growth under internal pressure. ANSYS has the provision for checking the global plastic deformation (GPD). It indicates the pressure level to cause complete plastic flow through the cylinder wall (i.e., bursting pressure). Failure pressure estimates from FEA (based on the global plastic deformation) were found to be in good agreement with test results of thin as well as thick-walled cylindrical vessels made of ductile steel materials [24].

6. DAMAGE TOLERANT APPROACHES

Damage tolerant approaches have been employed increasingly in the design of critical engineering components [25-27]. In these approaches, one has to assess the residual strength of a component with an assumed pre-existing crack. In other cases, cracks may be detected during service. Then, there is a need to evaluate the residual strength of the components in order to decide whether they can be continued safely or repair and replacement are imperative.

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PRODUCT LIFE CYCLE AND VISUALIZATION TOOLS FOR THE DEVELOPMENT OF PRODUCTS AND PROJECTS

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ABSTRACT

This note describes various Product Life Cycle and Visualization Tools available for the execution of Projects and development of Products. The note describes the Product Life Cycle Management System with its different segments under which the rapid product development and simulation software are exercised and also presents the various paradigms that are available as Visualization Tools during development, evaluation and finalization of the design. All these would help to design, and develop new products and also in the execution of new projects.

1. INTRODUCTION

Development of new projects or building new products have to harness the technologies that are available in the market place to make the project or product viable. The organization to develop the project is also important. New paradigms such as Virtual organizations have come about with the availability of tools such as the Internet, World Wide Web, PC and Video conferencing. These make it possible to carryout design in one place, manufacture in another place and market it in a third location. Hence it is important to have a plan for both the technologies to be used and the type of organizational set-up which would be able to deliver the infrastructure project or build the product.

A new project implementation or the development of a new product involves a large number of life cycle tasks. These have to be tracked from the requirements stage to its implementation stage and till its end of life. They involve a large number of activities and tasks and also involve a

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large amount/volume of data which gets created and transferred between the different stages and a large number of people to execute the same.

There is a need to manage mainly three things - the tasks, the people and the data in order to successfully complete the project – be it an infrastructural project or building a new product. In order to meet the quality standards, the tasks have to be completed to meet the functional requirements within the stipulated time and within the estimated effort and within the estimated cost. Hence without the proper Product Life Cycle tools and Visualization tools this would become near impossible in the present day context.

The objective of this note is to describe in brief the available Product Life Cycle tools and the various Visualization Paradigms that are available to meet the tasks.

2. TECHNOLOGY AND ORGANIZATIONAL DRIVERS

There have been rapid strides in technology and hence these have been the drivers for development for design, development and rapid building in the case of products and planning, simulation and rapid implementation in the case of infrastructure projects. These technologies are

1. Faster Computing Power
2. Better Graphics software and Commodity Graphics Hardware
3. Communications – High speed Networks
4. New Algorithms
5. New Solution Algorithms
6. PC and Video Conferencing
7. Network Security
8. Distributed Computing
9. Cloud Computing.

Similarly organizations have undergone sea change. Starting from steep hierarchies to virtual enterprises as listed below

1. Steep Hierarchies
2. Partnership
3. Matrix Organizations
4. Alliances (Customers, Suppliers)
5. Teams
6. Business Process Reengineering
7. Virtual Enterprise.

Hence these have resulted in making companies to bring out products which are more innovative, in the shortest possible time that have to be price competitive in the global market which can be designed and manufactured everywhere. This is shown very aptly in Fig. 1[1].

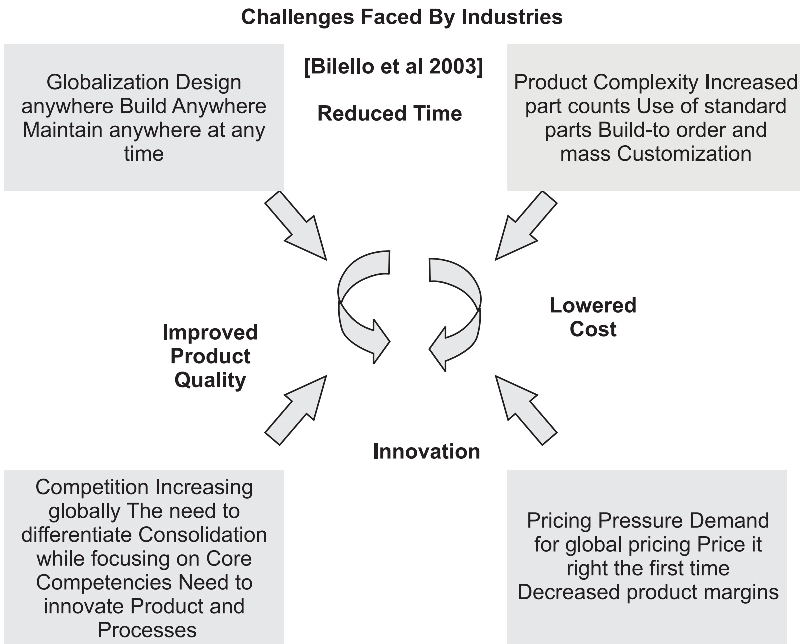

FIG. 1 CHALLENGES FACED BY INDUSTRY

A new project say an infrastructure project or a product development like an aircraft development or an automobile or ship or a high speed train contains many elements. There will be major and minor elements. They will comprise of different disciplines – geographical, historical, sociological, engineering (all branches). The various elements of the design could include:

- Route Maps
- Real Estate
- Design of the structures
- Product model.

For a project which is of a large size and nature, it is essential that a Product Life Cycle Management System (PLM) is used to manage the Project during its Product Development Life. Hence Product Life Cycle Management System and Visualization Tools are used not only in such a variety of Projects as railroads, highways, automobile production but also in pharmaceutical development, fashion design, jewelry design shopping malls and so as depicted in Fig. 2.

A Product Life Cycle Management is a tool to help manage three main items

1. Product or Project data
2. Processes for realizing the Product or Project
3. People for working on the Product/Project

FIG. 2 USES OF PRODUCT LIFE CYCLE MANAGEMENT AND VISUALIZATION TOOLS

In order to visualize the Product or Project, make decisions and finalize the product/project, Visualization tools are required and various Visualization paradigms are available for this purpose.

Therefore with the adoption of PLM many benefits accrue

- Helps to deliver more innovative products and services in a shorter time.
- Is able to shorten time to market.

- Establishes a more comprehensive and collaborative relationship with customers, suppliers, and business partners.
- Improves communication among departments.
- Improves the success rate of newly introduced products and.
- Reduces costs by taking advantage of the efficiencies and effectiveness that come from improved market intelligence and business collaboration.

3. PRODUCT LIFE CYCLE MANAGEMENT TOOLS

Product Life Cycle Management Tools have made significant strides. Initially they were not all encompassing and covers from conceptual to end of life. In the beginning it was just managing only CAD data when CAD started out and in the 1990's it was called Product Data Management where its focus was on functions. Towards 2000s it turned towards processes. Now it is on the bottom line. Over the years PLM implementations have been custom implementations to Tool Kit and Generic Applications to Innovations. Hence in short, on one side of the PLM implementation is the movement from a) Cost, Quality, Time to Market to Innovation and on the other side it is the engineering side b) Task Automation, Concurrent Engineering, Shared Environment to Collaboration [2].

The various stages are, Conceptual Design, Detailed Design and Prototype Manufacture or Construction, Series Manufacture or Implementation, Operations and Maintenance. The evolution of PLM systems over the years during the internet era and the extension of e-business across extended enterprises like suppliers and development partners has led to the growth of its use and increased the offerings by vendors [3]. The need to integrate business models with the technical information has also been established [4].

The Product Life Cycle Management software originally consisted of two main segments namely Product Data Management (PDM) which covered the Development Life Cycle from Conceptual Stage to Detailed Design and Prototype Manufacture or Construction and Enterprise Resource Process Manager (ERP) which managed the series Production. However the PDM segment used during the Conceptual Design phase is often called the Virtual Product Manger (VPM). It is closely tied to the authoring tools of the design package since it has to allow for large amount of changes [5]. To manage the requirements of the project of this magnitude at various levels a software is required. Requirements gathering and Systems Engineering (RSE) is an important segment of the PLM tool. This is usually a separate software. Finally once the product and the system has been deployed it has to be maintained then a software is required and that segment of the Product Life Cycle Management is called Maintenance, Repair and Overhauling (MRO). A new data manager is evolving which is called Simulation Process Management (SPM) or Simulation Life Cycle Manager (SLM) which is part of the PDM in that the activities and workflow will be part of the PDM but the data and processes it manages will be that of simulations [6, 7].

All these segments may be from different vendors. In general all the segments may be bought separately from different sources and implemented and integrated. An integration of VPM and PDM sourced from different vendors has been successfully put in place in the implementation of the PLM solution for the development of the Tejas Aircraft Design where the VPM Activity was done in ENOVIA and the PDM activity was done in Teamcentre Enterprise [8, 9, 10]. The data export was written in-house using STEP [8, 9]. Lately all vendors have tended to integrate the different segments into one software.

For the design of and development of the various elements of a Project, activities include

(i) Authoring or Creation of data (CAD)
(ii) Simulation or Computer Aided Engineering (CAE)
(iii) Visualization, Virtual Prototyping, Physical Prototyping build and Evaluation (VR, VP, CAM)
(iv) Optimize and Finalize
(v) Final Build.

The activities, design stages and the various segments of PLM are shown in Fig. 3. Engineering Data Management (EDM) is sometimes listed as a separate activity and the manufacturing activity listed as Computer Integrated Manufacturing (CIM) to encompass the complete manufacturing activity into PLM [11]. Need to link Customer Relationship Management (CRM) and Enterprise Resource Management (ERP) and the need to develop a PLM Strategy, carryout Digital Manufacturing and also the necessary for conducting an assessment for PLM implementation readiness is emphasized [11]. For the activities of CAD, CAE and CAM or CIM the software used would depend on the element that is being designed. For instance if the layout of the tracks, or a road system is to be done the authoring software would be a Geographical Information System (GIS), for infrastructure like stations, bridges, then the an Architecture Engineering and Construction(AEC) software among others would be used for the design. If it is a product like a coach or a locomotive then styling software or a Geometric modeling software (CAD) would be used.

Simulation or Computer Aided Engineering (CAE) software would be either a Finite Element Analysis (FEA) software for structural analysis [12] or a Computational Fluid Dynamics Analysis (CFD) for fluid flow or any of the CAE software for Simulation of Railway Systems [13]. For physical prototyping and to build products like coaches or locomotives, Computer Aided Manufacturing (CAM) software can be used. For buildings AEC can be used. For other activities like Virtual Prototyping and Visualization etc., it a system would have to be put in place for evaluation and finalization.

Optimization is part of many of the simulation software. There are a number of modules that carryout the functions under the segments of the PLM solution and these are described below. The application of PLM and visualization tools if one were to use it to rapidly develop a new paradigm for the country's transportation system can be found in Reference 14.

3.1 Requirements Generation, Analysis and Management

For a large project requirements generation, analysis and management is a very important activity and a proper software tool should be used for it. Most of the Project Life Cycle Management

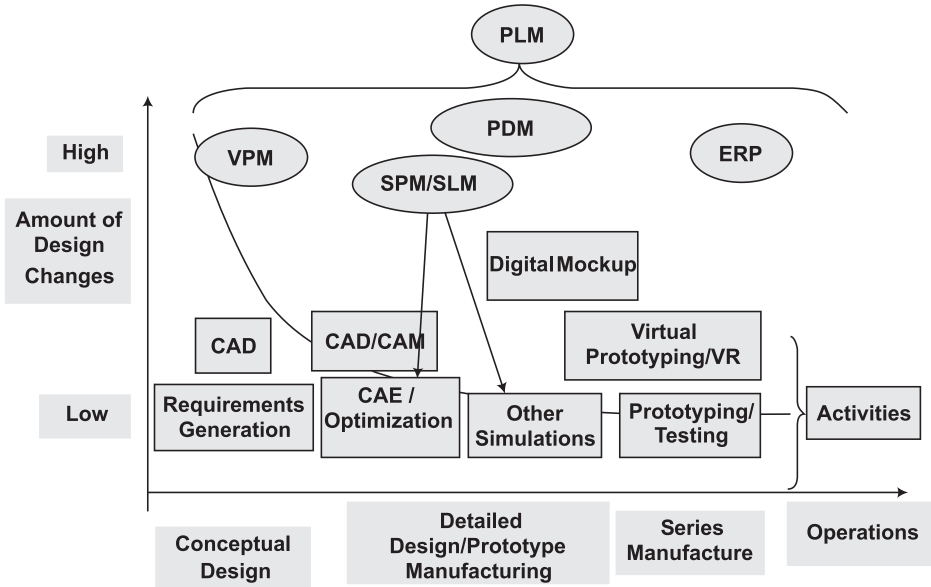

FIG. 3 PRODUCT DEVELOPMENT LIFE CYCLE

software available in the market comes with this module. The requirements generated can be put into the software; it can be changed, managed and updated. The software will properly track the requirements throughout the project and let the management know if there is a change and when it has been changed and by whom. If the project is being implemented at more than one place it would be a very important aspect of the total project.

3.2 Conceptual and Detailed Design Stages

During this stage of the design cycle the project design would evolve. Whatever is decided at this stage will affect the outcome of the project. Costs will depend on the design philosophies and designs chosen at this stage. Cost expended at this phase of the project would be small. Tools for Geographical Information System, Terrains, Architecture, Engineering, Construction (AEC), bio-informatics, Manufacturing (CAD/CAM) would need to be put in place and exercised. Next, simulations using CAE tools mentioned above will have to be used including optimizations (Fig. 3). The various modules of VPM/PDM that would be exercised during this phase of the design would be the Bill of Materials (BOM), Design Workflow Management, Change Management and Configuration Management. The design and engineering simulation can be put into a workflow which will be specific to the type of system being developed and to the organization. Figure 4 is a typical Design Workflow used in aircraft industries where the systems are incorporated and where weight control has to be exercised in the design [8, 9, 10].

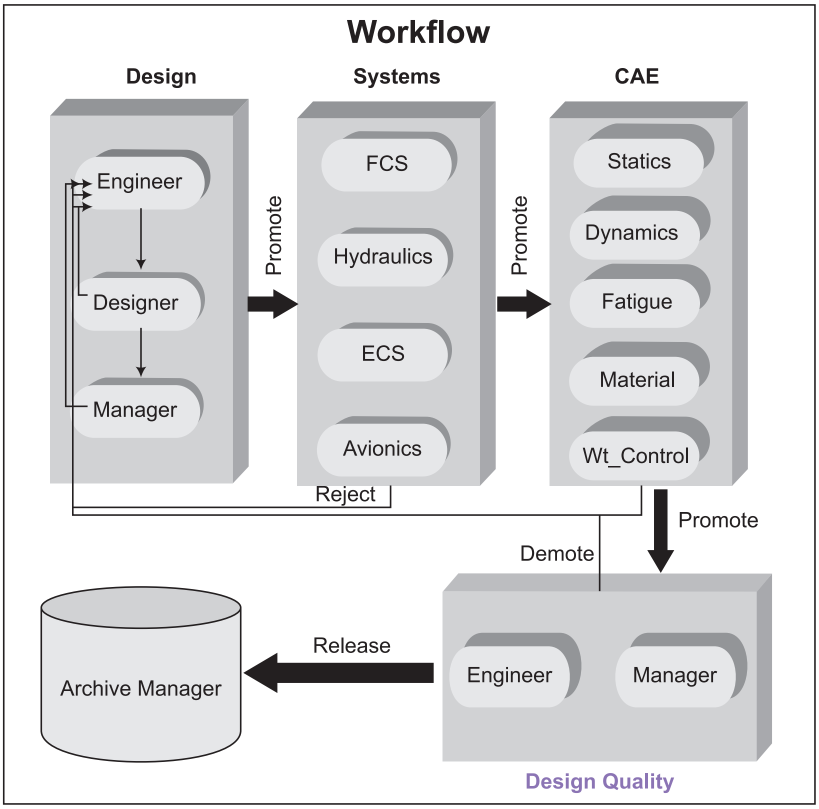

FIG. 4 DESIGN WORKFLOW FOR TYPICAL AIRCRAFT DESIGN

3.3 Detailed Design/Prototype Manufacture Stage

In this stage of the design, the changes to the design will be low; Process focus will be on quality and validation. Because of availability of VPM and PDM tools as the design is being made, it is visible to the manufacturing group and hence concurrent engineering work is going on but in a controlled way. Hence the process model is concurrent and controlled. Data model is released and any changes required will be through Engineering Change Orders (ECO) [5, 8, 9]. More CAE and other simulations would be run during this phase. Another important activity during the detailed design stage is the building of a Digital Mock-up (DMU). It is a collection of 3D models which are positioned to represent the form of the product. Each model is attached to a part in the product structure (BOM). The triangulated representation of the model is made so that a large number of parts can be visualized and interference checks can be made.

A typical manufacturing work flow is shown below in Fig. 5 where the design data resides in the VPM system and it is transferred to the PDM system from where the manufacturing work flow is controlled. If the element of the system involves building the track system or the infrastructure then there will be a work flow for that. This Build Workflow has to connect to the Design

Workflow Management, Configuration Management and the Change Management. Manufacturing stage generates many reports and Engineering Change Orders which have to be transferred back to the Design Stage. Provision has to be made in the Manufacturing Process for generating various types of reports.

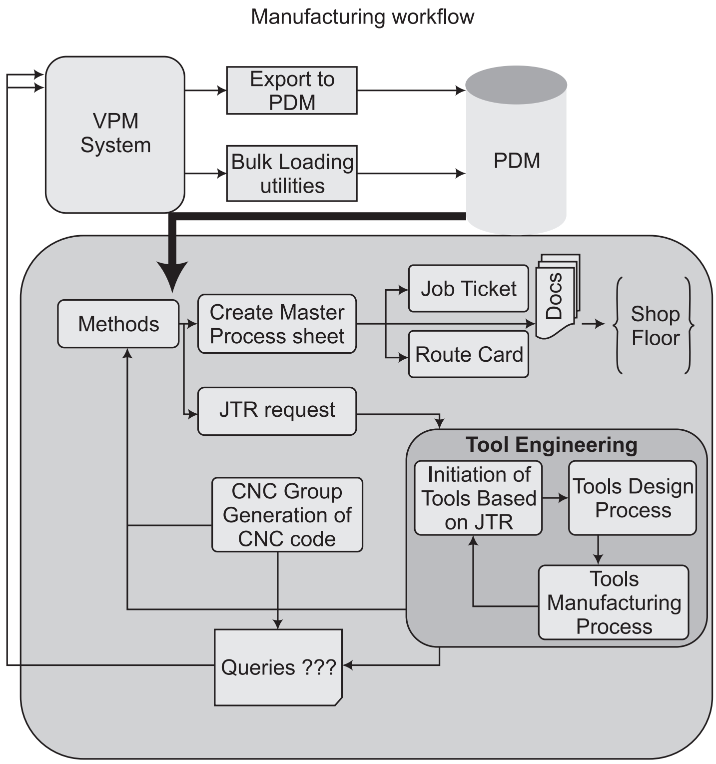

FIG. 5 MANUFACTURING WORKFLOW

4. SIMULATIONS, PROTOTYPING AND REVIEWS: VISUALIZATION TOOLS

Product Life Cycle Management Systems are good at managing the meta data. While a vault is there for storing data that is generated by the authoring tools, data including visualizations which are required for reviewing and those generated by simulations are not readily managed or served by the PLM systems. After the conceptual design, various simulations are carried out such as Finite Element Analysis, Thermal Analysis, Computational Fluid Dynamic Analysis and simulations involving railway models (tracks, running speed, traction, etc.). Models may be created and tests carried out. Or physical prototypes made and tests carried out. The results of these need to be examined at several levels and reviewed and the design approved.

In general there are several domains where raw outputs (models, analysis-results, field data, etc) produced by technical computations provide insufficient information into problem behavior [15]. For instance in general in a projcet there would be inputs such as

- Geographical Info Systems
- Visual Simulation (imagery, terrain...)
- Architecture, Engineering, Construction (AEC)
- Bio-informatics
- Medical imaging
- Ground and Oil exploration
- Manufacturing (CAD, CAM, CAE...)
- Others.

From these raw outputs, Visual imageries, such as 2D, 3D, animations, etc., are required to extract insights towards

(a) Understanding the problem behavior.

(b) Accelerating the problem solving cycle.

An example of visual Imagery produced from a GIS (maps), Engineering Construction (VR) and Computational Fluid Dynamics (CFD/CAE) are shown in Figs. 6(a), (b), (c) respectively.

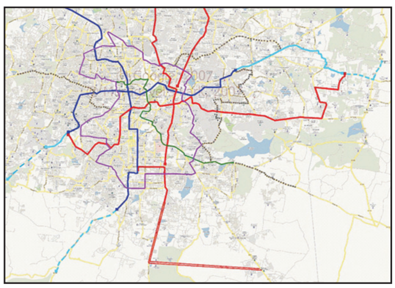

FIG. 6(a) GIS IMAGERY

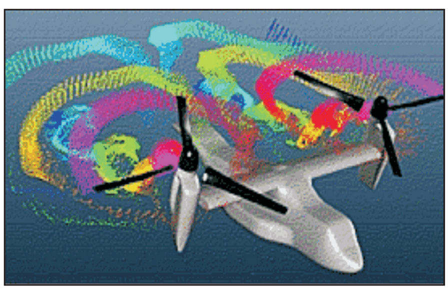

FIG. 6(b) CFD/CAE SIMULATION

FIG. 6(c) VIRTUAL REALITY REPERESENTATION

These raw outputs are produced by skilled research and development engineers, applications engineers and technology experts and scientists. However they are consumed, evaluated and need to be finalized by project managers, department or group or program heads, other departments, sales, marketing, customer support, other divisions, manufacturing, maintenance, quality, shop-floor, authorised customers and/or suppliers. The workflow for simulation, interrogation, modification and finalization is given in Fig. 7 [15].

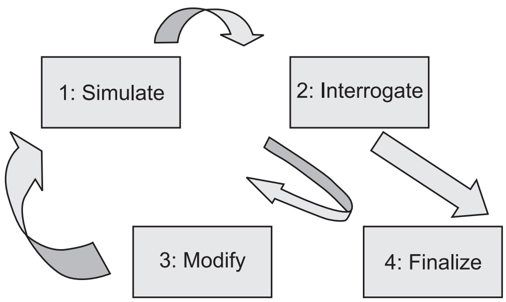

FIG. 7 WORKFLOW FOR SIMULATION, INTERROGATION, MODIFICATION AND FINALIZATION

Hence a number of implementations have evolved to evaluate, review and finalize the designs and simulations. Those important for are described below are the various visualization paradigms.

4.1 Virtual Prototyping

For a large project whether it is an infrastructure project or a development of a product it is necessary that the technology of Virtual Reality should be used as much as possible. For example, if it is a Transportation System then Virtual Reality implies that all the objects of such a system like the stations, the tracks, the trains, the bridges, the buildings will be in the computer world or the "Virtual World" but the effect on the person or persons perceiving these objects would be "Real". It would depend on what is put into the models what types of behavior and what types of finishes etc., are put into the model [14]. As simulations are performed on the models, they can be added and these can be visualized [16, 17, 18]. Behaviours can also be attached to the objects. Stereo Vision adds to the effect giving a better understanding of the objects. To the basic sense of seeing the other senses can be simulated like hearing, touching, smelling making the objects more real. Hence this is called Virtual prototype. Virtual Prototype is defined as a complete 3D description of the large Product Assembly of a Structure in the computer with facilities to visualize and analyze the form, fit and function of the product in real time. A Virtual Prototype allows for Large Visualizations, including Stereo, Walk throughs, Path File Simulations, Behaviours, CAE Simulations, Interference Checks both passive and active and build and repair [19, 20]. An immersive Visualization session is shown in Fig. 8.

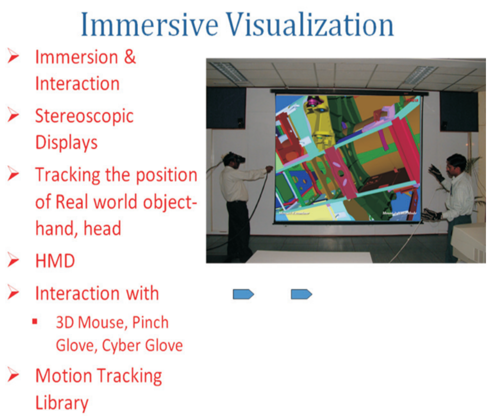

FIG. 8 VIRTUAL REALITY/VIRTUAL PROTOTYPING SESSION

The Virtual Reality Technology can be used for the different disciplines here such as Architecture and Construction, Art, Business, Serving the Physically Challenged, Education and Training, Engineering, Medical Service/Emergency, Entertainment and Marketing.

Since there will be multiple development centers and the public will have to be also brought and satisfied about the project it is recommended that one large Virtual Reality Centre with 3D Projection System and one Cave type be established at the Main Office [19, 20]. Desktop systems for the design engineers can be established at the individual offices. Head mounted Display Systems and haptic devices may be purchased if the need arises.

4.2 Visualization Servers and Three Tier Architecture using Web Browsers

This paradigm works on the similar principle as the three-tier business applications [15]. In order to bring the content to the consumers that are the managers, the authoring tools would generate the data and save them on some vaults (say the PDM vault). These would then be processed by Visualization Servers. Then a job scheduler would feed the data to the Web Server which would then serve the data to the end user who is using a net browser through a firewall via a http traffic. The architecture of the Visualization Servers is given in Fig. 9. The basic Paradigm for Engineering

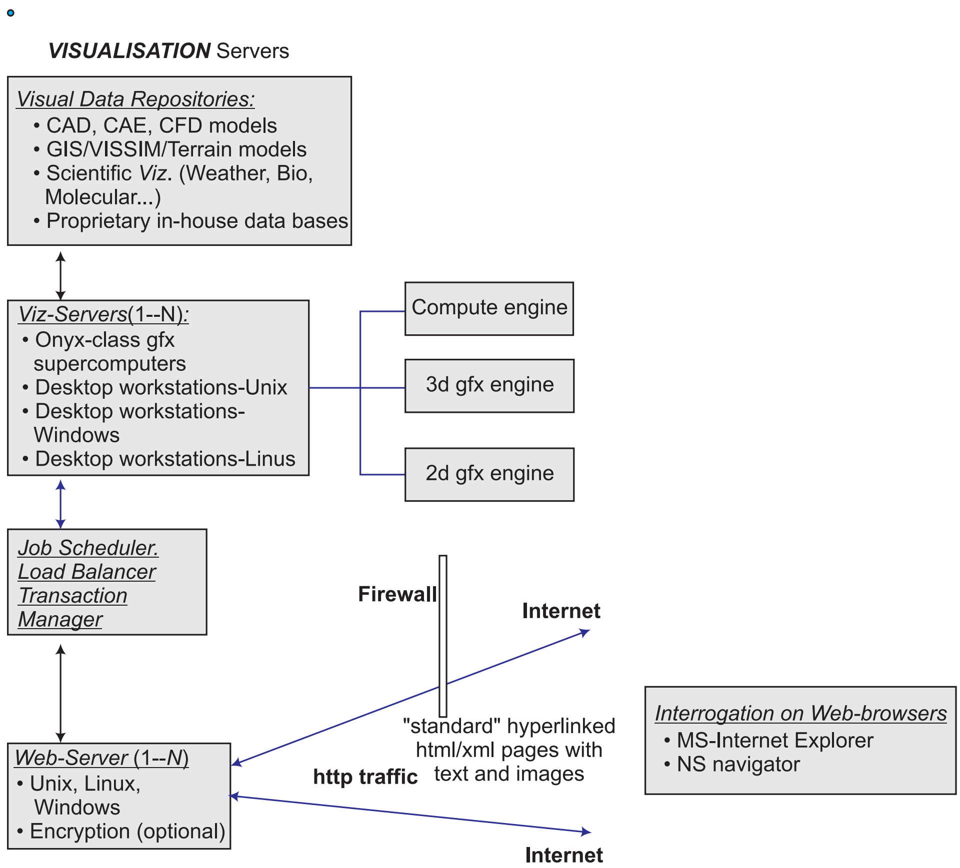

FIG. 9 VISUALIZATION SERVERS WITH THREE TIER ARCHITECTURE

Data Interrogation is “Browsing Through the Web”. The network traffic consists of web pages which is html plus 2D images. Hence the speed of processing can be enhanced by having faster servers while the client needs to only display the pages and need not have very high computational power. An implementation carried out at ADA is shown in Fig. 10 [21]. The product structure of the assembly of the typical aircraft fuselage using the Visualization Server is shown on the web browser and the parts can be identified on the browsers. If the compute time for data is very high then one can scale up the servers while it would not affect the time to serve the data. Tasks like rendering can be done in the background and data stored in the server. An individual CAD model may be very large in size and may take many person months to model on a system. Since it is made up of many surfaces of a highly complicated nature it may take a long time to render even on a very fast single processor system running for several days.

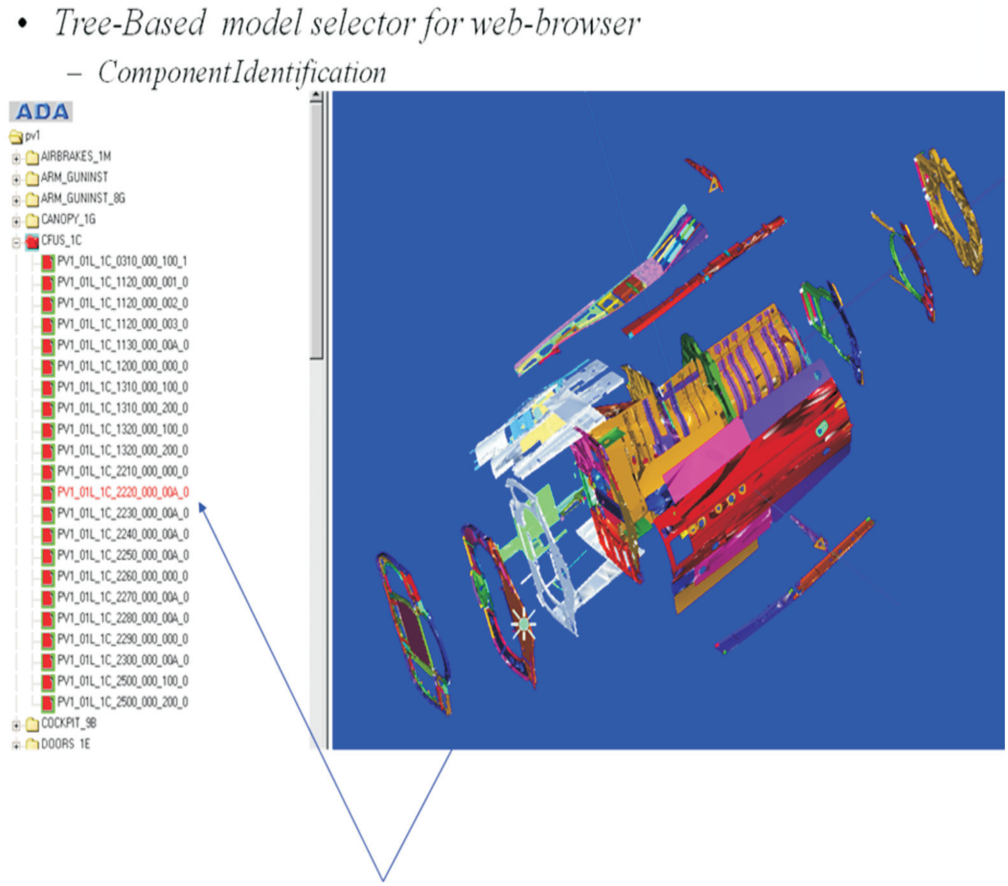

FIG. 10 TREE BASE PRODUCT STRUCTURE FOR WEB BROWSER USING VISUALIZATION SERVER

One may have to render it by running it on several multiprocessor systems to get a faster result. There have been many different methods developed for achieving high speed rendering by distributing it to various systems or a cluster of PCs [22, 23].

An example a locomotive designed using AUTODESK, MAYA for China Southern Railways took over 75 hours to render on a single server with 6000 frames.The same thing was rendered in 10 hours using Cloud Computing using 30 idle desk tops in about 10 hours using ANEKA MAYA Renderer [24]. These rendered data can be saved and served through the visualization servers.

4.3 Compact Data Format and Interacting with CAD Models

Another methodology for Visual Collaboration is to develop a compact data format for the 3D model and its attributes. One such format developed was the VIS. Format which contains the complete model information [25]. It was implemented for visualizing and Interacting with CAD models and generating an assembly/disassembly sequence for the aircraft radome using JAVA on the net as shown in Fig. 11. This methodology is useful since it allows one to program for specific uses in the project [25].

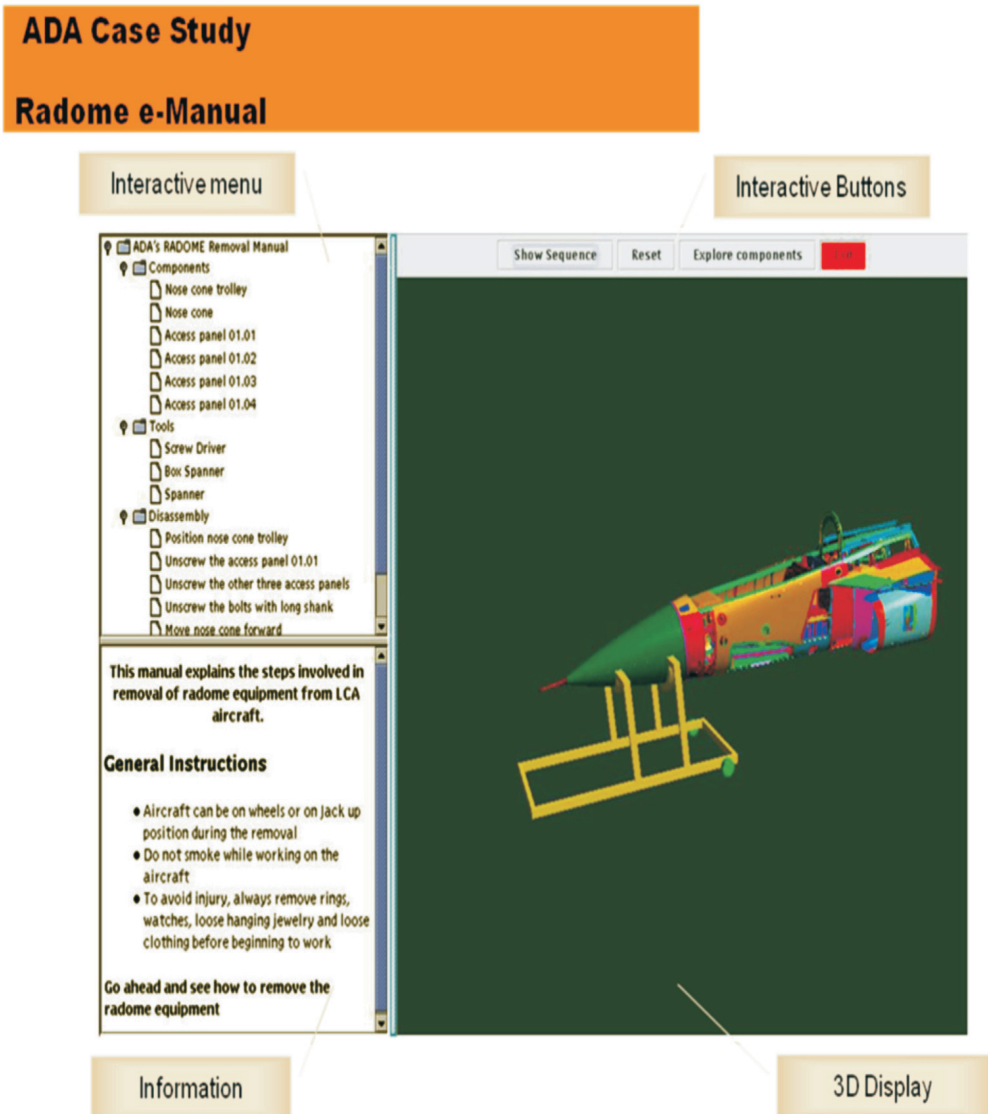

FIG. 11 IMPLEMENTATION OF ASSEMBLY PROCESS USING A VIS FORMAT FOR DATA ACROSS THE NET

4.4 Simulation Life Cycle Manager for Multi-Vendor CAD/CAE/CAM Data

It can be seen that the CAD/CAE/CAM data come from many applications and in different formats. Each application has its own Visualization and each has its native format. However as it has been shown above it does not allow for collaboration.

Hence a new segment to the Product Life Cycle Manager called the SPM or SLM has been developed [6, 7]. This is used to manage the simulation data and also provide a means for its evaluation and finalization through visualization and collaboration. Here a compact format is developed for extracting the data from the native CAX software for this purpose. Though for CAD visualization there are a number of formats available, for combining CAD and CAE there are very few in the market. One such is from Visual Collaboration Technologies [26]. It has a format called the CAX format which extracts from the native formats of the various CAD/CAM/CAE packages the relevant data in a reduced form for visualizing and sharing.

As seen in Fig. 6 it is essential that a simplified tool be required for visualization. Since the various design, development and managerial teams for this project will be at various locations a light weight tool is required.

It should be possible to bring in data from several applications and multi-disciplines. One such tool has been developed by Visual Collaboration Technologies called VCollabPro. The data from several applications can be brought from through VRML ar through the native format through an API called VMoveCAD and VMoveCAE for CAD and CAE files as shown in Fig. 12.

VCollabPro has extensive CAD visualization of the product. It can also be visualized in 3D Stereo with passive or active glasses [27]. Figure 13 shows the various platforms in which the data can be viewed. In the CAE environment it allows for displaying the displacements, stresses, strains, cut sections, hotspots, temperatures in a thermal analysis, stream lines and pressure plots in a CFD analysis, etc. In the CAD environment, it can viewed in the Stereo mode, as cut sections, as walk throughs etc. VCollab also integrates into the Optimization framework iSIGHT-FD for purposes of visualization of the design results [26].

VCollab Pro suite also has a software for presenting the results called VCollab Presenter which helps in documenting the data and integrating with the Microsoft's Powerpoint, Word and Sharepoint. There is a light weight viewer which is free and it can be used to view the results across the net when the results of the visualization are stored in the CAX format [26, 27].

VCollab Pro suite also includes a Portal called Marechi for sharing the data of the CAD/CAE/CAM/VR activities. This data can be shared within one's group or community. This is modeled similar to the Youtube format where it can be used informally and openly or in a secure environment within an organization unlike other general PLM offerings. Hence this is quite popular in the Universities. This is shown in Fig.14. The CAE/CAD/CAM/VR data is readily viewed with the VCollab PRO software or the free lightweight viewer.

4.5 Lightweight Visualization Format

Lightweight Visualization Format is a 3D data format and is used for product visualization, collaboration, and CAD data exchange. It contains combination of approximate (faceted) data,

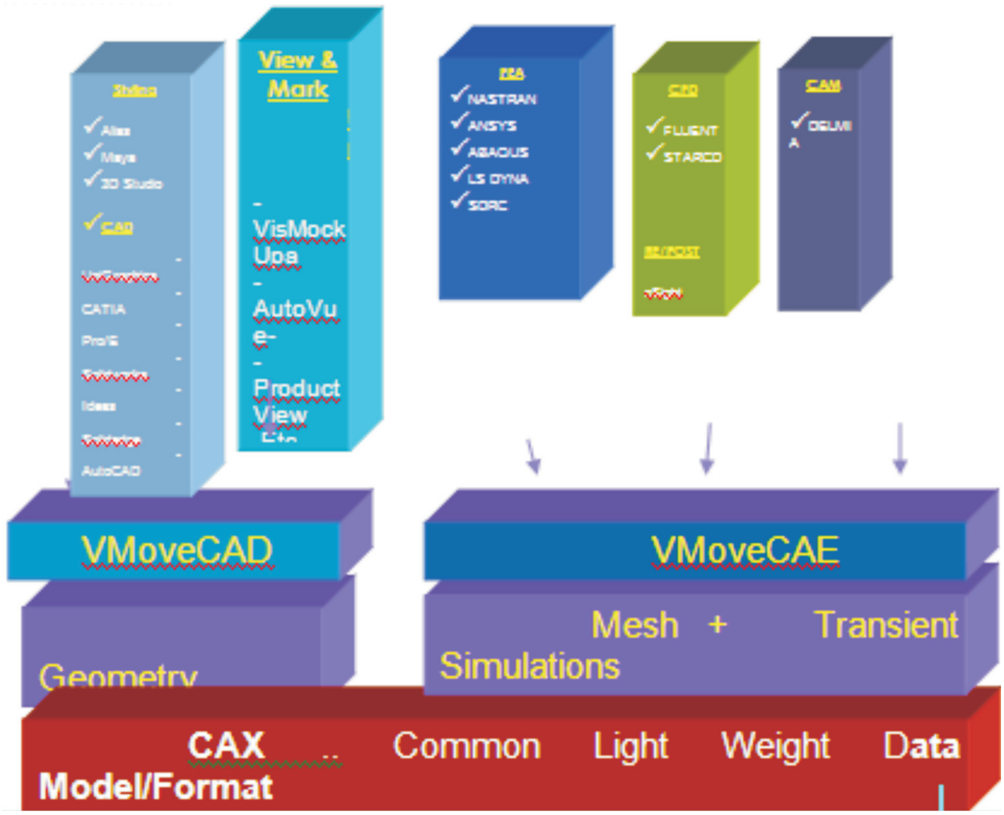

FIG. 12 GENERATION OF A COMMON LIGHTWEIGHT DATA MODEL FOR CAE DATA. (CAX FORMAT)

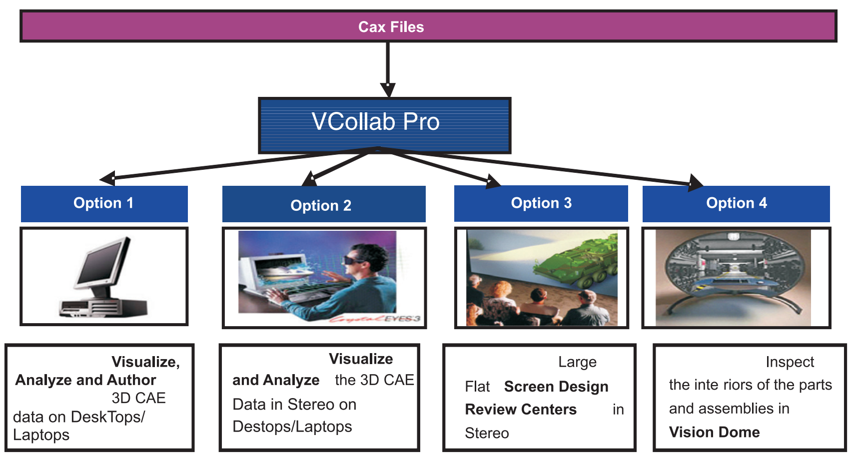

FIG. 13 VARIOUS PLATFORMS FOR IMPLEMENTING VCOLLAB PRO

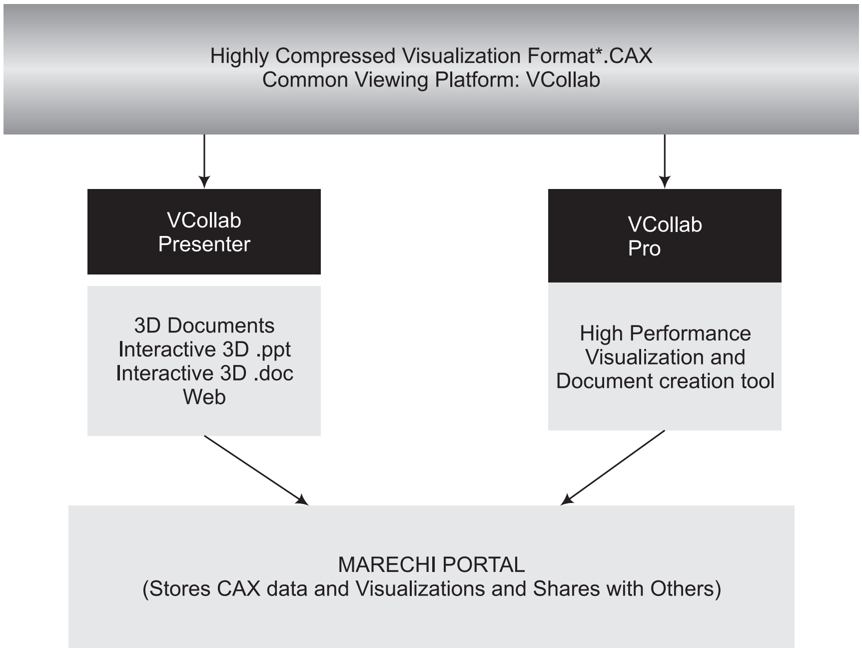

FIG. 14 PORTAL FOR STORING AND SHARING SIMULATION PROCESSED DATA AND VISUALIZATIONS

exact boundary representation surfaces (NURBS), Product and Manufacturing Information (PMI), and Metadata (textual attributes) either exported from the native CAD system or inserted by a product data management (PDM) system.

Lightweight Visualization are used extensively during the product development stages for collaboration, design in context across distributed work centers. With these, highly inherent complex product are developed efficiently with less time and effort as the components are quickly loaded, shaded and manipulated in real-time. The resulting multi-CAD assembly is managed such that changes to the original CAD product definition files can be automatically synchronized with their associated Lightweight Visualization files resulting in a multi-CAD assembly that is always up-to-date.

Lightweight Visualization files are inherently “lightweight” (~1-10% of the size of a CAD file) they are ideal for web collaboration. The Lightweight Visualization has build in security feature such that intellectual property does not have to be shared with inappropriate parties. As indicated above, Lightweight Visualization can contain any combination of data such that the right amount of information can be shared without exposing the underlying proprietary design definition information.

The Engineers across the Enterprise will work on Lightweight Digital mockup (DMU) to validate, assemble, dis-assemble a product without interferences long before a physical prototype could be produced. Leveraging Lightweight Visualization for digital mockup allows users to reduce or eliminate costly physical prototypes and enables decision-making to occur much earlier in the development process.

Lightweight Visualization thus used as a CAD interoperability format for exchanging design data for Collaborative Product Development, where Lightweight Visualization files are created by translating data from CAD systems such as NX (Unigraphics), Creo Elements/Pro, I-DEAS, Solid Edge, Catia, or Autodesk Inventor. Lightweight Visualization is supported by an open industry forum, the Lightweight Visualization Open Program that is an open, influential community of users, software vendors, and interested parties advocating the use of Lightweight Visualization as the visualization, collaboration and data-sharing standard for the PLM industry.

4.5.1 Large model rendering

Lightweight Visualization was created to support the interactive display of very large assemblies (i.e., those containing tens of thousands of components). The Lightweight Visualization file format is capable of storing an arbitrary number of faceted representations with varying levels of detail (LODs). When the whole product is displayed on the computer screen the hosting application displays only a simple, coarse, model. However, as the user zooms into a particular area, progressively finer representations are loaded and displayed.

The Lightweight Visualization data model is capable of representing a wide range of engineering data. This data can be very lightweight, holding little more than facet data or it can be quite rich, containing complete NURBS geometry representations along with product structure, attributes, Meta data and PMI. It also supports multiple tessellations and level-of-detail (LOD) generation.

4.5.2 Inference

Analyzing with all the properties like file size, Product structure, Dimensioning, data loss, design intent With all these Situation interoperating through Neutral CAD format, normally **STEP** Remains a best approach interoperating between two CAD system in particular. For interoperating within the PLM environment and for better Visualization the **Lightweight Visualization**–Lightweight Neutral format remains best in all aspects.

4.5.3 Essential features required of the Light Weight Format

The Lightweight CAD Neutral Format should have the following essential features as below:

1. It should be capable of bi-directional accurate, translation of geometric parameters, shape, surface, all graphic text based Annotated information and GD and T and PMI between Itself and its native CAD System and later versions.
2. It should be possible to design on one of the CADs above and integrate on Another...

It should absorb and exchange and create in single Neutaral CAD file all GD and T & PMI and all other annotated information automatically and seamlessly.

(a) Primarily the Lightweight Format (LWF) should be suitable for
   1. Collaborative Design
   2. Efficient Visualization of Models and all data
   3. Efficient Usability of the LWF object for design in any CAD for, add on design
   4. High dimensional Accuracy in the Translation
   5. DMU based engineering (DMU)
   6. Virtual X BOM and Configuration Control.

(b) Sustainment of Bi-Directional Multi CAD Geometric accuracy between Original CAD Models and the LWF models in all transactions such as
   1. CAD to LWF and back
   2. LWF to ANY CAD and back.

(c) The LWF Models should be suitable for direct use for CAE Processes (FEM etc.).

(d) The LWF Models of Parts and Assemblies should be suitable for use in designing, simulating, validating the manufacturing and assembly Processses through the Digital Manufacturing VR Software.

(e) LWF Models should be suitable for carrying out Assembly Tool Design , Simulation and validation and be compatible with any MCAD Software that may be used by the Tool Designer or the Robotics and Automation engineer in the community collaboration mode.

(f) GEOMETRY In the case of the geometry, it is specified that a deviation of no more than 1% of the original values will be allowed for volumes and surfaces and a deviation of no more than a sphere of diameter 50 Microns for the position of the center of gravity.

(g) Auxiliary geometry such as points, axes and surfaces, as well as 3D lines, should also be visible in the same contrast as original in the receiving systems.

(h) PMI annotations should be displayed graphically tables text boxes etc)as in the sending system and should also be exactly reproduced and recognized as PMI elements in the receiving system.

(i) Material data-material Specs/condition/special process ref etc should be transferred to the receiving system.

(j) The RGB transfer efficiency should be the highest.

(k) The hierarchal assembly depictions as sent under DMU based configuration Control should be received at100% accuracy at the receiving end and vice versa.

(l) The position of the parts should not change in the assemblies between the sent DMU data and received data.

(m) There should be means to check the tally of the product structure between sent and received Model Based Data in the LWF.

(n) The LWF model will be used as DMU for Configuration Control of product and **Process** and as such be under governance of the PLM's Configuration control system.

5. PROJECT MANAGEMENT AND DOCUMENT MANAGEMENT

Project Management is a very important activity in such a large project and all activities need to be tracked. A proper way of estimating the tasks, manpower allocation, work in progress etc need to be done in order to see that the project gets completed on time or within some tolerance levels. Document management is also very important as traceability has to be maintained. In the LCA Project the PLM tool was used to track the progress of the Design and Manufacturing activity using a active html link to the status of the release of the models. Hence delays could be traced and corrected and work could be speed up [8, 9, 10]

6. MANAGEMENT OF THE PLM SYSTEM

The PLM system will be installed on a large number of workstations, with many software licenses. Managing such a system is not a trivial task. The system may also include cloud computing. A system of redundant software licences needs to be put in place to reduce down times. Management of large systems needs to be optimized taking into consideration the number of systems, the licenses available and the user requirements and this has been successfully implemented for the Tejas aircraft design [10].

7. OTHER SYSTEMS, TOOLS AND SOFTWARE

There would be other systems, software and tools required to carryout the project of this size. As mentioned an Enterprise Resource Software (ERP), would be required or a CRM (Customer Resource Management) among others. An ERP solution for rolling stock which is under implementation in the Indian Railways can be used as a model [28]. Computer services and different types of architecture like Service Oriented Architecture (SOA) or Cloud Computing may be required for the project and integrating business models into the PLM solutions [4].

8. SELECTION OF A PLM SYSTEM

There are many PLM systems available in the market. They come bundled with the various elements or modules such as the ERP system, the VPM system, the SLM or the SLM, the CAD system, the CAE module, the CAM, the PDM system, the Requirements module etc. It is generally good to go for a multivendor offering of the various system. Generally because of the nature of the tasks and applications, it will be seen that software from one vendor may not fit for all applications. There have been studies to determine a company's PDM requirements using a Quality Function Deployment for Collaborative Product Development [29]. Subsequently they have come up with an Objective Approach to identifying the strategic elements of a PDM system [30] which has been further enhanced by other workers in the field using field surveys [31].

However in addition it is best to also carryout a pilot study and implement a few of the processes and put the people and data into the system.

9. ACCEPTANCE OF THE PDM SYSTEM

If the PDM system is being implemented for a new project then it can be used from the first day of the project and there will be no resistance from the users. However if it is an existing project then there will be resistance from the existing users to use the PLM system. Also there is a requirement to have all the legacy data put into the system. If the PLM system is being implemented by the Vendor who is supplying the software he will not be interested in spending the time to put the legacy data since it is time consuming and the work is not an interesting task. However this should be made as part of the contract before the system is accepted. Otherwise users will not use the system.

10. SUMMARY

These notes describe the Product Life Cycle Modules and the various Visualizations Paradigms available for building a product or a large infrastructure efficiently within the estimated time, effort and to the requirements such that it meets all the quality objectives. The usage of PDM during the various phases of the life cycle would vary from around 20% in during conceptual stage, 100% in Product Design, to about 40% during Prototyping and Testing. Then it comes down from about 25% during Process Planning to about 10 % during service to around 2% during Removal and disposable. Even though it is quite small at the end it still allows one to keep tract of the product till the very end of life.

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SUPPORTED LAYERED DOUBLE HYDROXIDE ADSORBENTS FOR DEFLUORIDATION OF WATER

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ABSTRACT

Layered double hydroxides (LDHs) were supported on agricultural waste materials viz. coconut coir and areca nut fibers and the adsorption properties of these supported materials for fluoride adsorption were studied. Two different supported LDHs (Zn/Al and Mg/Al) were prepared and the effect of preparation method (co-precipitation in aqueous medium, direct deposition), relative metal concentrations and nature of support on the fluoride adsorption capacity was studied. Supported LDH prepared by direct deposition method exhibited higher fluoride adsorption capacity compared to unsupported LDH and that prepared by co-precipitation method.

1. INTRODUCTION

Layered double hydroxides (LDH) have attracted considerable attention in the recent decade for their wide application in the selective removal of toxic-hazardous pollutants from aqueous systems [1-4]. They consist of flat two-dimensional structural network composed of different hydroxy layers of bivalent and trivalent metal ions. The positively charged layers of mixed metal hydroxides require the presence of interlayer anions to maintain the overall charge neutrality. They have the general formula $[M_x^{2+} M_y^{3+}(OH)_{2(x+y)}]\ A_{y/n}^{n-}.\ mH_2O$, where M^{2+} is a bi-valent metal ion like Zn, Mg, Cu, Co, Ni, etc., M^{3+} is a tri-valent metal ion like Al, Fe, Cr, etc., and A^{n-} is the interlayer anion. Presence of large interlayer spaces and significant number of exchangeable anions make the LDHs attractive for application as ion-exchangers and adsorbents. The defluoridation capacity of layered double hydroxide (LDH) adsorbents has already been established in laboratory-scale studies [5, 6]. LDHs are found to be very good adsorbents for defluoridation of water but they suffer from some limitations, which restrict their real-life application. Though the LDHs have very high specific surface area, the available surface area is always less than the actual due to the

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agglomeration tendency of the LDH nano-particles. This characteristic makes it very inconvenient to pack in fixed bed columns for continuous operation. Fixed bed columns for water treatment packed with fine LDH particles give huge pressure drop. To overcome these limitations, we thought of supporting the LDH on suitable support material. It may also be possible to enhance the ion-exchange/adsorption capacity of the LDH by dispersing the fine LDH particles on suitable low-cost, natural, bio-degradable material. A unique study on cellulose supported Zn/Al LDH revealed that fluoride adsorption characteristic of the LDH was greatly enhanced by supporting on cellulose [7] as high dispersion of the LDH particles on cellulose surface provides better accessibility of the adsorbate ions (fluoride) to the active sites of LDH. Also, there is no report till date on such supported LDHs and their use for adsorptive removal of fluoride in water, except our previous publication [7].

The present communication reports synthesis of supported LDH adsorbents and their application for defluoridation of water. Agricultural waste materials like, coconut coir and areca-nut fiber were used as support materials for the LDH. Two different techniques namely, co-precipitation and direct deposition, were used for supporting the LDH particles on the support materials. The supported LDHs were used for defluoridation of water and the results were compared with unsupported LDHs.

2. MATERIALS AND METHODS

2.1 Materials and Reagents

AR Grade $AlCl_3$, $ZnCl_2$, $MgCl_2$. $6H_2O$ and NaOH procured from sd fine-CHEM limited were used in the synthesis of LDHs. H_2SO_4, HNO_3 and H_3PO_4 acids used for chemical treatment of the supports were laboratory grade reagents from Merck. Stock solution of fluoride (1000mg/l) for defluoridation study was prepared from AR Grade sodium fluoride (MERCK) and stored in polypropylene bottles. Distilled water was used for preparing the solutions.

2.2 Processing of the Support Materials

Two different materials *viz.,* coconut coir (CoC) and areca-nut fiber (ArF) were used as supports for the LDHs. Fibers of the coconut and areca-nut coir were separated and kept in water for 2 days, washed to remove the soluble impurities and dried in an air oven at 40°C for 2 days. 10 g of the washed areca nut fibers was treated with 500 ml of 2M NaOH solution for 2 days for chemical activation followed by washing with distilled water and drying in an air oven at 40°C. This alkali treated areca-nut fiber is referred to as AArF in the paper. Chemical activation of washed coconut coir was performed by contacting 5 g each of the coir (CoC) in 200 ml of 0.5 N acid solutions (H_2SO_4, HNO_3 and H_3PO_4) for two days. The coir was then washed repeatedly with distilled water till the pH of the washings was neutral followed by drying of the treated coir in oven at 40°C. The H_2SO_4, HNO_3 and H_3PO_4 treated coconut coir samples are named SCoC, NCoC and PCoC respectively.

2.3 Synthesis of unsupported LDHs

Zn/Al and Mg/Al LDHs (M^{2+}/M^{3+} molar ratio = 2) were synthesized by co-precipitation method. An aqueous solution (total metal concentration: 1 M) containing chloride salts of M^{2+} and M^{3+} (Mg/Al or Zn/Al) was co-precipitated using 2M NaOH solution at 60°C maintaining a constant pH of 9.5-10. The precipitate formed was aged for 24 h, separated using centrifuge, washed thoroughly with distilled water till the washing was neutral to litmus and subsequently dried at 60°C in an air oven till constant weight was obtained. A detailed synthesis procedure of the layered double hydroxides is described in our previous article [5]. Zn/Al and Mg/Al LDHs prepared following the above mentioned procedure are designated as ZA2 and MA2 respectively.

2.4 Synthesis of Supported LDHs

2.4.1 Co-precipitation

Co-precipitation of supported LDH was carried out by simultaneous addition of $ZnCl_2$-$AlCl_3$ solution (Zn:Al molar ratio 2:1) and 2M NaOH solution to the areca nut fibers dipped in 100 ml water at 60°C. pH of the slurry was maintained between 9.5-10 during the whole process. The LDH deposited areca nut fiber was aged overnight with continuous stirring. The supported LDH was washed with distilled water over sieve to remove the free LDH particles and to make the mass neutral. The solid mass was then dried in air oven at 50°C and the weight of the resultant dried mass (AArFSZA2-C) was recorded.

2.4.2 Direct deposition

Direct deposition of LDH on the areca nut fiber was performed by dipping 0.5 g of alkali treated areca nut fiber (AArF) in 7 ml of a mixture of $ZnCl_2$-$AlCl_3$ solution (1 M, Zn:Al molar ratio 2:1). The mixture was stirred occasionally and allowed to dry naturally for 40 h. To the wet mass 4 ml of 2M NaOH solution was added drop-wise for precipitation of the LDH. The LDH precipitated over the fibers was kept overnight and then washed with distilled water to remove free LDH particles and to make the mass neutral. The solid mass was then dried in air oven at 50°C and the weight of the resultant dried mass (AArFSZA2-D) was recorded.

2.4.3 Coconut coir supported LDHs

Coconut coir supported LDHs were synthesized only by direct deposition method. LDH with two different M^{2+}/M^{3+} ratios were synthesized on coconut coir. 1g of each acid treated coir was wetted with 22 ml of $ZnCl_2$-$AlCl_3$ solution (Zn:Al molar ratio = 2:1) and kept open to atmosphere for 40 h with occasional stirring. To the wet mass 2 M NaOH solution (22 ml) was added for precipitation of LDH. The treated coir with LDH precipitated on it was left for 3 days for air drying and subsequently washed with distilled water to remove free LDH particles and to wash off the excess alkali. The solid mass was then dried in air oven at a temperature of 50°C and the weight of dried mass was recorded. The above procedure was followed for all the acid treated coir samples for supporting Zn/Al LDH on them and they were named as SCoCS-ZA2, NCoCS-ZA2 and PCoCS-ZA2. Similarly Mg/Al LDH was deposited on each acid treated coir sample using $MgCl_2$-$AlCl_3$

salt solution (Mg:Al molar ratio = 2:1) and they were named as SCoCS-MA2, NCoCS-MA2 and PCoCS-MA2. The LDH loading (%) on the support materials was calculated from the difference in weight of the initial support and the supported LDH obtained after drying.

2.5 Batch Adsorption Experiments

The fluoride adsorption capacity of the unsupported and supported LDHs was estimated by performing batch adsorption experiments. 50 ml of fluoride solution having 10 mg/l concentration was taken in a poly-propylene (PP) bottle and contacted with 0.2 g of adsorbent at 28°C in a thermostatic shaker (Julabo SW-21C). The solution was tested for fluoride ion concentration at different time intervals. Concentration of fluoride in water was measured using ion-sensitive electrode (Metrohm 781 pH/Ion meter). The adsorption capacity of the adsorbent was calculated using the formula:

$$Q_t = (C_0 - C_t)*V/(W*1000) \quad (1)$$

Q_t is the adsorption capacity at time 't' (mg/g), C_0 is the initial fluoride concentration (mg/l), C_t is the fluoride concentration at time 't' (mg/l), V is the volume of the fluoride solution (ml) and W is the weight of the adsorbent (g).

3. RESULTS AND DISCUSSIONS

Loading of LDH on different supported LDHs presented in Table 1 shows that Zn/Al LDH could be supported on both the supports (areca nut fiber and coconut coir) and better LDH loading was obtained for Zn/Al LDH than Mg/Al LDH. This may because of the low adhesion of the Mg/Al LDH, and the free LDH particles getting lost during water washing at the end of the synthesis.

Table 1. *Loading of LDH on the different support materials*

Supported LDH	Loading of LDH (%)
AArFSZA2-C	37.7
AArFSZA2-D	47.4
SCoCS-ZA2	7.4
NCoCS-ZA2	56.9
PCoCS-ZA2	40.5
SCoCS-MA2	10.8
NCoCS-MA2	3.9
PCoCS-MA2	1.8

Defluoridation capacities of the areca nut fiber supported Zn/Al LDHs, unsupported Zn/Al LDH, raw support (areca nut fiber) and alkali treated support, obtained from batch adsorption study are presented in Fig. 1. The raw areca nut fiber and its alkali treated form had no defluoridation capacity.

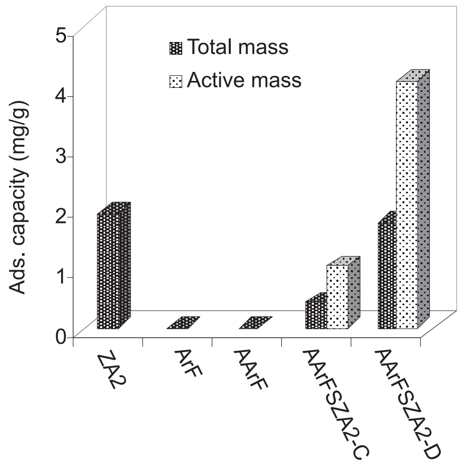

FIG. 1 DEFLUORIDATION CAPACITIES OF SUPPORTED LDH, ACTIVE LDH PRESENT ON THE SUPPORT AND ARECA NUT FIBER (V: 50 ML; C_0: 8.1 MG/L; W: 0.2 G; T: 240 MIN)

Supported Zn/Al LDH showed reasonably good fluoride adsorption capacity and the best result was obtained on LDH supported by direct deposition method. The fluoride adsorption capacity calculated in terms of active mass present in the support (LDH) shows that supporting of the LDH enhances its defluoridation capacity to a large extent. The enhancement in defluoridation capacity of the LDH in its supported form may be due to dispersion of the fine LDH particles on the support which allows better accessibility of the fluoride ions for the active sites of the LDH.

Defluoridation capacities of raw and acid treated coconut coir are presented in Fig. 2. Figure 2 shows that the coconut coir support initially had negligible adsorption capacity which increased with acid treatment and the increment varied with the acid used. The activity of the coconut coir on treatment with different acids, measured based on its fluoride adsorption capacity follows the order: Nitric acid > sulphuric acid > phosphoric acid.

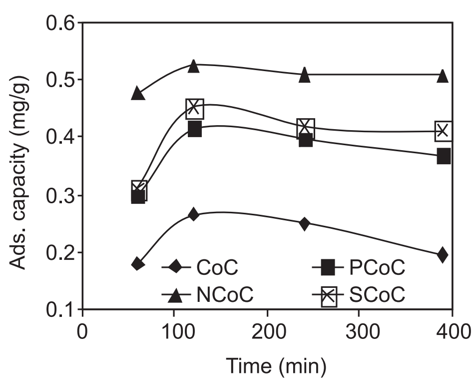

FIG. 2 DEFLUORIDATION CAPACITIES OF RAW AND ACID TREATED COCONUT COIR (V: 50 ML; C0: 8.2 MG/L; W: 0.2 G)

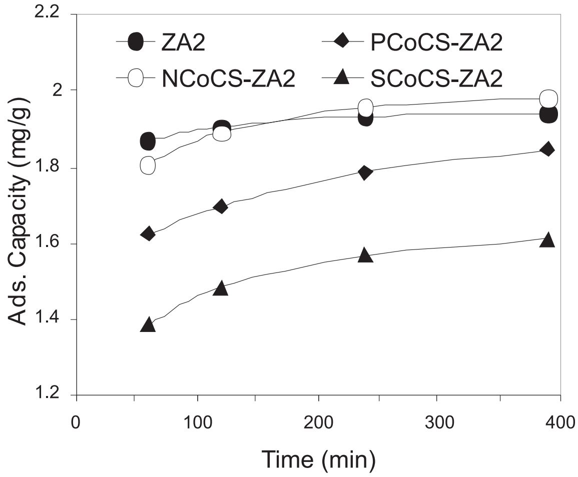

FIG. 3 A COMPARISON OF THE DEFLUORIDATION CAPACITIES OF THE UNSUPPORTED AND COCONUT COIR SUPPORTED ZN/AL LDH (V: 50 ML; C0: 8.1 MG/L; W: 0.2 G)

A comparison of the defluoridation capacities of the unsupported and coconut coir supported Zn/Al LDHs have been presented as Fig. 3. Figure 3 reveals that the adsorption capacities of ZA2 are similar although the percentage loading of LDH on the supported adsorbent is only 56.9%. Figure 3 reveals that the adsorption capacities of unsupported LDH and NCoCS-ZA2 are similar although the percentage loading of LDH on the supported adsorbent NCoCS-ZA2 is only 56.9%. The adsorption capacity of LDH based on the active LDH present on different supported adsorbents has been estimated by material balance calculations and is presented in Fig. 4. These values have been compared with the adsorption capacity of unsupported ZA2 and the supported adsorbent (based on total weight of the supported adsorbent) in Fig. 4.

It is clear from Fig. 4 that Zn/Al LDHs supported on CoCS are more active in fluoride adsorption in aqueous medium compared to its unsupported form. Activation of the coconut coir supports using nitric acid showed better results for both Zn/Al and Mg/Al. However Mg/Al LDH did not have good adhesion on the supports and the loading of this LDH on the supports was small. The supported Mg/Al LDHs showed very low defluoridation capacity, due to low LDH loading, which is the major active material for fluoride adsorption. Among all the supported adsorbents, NCoCS-ZA2 showed maximum defluoridation capacity of 1.98 mg/g, which is equivalent to the unsupported Zn/Al LDH (1.94 mg/g) although the LDH loading was only 56.9% of the total supported adsorbent.

4. CONCLUSIONS

Supported layered double hydroxides (LDHs) were synthesized by supporting the LDH on agricultural waste materials like, coconut coir and areca nut fibers by direct deposition method.

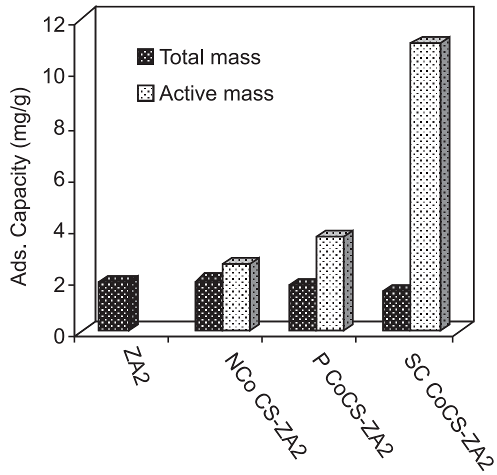

FIG. 4 DEFLUORIDATION CAPACITIES OF UNSUPPORTED AND COCONUT COIR SUPPORTED LDH ALONG WITH THE ADSORPTION CAPACITY OF THE ACTIVE MASS (CALCULATED BASED ON MATERIAL BALANCE) (V: 50 ML; C_0: 8.1 MG/L; W: 0.2 G; T: 360 MIN)

Better LDH loading was obtained with Zn/Al LDH than Mg/Al LDHs. Supported Zn/Al LDHs showed defluoridation capacity equivalent to the unsupported Zn/Al LDH although the amount of active materials (LDH) in the supported adsorbent was within 47-57%. Also an enhancement in the defluoridation capacity of the LDH was observed in the case of supported LDH due to dispersion of the LDH nano-particles on the surface of the support materials, which allows better accessibility of the fluoride ions for the active sites of the LDH. The results clearly reveal that the defluoridation capacity of the LDH increased on supporting them on suitable support material.

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SIMULTANEOUS FEATURE SELECTION AND CLASSIFICATION USING BIOGEOGRAPHY BASED OPTIMIZATION AND SUPPORT VECTOR MACHINES FOR PROCESS ENGINEERING

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ABSTRACT

Large scale industrial processes have several governing parameters which need to be tuned for optimal performance. Due to complexity of the system behavior it is now customary to employ data driven models for maximizing the required performance criteria. Data driven models routinely employ classification and regression tasks. Recent methodologies from machine learning and Artificial Intelligence are being increasingly employed for classification and regression tasks. Classification is useful in several industrial processes for grouping the tasks and system states into distinct sets. We have employed Support Vector Machines classifier which is rigorously based on statistical learning theory. In classification it is contingent to identify those domain features which correlate with the task at hand. In this work we present the recently proposed Biogeography based Optimization hybridized with Support Vector Machines (SVM) forsimultaneous feature selection and classification in complex industrial datasets. Our results demonstrate that BBO can very well be applied as a robust feature selection technique to extract optimal parameters or features from historical datasets in problems pertaining to process optimization.

1. INTRODUCTION

Newer techniques from machine learning and artificial intelligence are being increasingly used in areas where optimal design, operation, and control of various chemical, physical, and biological processes are required.Some of the most popular techniques viz. Support Vector machines and Random Forests have been used with great success which include fault detection [26, 39], identification of regimes of reactor operations [27], classification of biomedical signals

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[28], identification of protein and gene functions [15], cancer classification [8, 12], modeling of quantitative structure activity relationships[29-30], structure property relationships [31] and estimation of parameters required for conducting large scale mass transfer operations[32]. Many of these have several governing and informative parameters that need to be selected from a massive search space. To facilitate efficient and fast computational analysis, hybrid algorithms involving filter and wrapper techniques hence need to be used.

Data mining (DM) is the process that results in the discovery of new patterns in large data sets. The overall goal of the data mining process is to extract knowledge from an existing data set and transform it into a human-understandable structure for further use. It involves the automatic or semi-automatic analysis of large quantities of data to extract previously unknown interesting patterns such as groups of data records (cluster analysis), unusual records (anomaly detection), dependencies (association rule mining) and rules to classify observations under specific labels (classification rule mining)[1].

Classification is a well-recognized DM task and it has been studied extensively in the fields of statistics, pattern recognition, decision theory, and machine learning literature etc. In a classification operation, one may use an appropriate algorithm to induce a classification model from a dataset. The objective of the classification model, thus built, is to predict the class that an example belongs to.

Our major focus in this article is the application of evolutionary techniques hybridized with classifiers based on statistical learning theory forsimultaneous feature selection and classification of massive datasets. Generally, a dataset may consist of a collection of records/examples. Each such example is composed of many attributes/features. The complexity of the data mining task increases if the dataset dimensions are huge i.e. having tens of thousands of features. To overcome this problem, one may select informative features from the data to aid in the construction of efficient classifiers. In a classification task, the objective of a data mining system is usually to classify examples/records using a training dataset that consists of the class labels for each example. A data mining algorithm therefore induces a classification model by learning the various relationships between the examples and the class labels. Consequently, this classification model may be used to predict class labels for unknown examples i.e., examples without class labels. Such methods of data mining activities where, a training set is involved may be categorized as supervised learning problems.

In the following sections, we present a novel approach for feature selection using a recently proposed evolutionary technique known as Biogeography-based Optimization. This study explores the application of the hybrid BBO-SVM technique for simultaneous feature selection and classification. In the process, we used the popular wine dataset with 3 classes [33] and a 2-class fault detection dataset obtained from the Tennessee Eastman Process (TEP) [36, 37].

2. FEATURE SELECTION

In machine learning and statistics, feature selection [13] is the process of selecting a subset of relevant features for construction of robust learning models. Feature selection is a particularly important step in analyzing complex data obtained from many experimental techniques in biology, such as microarray gene expression experiments. The data owes its complexity to a large number of variables (features) but a very low number of samples. By removing the most irrelevant features from the data, feature selection helps improve the performance of learning models by (1) reducing the curse of dimensionality (2) by speeding up the learning process (3) by improving model interpretability.

Feature Selection also entails subset selection where a subset of features as a group is evaluated for suitability. Subset selection algorithms can be categorized into Wrappers and Filters [12]. Wrappers use a learning algorithm to traverse through the space of possible features and evaluate each subset by running a model on the subset. Wrappers can thus be computationally expensive. Filters, on the other hand, evaluate the suitability of features considering the inherent characteristics of the individual features without making use of a learning algorithm. Methods based on statistical estimates come under this category.

Many popular evolutionary approaches have been earlier used for feature subset selection problems *viz.,* Genetic Algorithms [14], Ant Colony Optimization [15], Particle Swarm Optimization [16] etc. In this study, we discuss the application of a recently proposed Biogeography based Optimization approach to feature selection problems.

3. BIOGEOGRAPHY BASED OPTIMIZATION

Biogeography-based Optimization has been inspired by the study of dynamic processes involving distribution of species over a geological period of time. In 2008, Simon [2] made use of the evolutionary processes of biogeography to an aircraft sensor selectionproblem and thus introduced the Biogeography-based Optimization (BBO) technique. It is a population based optimization algorithm that operates using a set of candidate solutions over a number of generations. It thus mimics the geographical distribution of species to represent the problem and employs the species migratory behaviour to redistribute solution instances across the search space to obtain globally optimal or near optimal solutions. In recent years, BBO has been used to solve a number of discrete and continuous optimization problems *viz.,* Traveling Salesman Problem [3, 4], satellite image classification [5], robot controller tuning [6], disease diagnosis [7], gene extraction and cancer classification [8].

According to BBO, an ecosystem (a population) may consist of a set of habitats (solutions). Each habitat has a Habitat Suitability Index (HSI) which indicates the suitability of the same. For optimization problems, the HSI is also related to the fitness function of a solution (or habitat). Consequently, the HSI is dependent on a number of factors that may affect the suitability of a habitat. These factors are known as Suitability Index Variables (SIVs).Thus, HSI may be represented as a function of its SIVs as shown below

$$HSI(\text{Island}) \rightarrow f(SIV1; SIV2; :::; SIVj)$$

Later BBO tries to improve the fitness landscape of the ecosystem over a number of generations. Such an improvement is achieved by the application of an operator called migration that mimics the natural form of species migratory behavior. The underlying assumption of migration follows a linear model of emigration and immigration rates of species across various habitats as shown in Fig. 1.

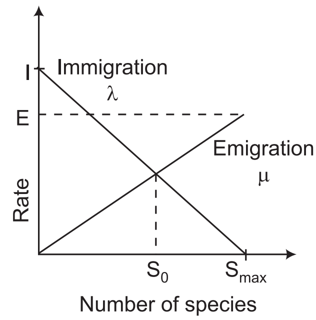

FIG. 1 MIGRATION RATE VS. NUMBER OF SPECIES

After the initial ecosystem of habitats has been generated, the number of species needs to be computed for each habitat. As seen in Fig. 1, the migration rates (immigration and emigration) of each habitat depend on the number of species in each habitat. In this case, we may, thus, map the count of species of a habitat to an arbitrary function of the HSI as shown next.

$$\text{Species } Ct(\text{Habitati}) \rightarrow f(HSIi)$$

Therefore, habitats with good HSI have higher number of species and display a higher emigration rate in contrast to bad HSI solutions which have lower number of species and thus exhibit a higher immigration rate. BBO thus probabilistically facilitates the transfer of SIVs from good and bad habitats using probabilistic techniques, towards driving the overall ecosystem towards a better fitness landscape. To compute the immigration and emigration rate of a habitat, we employ the use of Eqs. 1 and 2.

$$\lambda k = I\left(1 - \frac{k}{n}\right) \tag{1}$$

$$\mu k = \frac{Ek}{n} \tag{2}$$

Here k denotes the count of species in the k^{th} habitat and n is the maximum number of species considered by the model. E and I are maximum emigration and immigration rates which are both typically set to 1. The BBO migration algorithm is stated next.

Migration

Select H_i with probability proportional to λ_i

for j = 0 to n do

Select Hj with probability proportional to μ_j

if Hj is selected then

Randomly select an SIV from H_j

Replace a random SIV in H_i *with the selected SIV in* H_j

end if

end for

As shown above in migration, a habitat proportional to the immigration rate is selected and then correspondingly, a habitat proportional to the emigration rate is also selected. Internally, for each of the emigrating island which is selected, a random SIV is shared with the immigrating island.

BBO also mimics the occurrence of sudden events, using a mutation function which may be described as below.The process of mutation iterates over all the candidate solutions and depending on their mutation probability, may be performed on a habitat.

Mutation

for j = 0 to m do

Use $\lambda_j\ \mu_j$, *of habitat Hj to compute the mutation probability Pj*

Select a random SIVfrom H_j *with probability proportionalto Pj*

if H_j *is selected then*

if rand < q0 then

Replace the selected SIV in H_j*with a probabilistically exploredSIV from the set of variables*

end if

end if

end for

HSI of the modified habitats are then recalculated after the process of migration and mutation ends. The newly rearranged population is now carried over to the next generation where the above processes are again repeated till a suitable termination criterion is satisfied. Figure 2 illustrates a generalized flow of the Biogeography based Optimization process.

4. FEATURE SELECTION USING BIOGEOGRAPHY BASED OPTIMIZATION

As described before, Feature Selection algorithms can be mainly categorized as: wrappers and filters [8, 12, 15]. The present work describes a hybrid filter-wrapper approach using Biogeography-based Optimization for selecting a subset of features from the given datasets [8]. In particular, to enhance performance of the BBO algorithm, we feed a weighted heuristic ranking of features to the BBO-wrapper. The weighted ranking is obtained by a weighted combination of numerous filter algorithms which report a ranking of the features. The weighted ranking thus helps to deal with a wide variety of datasets by adjusting weight assignments to different filters. A hybrid filter-wrapper algorithm employing BBO and SVM is described next.

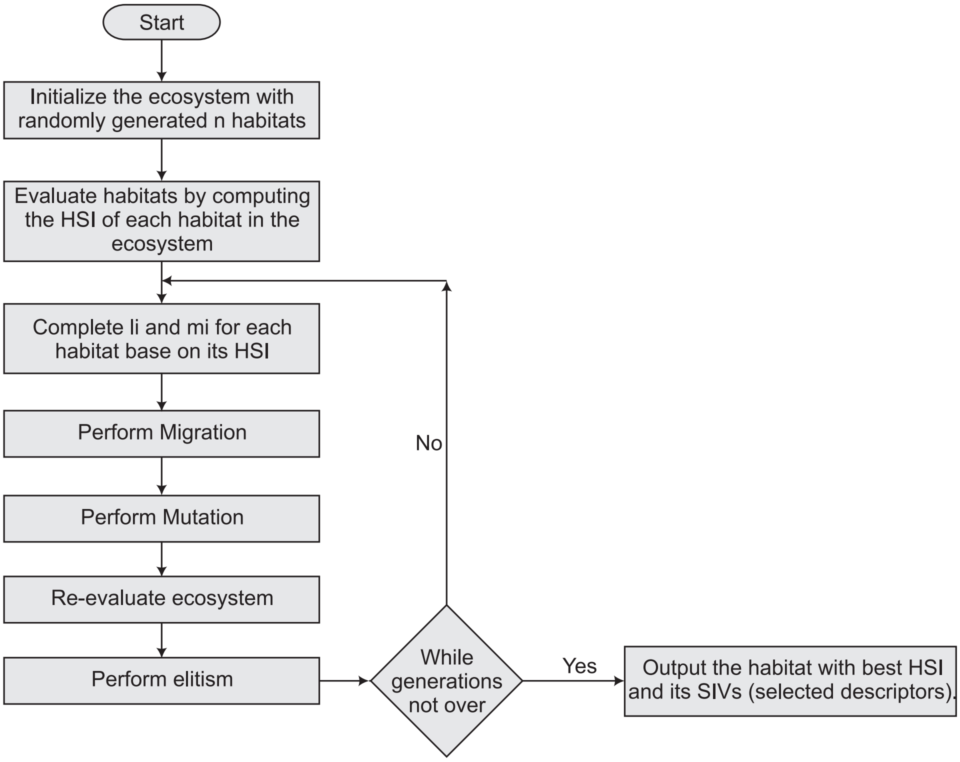

FIG. 2 BIOGEOGRAPHY BASED OPTIMIZATION

4.1 Weighted Heuristic Ranking

The heuristic information is obtained by computing a weighted index of the features in the dataset using Information gain (IG), Chi-Square (CS) and CFS (Correlation-based Feature Selection) measures. These measures can be determined from the Weka data mining library [18].

IG is a suitability score based on entropy-based measures of features that may have the best capability to separate the samples into individual categories. Features with higher IG values are thus considered to be "informative". Hence, the top scored features are considered to be more relevant.

CS is used to estimate the lack of independence between a feature and a class. We scale the CS scores in the range of 0-1.

CFS measures the relevance of feature subsets by considering the importance of individual features for predicting the class label along with the level of inter-correlation among them. For best performances, the features selected by the CFS algorithm are assigned a value of 0.8 and the rest as 0.2.

$$Wt_{\text{feat}} = wig \times IG + wcs \times IG + wcfs \times CFS \tag{3}$$

Thus the weighted score for each feature assessed by Eq. (3) is later provided as heuristic information to a BBO wrapper as described in later sections.

4.2 Support Vector Machines

Support Vector Machines (SVM) constitute a class of learning algorithms based on statistical learning theory that was developed by Vapnik [19-20]. SVM is extensively used for classification and regression purposes. It employs a maximum margin hyper plane to separate a collection of linearly separable binary-labeled data. In cases where problems are linearly non-separable, SVM transforms the input space into a higher dimensional variable space and then finds an optimal linear hyperplane for the separation. SVM also employs proper kernel functions to tackle intractability issues, so that all computations can be carried out in the original space itself.

In this work, we employ the libSVM software suite [21] and the e1071 [22] R package for our analysis.

4.3 Hybrid BBO-SVM based Feature Selection Approach

For the feature selection problems, we mainly employ a hybrid weighted filter-wrapper using BBO with SVM for an improved traversal of the feature search space. A candidate BBO habitat (solution) representation may look like as below.

As per this representation we try to search for an optimal feature subset which has a fixed size of 7 (this represents a possible subset size much lesser than the total number of features). Each cell of this list is an SIV i.e., a feature index. Accordingly, the ecosystem will consist of a set of such habitats. The HSI of each habitat is assessed by the construction of a corresponding reduced dataset that is sent to an external classification function like SVM. These classifiers subsequently report a 10 fold cross validation accuracy which is assigned as the HSI of the corresponding habitat.

After the initial construction of a random ecosystem of habitats, migration is performed as described in section 3. In the process, SIVs from better feature subsets may be transferred to low performing subsets, thereby improving the overall fitness landscape. After migration the classifiers are employed to recalculate the HSI of the habitats.

During mutation, based on a mutation probability rate, a habitat may be selected from which a random SIV or feature index may be mutated i.e., replaced using a weighted ranking of features as described before. For this, we exploit the heuristic knowledge by probabilistically selecting features which have non-zero values in the weighted feature ranking. After mutation the HSIs are recalculated and the process continues for later iterations until a termination criterion is satisfied. After the termination criterion is satisfied, the habitat with the best HSI reports the most optimal feature subset. Figure 3 illustrates the hybrid filter-wrapper approach for feature selection using BBO.

20	2	5	7	12	17	6

FIG. 3 BBO HABITAT REPRESENTATION

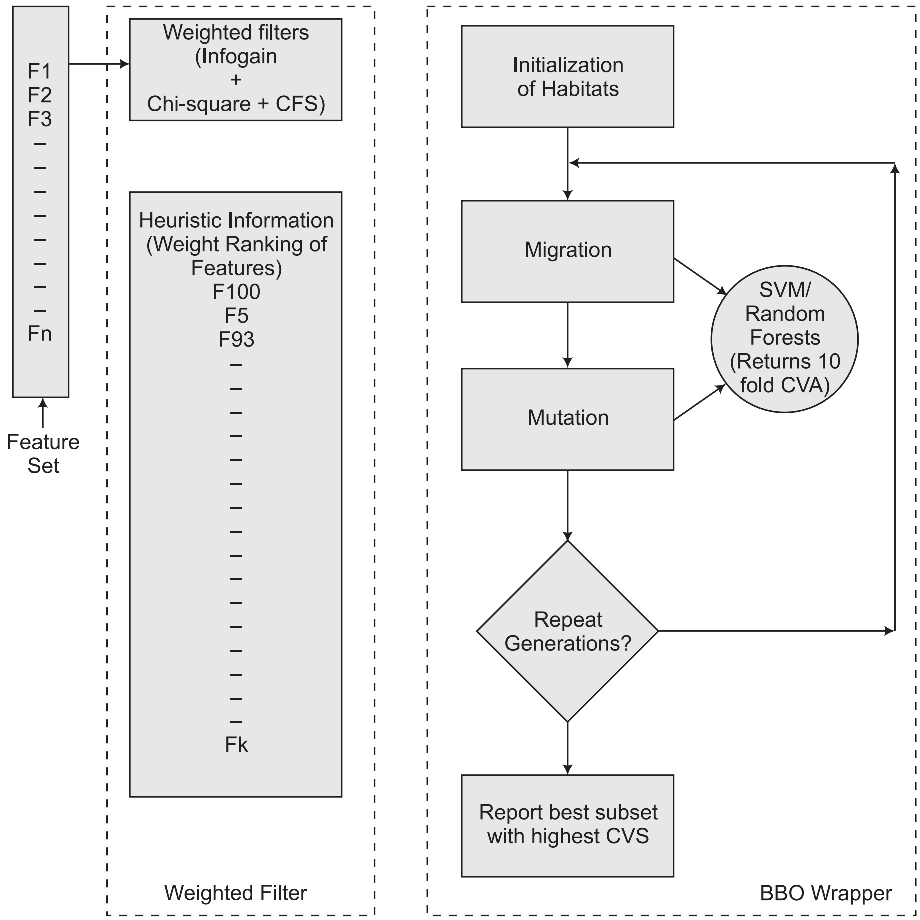

FIG. 4 A HYBRID FILTER-BBO WRAPPER FOR FEATURE SELECTION

5. RESULTS

We have used twoclassification datasets for evaluating the hybrid BBO technique as described before. These are: (1) Wine Data Set and (2) Fault Detection dataset.

5.1 Case Study I: WineDetection (Multiclass Problem)

For the wine dataset, data are the results of a chemical analysis of wines grown in the same region in Italy but derived from three different cultivars. The analysis determined the quantities of 13 constituents found in each of the three types of wines [33]. The dataset consists of 59 wines of first cultivar, 71 of second and 48 wines of third cultivar. Table 1 lists the parameters used by BBO and SVM.

Table 1. *Algorithm Parameters*

Algorithm	*Parameters*
Population size, No of generations (BBO)	50, 100
wig, wcs, wcfs	0.3, 0.3, 0.4
SVM Kernel, Cost	RBF, 1000

Table 2 lists the 10 fold classification cross validation accuracies for the given subset sizes for the wine and sonar datasets.

Table 2. *10 fold classification cross validation accuracies*

Dataset	*BBO-SVM(Subset Size)*
Wine	96.06%(5)

5.2 Case Study II: Fault Detection (Binary Classification)

Tennessee Eastman Process (TEP) is a benchmark classification problem in process engineering. The TEP simulator can report 21 different types of faults entering in the process due to various disturbances. Once a fault enters the system, a number of variables may get affected. In this context, we undertook the task of classifying faults due to random variation in the feed temperature and step change in the reactor cooling water inlet temperature [36-38]. The data comprises of 51 variables and 602 observations. The 51 variables in the process represent the various pressures, temperatures etc., that can be monitored over a period of time. Controlling the process with desirable dynamics therefore turns out to be a challenging task. The BBO-SVM parameters and the 10 fold classification accuracy results are shown in Table 3 and 4.

Table 3. *Algorithm Parameters*

Algorithm	*Parameters*
Population size, No of generations (BBO)	50, 25
wig, wcs, wcfs	0.3, 0.3, 0.4
SVM Kernel, Cost,Gamma	RBF, 32768, 0.0001220703125

Table 4. *10 fold classification cross validation accuracies*

Dataset	*BBO-SVM(Subset Size)*
TEP Fault Detection	93.35%(15)

In earlier instances, the highest classification accuracies have been reported above 93% for the wine dataset [34, 35]. Similarly for the TEP dataset, the hybrid BBO-SVM is able to build robust models using 15 most informative variables (extracted by BBO). In comparison our results have shown a marked increase in classification accuracies when a hybrid filter-wrapper using BBO and SVM is employed for feature selection and classification.

6. CONCLUSION

In this study, we have described a hybrid BBO-SVMwrapper algorithm combined with weighted filter ranking to design a feature selection method and have tested the same on two process engineering datasets yielding impressive results. The hybrid combination of high performance classification (SVM) combined with efficient feature selection (BBO) is quite effective and can be applied with confidence to several other large scale problems.

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POWER SYSTEM STATE – ESTIMATION

P. V. BALASUBRAMANYAN

ABSTRACT

STATE-ESTIMATION (SE) is the process of assigning a value to an unknown system state variable based on measurements form that system according to some criteria. Usually, the process involves imperfect measurements inherent in the process and therefore estimating the system state is based on statistical criteria that estimate the true value of the state variable so as to minimize or maximize the selected criteria. A commonly used and familiar criterion is that of minimizing the sum of squares of differences between the estimated and 'true' (i.e., measured) values.

Power System Static State Estimation (PSSE) is a proven technique for providing modern energy control systems with reliable real-time database for security monitoring and on-line control. The state estimation processes real-time raw measurements to obtain optimal estimates of voltage magnitudes and angles at all buses, which determines the static state of the Power System (PS).

The estimation problem of PSSE is usually formulated as a non-linear least-square problem. Among state estimators based on the normal equations approach, the weighted least-square (WLS) estimator provides reliable estimates but is slow, mainly due to its requirement for updating and factorization of the full-matrix in every iteration. The decoupled state-estimator requires less computation time per iteration and less storage requirement than WLS.

The concept of P-δ, Q-V decoupling technique as applied in load flow studies is extended to state estimation technique also which reduces the storage requirement and also the time for convergence.

The most common approach to the SE problems is to formulate it as a non-linear problem usually solved by an iterative procedure based on successive liberalization; in every iteration, one has to solve a linear least-squares problem. Associated with WLS Estimation is a set of redundant equations is to be solved to yield the solution. These equations are 'Normal Equations' and are solved using Cholesky factorization. The normal equations are very satisfactory with respect to preserving sparsity, but they may give raised to numerical ill conditioning. Methods using orthogonal transformations, such as those of householder have far better stability properties.

The method of Data Equations, which uses the Householder orthogonal transformations, is more efficient than the conventional method of normal equations. Also it is less prone to computer round off errors and is more numerically stable. The standard approach to the solution of WLS state estimation in power system is that is the iterative normal equation method. Occasional ill conditioning has been experienced with this method. Alternative approach to state estimation is

based on 'Orthogonal transformation'. These methods have improved numerical behavior, but generally their sparsity suffers when the measurement redundancy is high.

In this paper the decoupled estimator based on transformation method is presented using different algorithms and the results agree with the method of normal equations. Measurements are transformed into new 'measurements 'that are functions of the states and of the original measurements.

In PSSE redundancy rate is an important aspect. Estimator obtained from various redundancy rates, by considering active and reactive redundancy separately obtained by uniformly distributing the measurements over the system is presented.

Line flows and bus injection measurements required for state-estimation studies has been obtained from load-flow computations. Error (noise) terms (σ = 0.01 and 0.001) are added to these measurements. The error vector being simulated using a random number generator. Convergence tolerance of 0.001 PU and 0.001 radians are used for V and δ, respectively. Results obtained for various combinations of measurements, and with different order of processing these measurements have been presented. Measurements are classified as:

Type 1, 2 measurements:	Power injection (active and reactive)
Type 3, 4 measurements:	Power flows (active and reactive)
Type 5 measurements:	Voltage magnitudes

Different possible cases can be analyzed are:

Case 1:	1, 2, 3, 4, & 5 Type measurements
Case 2:	1, 3, 4 & 5 Type measurements
Case 3:	1, 2, 3 & 4 Type measurements
Case 4:	3 & 5 Type measurements

It is important that at least few voltage measurements (NBUS/10 to NBUS/5) must be included while estimating the states. When line-flows only are used as measurements, solution takes large number of iterations to converge.

1. INTRODUCTION

In Power System planning, when evaluating the state of the system, usually it is possible to start with fixed, predetermined values and therefore the conventional deterministic Load-Flow (LF) calculation is adequate. But in real-time power system control the information about the system has to be obtained from a set of measurements. Two problems arise – the inaccuracies present in the measurements, and the usual redundancy in the number of measurements. Conventional Load-Flow algorithms are not suited to overcome these problems. On the other hand there is no possibility to make use of redundancy and, the effects of errors in measurements are not taken into account – this leads to large deviations between the deterministically calculated and the true state of system. Hence, the application of State-Estimation algorithms which takes certain statistical features of measurement inaccuracies as a base, and calculates in a mathematical/statistical way an estimate of the power system.

Power system state-estimation is digital data processing algorithm for converting telemetered readings and topological information, including redundant measurements into reliable estimate of power system state-vector. The measurement and telemetering equipment in power system is inherently subjected to systematic and random errors. For minimizing the error present in the measurements, the principle of 'ESTIMATION' is applied. The principle of 'estimation 'serves well for this purpose. Once the states are known all of the steady-state variables, including those that are not telemeterd or that is, for some reason missing can be readily calculated. The state variables to be estimated are the voltage magnitudes and phase angles at each of the N busses of the system by representing available measurement equations. Since phase angles are all relative to some fixed reference the angle at the slack bus is set equal to zero and the phase angles at the remaining busses are specified with reference to this. Therefore (2N-1) states are to be estimated.

In literature various methods have been proposed for evaluating PSSE. The usual method employed to obtain optimal estimate from an over determined system of equations is that least-square are generalized inverse [20, 21]. State-Estimation based on these techniques has been proposed by number of authors [1, 2, 3, 4]. However, the least-squares solutions are only optimal when the measurement assumed is Gaussian. Basically most of these methods are based on Weighted Least Square (WLS) approach. Since weighed sum of the squares of the residuals is minimized, these are termed as WLS estimators. When the noise (present inherently) in the measured data possesses certain statistical property, the resulting estimates are known as Unbiased and minimum variance estimates. The measurements in power system are nonlinear functions of the state variables. Due to nonlinear measurements, in the WLS approach an iterative process based on successive linearization is applied, so that reliable estimate can be obtained.

The concept of state estimation in power system using static model was first suggested by Schweppe [1, 3] first suggested the concept of state-estimation in power system using static model. The suitability state-estimation technique in real systems has been demonstrated by Larson et.al. [4] Schweppe and Messiello [14] considered a tracking state-estimator, assuming estimator updating is less compared to the scanning time. Dopazo etal [5] proposed state-estimation algorithm based on line flow only. Deb. etal [15] proposed sequential state estimator. Debs and Lawson [13] proposed dynamic state estimator. These algorithms are based on method of normal equations. The PSSE is formulated as WLS problem. The problem is solved by the iterative normal equations method. The methods of normal equation fails are leads to erroneous results in case of rank deficient or ill-conditioned situations. (Golub 1965; Hanson and Lawson [22]). To overcome the numerical instability Golub proposed the use of householder orthogonal transformation to the estimation problem. The normal equations may occasionally become ill conditioned. Alternative approaches based on orthogonal transformations that overcome numerical ill conditioning have been proposed to solve the WLS state estimation. Rao and Lu [16] proposed method of data equations for sequential processing of measurements for estimation. Monticelli etal [18] proposed a hybrid approach combining the sparcity of the normal equations method and the numerical robustness of the orthogonal transformation method.

Singular Value Decomposition (SVD) [21, 22] method is a novel method to solve state estimation problem. SVD method is efficient and specially suitable for large systems, based on transformation, which is less error prone and is more stable.

2. POWER SYSTEM MEASUREMENTS

The power system measurements are normally nonlinear functions of the states. In order to apply SVD algorithm to PSSE the measurement equations need to be modified for use by the algorithm. These measurements are telemetered to the central control station for the purpose of SE. Depending upon the way the data is received, and multiplexing facilities available, either all the measurement are available prior to the initiation of the estimator or the measurements are received sequentially for processing. Complex bus voltage at all busses constitutes the state variables of power system. These are to be estimated from the other variables that can be measured.

For an N bus system with M line the following number of measurements can be obtained depending upon the meter placement.

Sl.No.	*Type*	*No of Measurements*
1.	Type 1 + Type 2 at all buses	2(N-1)
2.	Type 1 + Type 2 + Type 5	2(N-1) + L
3.	Type 3 + Type 4	4M
4.	Type 3 + Type 4 + Type 5	4M + L
5.	Type 1 + Type 2 + Type 3 + Type 4	2M + 2(N-1)
6.	Type 1 + Type 2 + Type 3 + Type 4 + Type 5	2M + 2(N-1) + L
7.	Type 1 + Type 2 + Type 3 + Type 4 + Type 5	4M + 2(N-1) + L

2.1 Redundancy of Measurements

The complex voltages at all the busses in a power system are not available directly for measurements. These are to be ESTIMATED from other variables of the system which can be measured (to be more precise, which can be metered). The power injections, power flows and voltage magnitudes at certain buses of the system can be metered.

Essential parameters of SE are the redundancy rate of the measurements. This is the ratio between the number of usable and the number of state-variables. This ratio should be grater then 2 and be obtained with measurements distributed uniformly over the system in order to be able to detect erroneous measurements. In practice, the redundancy of the installed measurements should be little higher then two, to take into account the various operation layouts used and to cover unavailability's of transmission and telemetring equipment failures. Redundant measurements do contain useful information about the system. Through, increased redundancy improves the accuracy of the estimator; the solution may still be obtained with no redundancy. Redundancy rate for the installed measurements of the order of 2.75 has proved to be satisfactory.

Since active and reactive powers are independent to a certain degree, redundancy rate of 2.0 must be considered. An active redundancy rate is the ratio of the number of active power measurements to the number of nodes (N-1). Reactive redundancy rate is the ratio of the number of reactive power and voltage measurements to the number of node (N).

2.2 Voltage Measurements

Voltage measurements can be of a reasonable number (NBUS/10 TO NBUS/5) and correctly distributed over the network. These measurements furnish the general level of voltages essential.

2.3 Pseudo Measurements

The state estimation procedure fails completely when the availability of measurements goes on reducing because of telemetry failure or for any other reason. Under this condition, the network is said to be 'unobservable'.

Large power system network will have missing data leading to an unobservable state. Under these conditions, procedure-involving use of 'pseudo measurements' is required to be incorporated, so that the estimator continues to calculate the 'state', and to make the network observable. Pseudo measurement is used in the SE just if it were an actual measured value. It is preferable to assign a large standard deviation (SD) to the pseudo measurements. So that, the large SD allows the estimator algorithm to treat the pseudo measurement as if it were a measurement as if it were a measurement from a very poor quality metering equipment.

3. STATE ESTIMATOR IN ENERGY CONTROL CENTRES

In energy control centers state-estimator plays a very important role [11, 12]. The system gets its information about the power system from remote terminal units that encode measurement transducer outputs and circuits breaker/switches status information into digital signals that are transmitted to the operations centre over communication circuits. This is needed to cause the breakers/switches in any sub-station can cause the network configuration to change. Also, the control centre can transmit control information such as lower/raise instruction to generators and open/close instruction to circuit breakers and switches.

The electrical model of the power system and transmission system is sent to the SE program together with the analog measurements. The output of the SE consists of all bus voltage magnitudes and angles, transmission line flows, calculated from the bus voltage magnitude and phase angles and bus loads and generations

3.1 Decoupled State-Estimator

The concept of P-δ, Q-V decoupling technique has been successfully applied in Load flow studies [18]. This is also extended to SE technique. This reduces the storage requirement and also the time for convergence. It can be recalled that the sensitivity relationship in a power system (PS) is that–

(a) The phase angles are more sensitive to the changes in real-powers.

(b) The voltage magnitudes are more sensitive to the changes in reactive power.

Therefore, the error in measurement of real power should have insignificant effect on estimation of voltage Magnitude. Similarly the error in reactive power measurement should cause insignificant error in voltage angle estimation.

The general estimation consists of estimation the state-vector [X] based on a set of observation [Z] in the presence of an error vector [W]. Mathematical model describing the functional relations between [X], [Z] and [W] is expressed in the form of a set of non-linear equations, which relates the measurement [Z] and the true state-vector [X].

$$Z = [F(X)] + [W]$$

Where, $Z = [Z_A\ Z_R]$ Measurement Vector

$Z_A = [P_{KM}\ P_K]$ Active Measurement Vector

$Z_R = [Q_{KM}\ Q_K\ V_K]$ Reactive Measurement Vector

F(X) : Non-linear function relating the measured quantities to the states,

Z : Measurement vector of size (M × 1),

X : State vector, formed by (N-1) bus voltage angles (the reference bus angle is Known)

N : Bus voltage magnitudes,

M : Number of measurements,

n : Number of state variables,

P_{KM} : Active power flow measurement,

P_K : Active power flow injection measurement,

Q_{KM} : Reactive power flow measurement,

Q_K : Reactive power flow injection measurement,

V_K : Voltage magnitude measurement.

A brief description about Singular Value Decomposition is given in Appendix I.

4. SYSTEM STUDIES

Line flows and bus injections required for state-estimation studies (as true measurements) to be obtained from load-flow computations. Error or noise terms ($\sigma = 0.01$ and 0.001) can be added to these measurements. Measurements are used with random errors, using random number generating algorithm, so as to be representative of values drawn from a set of numbers having a normal probability density function with zero mean and variance for each measurement. Convergence tolerance of 0.001 PU and 0.001 radians are used generally for voltage magnitudes and phase angles respectively.

4.1 Effect of Mix of Measurements

The measurements may be classified into 3 different groups:

- Active and Reactive injection at all buses (Type 1 and 2),
- Active and Reactive line-flows at both ends of all the lines (Type 3 and Type 4), and
- Voltage magnitudes at all the buses (Type 5).

The combination of (Type 1, 2 + Type 3, 4 + Type 5 and Type 3, 4 + Type 5) converged in the same number of iterations. When a combination of (Type 1, 2 + Type 3, 4) is tried, the equations have not converged. This gives an understanding that the presence of bus injection measurements without voltage magnitudes may lead to convergence problems. When line flows only are used as measurements the solution overshoots initially and takes large number of iterations to converge.

4.2 Order of Processing the Measurements

In practice the availability of different types of measurements for estimation purpose will follow different sequence. The digital data processing algorithm must be capable of processing algorithm must be capable of processing measurements irrespective of order, and give reliable estimator. The SVD algorithm serves well for this purpose.

4.3 Effect of Measurement Redundancy

In practice, high redundancy ratio is not realistic due to economic limitations. If the metering is good enough, with a redundancy ratio in between 1.2 to 1.6, the estimator can give an accurate estimate. (Assuming, that the system is not ill–conditioned). Fundamental assumption for successful performance of state estimation algorithm is that the measurement system should have a degree of redundancy grater then 1 (redundancy = No of measurements/No of states). Though the accuracy improves with higher redundancy it reflects on metering cost. Requirements of more sensible measurements and locations can therefore be considering the active redundancy rates independently.

5. DISCUSSION

The estimation problem of PSSE is usually formulated as a non-linear least square problem. Among state estimators based on normal equation approach the WLS estimator exhibits excellent convergence reliability and filtering performance but fails to be satisfactorily fast, mainly due to its requirements for updating and factorization of the full sized information matrix every iteration. The decoupled estimators require less computation time per iteration and less computer storage then WLS. They however may suffer from slow convergence and biases either in heavy system loading conditions or in the presence of transmission lines with large R/X ratios. In the basic WLS algorithm relinearization necessities recalculation of all the large matrices. This may be accounted as a large drawback of the method. Since it is difficult to predict how frequent re-linearization is necessary.

Based on the studies certain general observations can be made, and the experience is that if the line measurements are used, two different measurements can be obtained for each line connected to a particular bus. Injection measurements regardless of how many lines are connected to the bus.

It is interesting to note that, voltage magnitude measurement equation contains only one variable and therefore provides no coupling between two sets of equations (the measurements can always be grouped with the set that contains that particular voltage). Therefore, it is desirable to limit the number of measurements are taken. Line flow measurements appear to have economic advantages since they should have a higher information content to cost ratio. The line-flow tracking and generalized estimators are extensions of basic power flow methods. SE provides a suitable tool for system operations and will extend the operators facility for observations. SE application not only provides a step toward security enhancement by providing a feasible means of complementing the information acquisition system as a data base, but also improvements may be acquired in the area of improved economic operations, regulation etc., since SE is sensitivity modeling errors the results in real time will be degraded, this sensitivity will provide a means for the detection and identification of modeling errors.

6. CONCLUSIONS

The SE based on least squares approach minimizes weighted sum of the errors between measured and calculated system variables. The difference between the load flow calculation and SE method is that, conventional load flow calculations do not take into account, the SE uses the available telemetered measurements along with certain aprior information about the system to estimate the states. SSE is digital data processing algorithm to obtain BEST estimate, which minimizes certain objective function gives a set of redundant measurements. It is important to obtain a reliable estimate even for much disturbed measurement data, than an accurate estimate of the state. State estimator can detect the presence of bad data and identify which data is in gross error. This basic property is the justification for including estimator in control centers. State estimator as an integral part of the measurement system is one of the requirements for computer based monitoring and control schemes for electric transmission systems using real time measurements.

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APPENDIX I

Singular Value Decomposition (SVD)

The over determined system of equations of the form Ax = b are solved using singular value decomposition (SVD). SVD plays a useful role in analyzing square, invertible matrices and its full power is realized in the analysis of non square possibly rank deficient matrices which arise in linear least square problems. The objective of the algorithm is to find orthogonal U and V matrices, so that $U^T AV = \Sigma$ is diagonal. The individual components of Σ are $\sigma_{ij} = u_i^T Av_j$ by proper choice of U and V it is possible to make most of the σ_{ij} zero. SVD of an (mxn) real matrix A is any factorization of the form $A = U \Sigma V^T$, where U is (m × m) and V is (n × n) orthogonal matrices. Σ is (m × n) diagonal matrix, with $\sigma_{ij} = 0$ if $I \neq j$ and $\sigma_{ii} = \sigma_I \geq 0$. Applying the SVD to the system equations Ax = b, where A is (m × n) real matrix, b is an m-vector and x is an n-vector: we get $(U \Sigma V^T)$ x = b and hence $\Sigma_z = d$ (diagonal equation), where $z = V^T x$ and $d = U^T b$. From these equations x vector is evaluated. SVD method is more useful when least squares solution has to be updated as new data is available.

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POWER SYSTEM PLANNING AND MODELING STUDIES

P. V. BALASUBRAMANYAM

SECTION 1: POWER SYSTEM PLANNING STUDIES

1. THE MAIN OBJECTIVE OF THE POWER SYSTEM PLANNING STUDY IS TO

(a) Carrying out the load forecast for the plan period. Determine the short term, medium term and long term generation plan based on surplus/deficit scenario of generation to meet the forecasted demand. Generation planning to meet the reliability criteria as per grid code.

(b) Optimal and reliable evacuation of power from new generating plants as per grid code and also import/export from other States/Regions in case of Deficit/Surplus in generation.

(c) Study and plan reliable transmission network of 132 kV and above (in some states 66 kV and above), to meet the growing demand in line with the guidelines specified in the Grid code.

(d) Examine the adequacy of inter-state and inter-regional lines proposed by Central Transmission Utility for meeting the demand of the State and also export of power to the neighbouring States/Regions in case of surplus.

(e) Year wise addition of Transmission system (both transmission lines and substations from 132 kV/66 kV to 400 kV).

(f) To bring down the technical losses of transmission network to an optimal level.

1.1 In General, Planning of Reliable Transmission System Involve Major Challenges such as

- Right of Way (RoW)
- Flexibility in Line loading and Regulation of Power
- Improvement of Operational efficiency.

1.2 The Following Measures Needs to be Attempted to Meet the Above Challenges

- Increase in transmission voltage
- Upgradation of transmission voltage

- High Capacity 400 kV multi-circuit/bundle conductor lines
- High Surge Impedance Loading (HSIL) line
- Compact towers
- Increase in current High Temperature Low Sag (HTLS) conductor line
- Reduction of land for sub-station
- Regulation in power flow/application of FACTS devices
- Improvement of operational efficiency with condition based monitoring and
- preventive maintenance.

1.3 Adoption and absorption of new technologies as part of transmission planning is essential in meeting the above challenges

Compact towers, High Temperature Low Sag (HTLS) conductor line, Gas Insulated Substations (GIS), FACTS devices, increased transmission voltages etc. need to be considered in the transmission plan to meet the challenges, and to have flexibility in line loading and regulation of power keeping in view Right of way requirement.

1.4 Technological Options as given below need to be considered for reinforcement, to overcome overloading of lines, transformers, low voltage pockets etc.

- 400 kV AC, 765 kV AC, 1200kV AC Lines with Compact towers
- HVDC/UHVDC (+/– 500 kV, +/– 800 kV) Lines with Compact towers
- High Surge Impedance loading lines
- Series compensation for transmission capacity enhancement
- Dynamic reactive power compensation - TCSC, SVC, STATCOM/FACTS
- Switchable Shunt Reactors, Controlled Shunt Reactors.

2. THE POWER SYSTEM PLANNING COVERS THE FOLLOWING STUDIES

(i) Power flow studies
(ii) Stability studies-transient, dynamic and voltage stability
(iii) Short circuit studies
(iv) Load forecasting studies
(v) Reactive power compensation studies.

The purpose of carrying out the studies is:

- Power flow studies for assessing the adequacy of the various transmission alternatives under various operating and dispatch conditions.
- Short circuit studies for assessing the fault level in different transmission system configurations and establish the requirement of fault current limiting devices (if any). Short circuit withstand capability of associated electric equipment.

- Stability studies for assessing the dynamic behavior of the system under certain disturbance conditions and security and reliability of the various transmission alternatives.
- Reactive Power Compensation studies for establishing the requirements of compensation devices (static and dynamic) to maintain the required voltage profile within prescribed limits and also meet the voltage stability requirements.

3. POWER FLOW STUDIES

The main objective of power flow studies is to determine the voltage profile and the power flows in the system for various load and generation conditions. Such studies are essential in planning the future development of the system, since satisfactory operation of the system depends on knowing the effect of interconnections with power systems, new loads, new generating stations, and new transmission lines before they are installed. A number of operating procedures can be analyzed including contingency conditions such as loss of generator, transmission line or a load.

Generally the system must meet a pre-defined set of criterion:

- Voltage criteria
- Flows on lines and transformers to be well within the defined thermal ratings
- Generator reactive power outputs must be within the limits of generator capability curves.

Thus, the load flow analysis provides a planner to design a system that has good voltage profile and acceptable line loadings during normal operation and that will continue to operate acceptably under certain contingency conditions such as transformer outage, line outage etc. Performing a series of load flow studies provides operating knowledge in a short time that might take years of actual operating experience to obtain.

To account for the seasonal variations in load demand and generator availability the following loading conditions will be considered:

(a) Peal Load conditions,

(b) Off-peak load conditions.

The studies for the peak load condition will establish the requirements for voltage improvement measures while the off-peak load condition will establish the requirements for voltage limitation and control.

Load flow study is required to be conducted for various operating conditions like Maximum Generation, Maximum Load, Minimum Generation and Minimum Load.

3.1 Steady State Contingency Analysis

Contingency analysis refers to scheduled outages of major system components likes lines transformers etc. without considering faults in the system. They are studied through load flows. The component outage is simulated as status alteration interactively during load flow after obtaining initial load flow convergence. A post contingency load flow is re-conducted to examine if the system is stable and also see the extent of overloading on other adjacent lines, transformers etc.

3.2 Outcome of Power Flow Studies

- Active and Reactive Losses occurring at different voltage levels such as 132 kV, 66 kV and 33 kV
- Tie line flows between state utilities and neighboring states
- Identification of heavily loaded and lightly loaded lines
- Identification of Low Voltage buses indicative of size and placement of reactive compensation
- Steady state contingencies that are critical will also be identified.

4. STABILITY STUDIES

The planning, operation and control of a power system are to a significant extent governed by stability considerations. Transient or steady state stability of a power system is its capability to operate stably without loss of synchronism after a large or a small disturbance respectively. Voltage stability, on the other hand, is the ability of the system to provide adequate reactive power support under all operating conditions so as to maintain stable load voltage magnitudes within specified operating limits in the steady-state.

The voltage stability is now a serious concern to the electric utility. Many large interconnected power systems are increasingly experiencing abnormally high or low voltages and voltage collapse. These voltage problems are associated with increased loading of transmission lines, insufficient reactive supply, and transmission of power over long distances.

Successful operation of a power system depends largely on its ability to provide reliable and un-interrupted service to load. This requires running of synchronous machines in parallel with adequate capacity to meet the load demand. If at any point of time a generator loses synchronism with the rest of the system, significant voltage and current fluctuations may occur and transmission lines may get automatically tripped by the protection system. Conditions may arise where synchronizing power for one or more machines may not be adequate and impact in the system may cause these machines to lose synchronism. Time Domain simulations are used for studying the transient and dynamic stability of power system.

Power System stability is the ability of the various synchronous machines in the system to remain in synchronism with each other. Power System stability can be broadly classified into two categories, one dealing with the synchronous operation of the power system – ***angle stability*** and the other addressing the maintenance of acceptable voltage level – ***voltage stability.*** Depending on the nature of disturbance, angle stability is further classified as small signal and transient stability, whereas both static and dynamic phenomena have been applied in the study of voltage stability.

Power system must also be capable of withstanding *large disturbances*, such as short-circuit on a transmission line, loss of a large generator or load, or loss of a tie between two subsystems. The system response to a disturbance involves much of the equipment. For example, a short-circuit on a critical element followed by its isolation by protective relays will cause variations in power transfer, machine rotor speeds, and bus voltages; the voltage variations will actuate both generator and transmission system voltage regulator; the speed variations will actuate prime mover governors; the change in tie line loadings may actuate generation controls; the changes in voltage and frequency will affect loads on the system in varying degrees depending on their individual characteristics.

The stability studies will be performed for the peak load condition, which will be the critical operation condition for the stability of the system. Transient Stability as well as Dynamic stability of the system will be investigated by subjecting the system to faults and other specified perturbations.

4.1 Fault Cases

The main test for transient stability of the system is analyzed by subjecting the system to faults. This will be done in a progressive manner from the less onerous to the more onerous. In case the system fails to survive any of the fault conditions, application of the next onerous fault will be terminated. Depending on the nature of the instability, the system will be subjected to improvements or strengthening measures comprising of addition of more lines, voltage up gradation, additional shunt compensation, series compensation or Static Voltage Compensators (SVC's) and the performance of the system reassessed.

Fault clearing time of 100 ms will be assumed for Single-line-to-Ground and three-phase-to ground faults for 400 kV systems. For faults in 220 kV and 132 kV systems the corresponding values will be 160 msec.

4.2 Outcome of Stability Studies

- Results of stability studies will be useful in fine tuning the control parameters of exciters, Power system stabilizers, governors and turbines
- Indicates the locations for providing of reactive power sources in the system
- Performance of the system under steady state and dynamic conditions for (n-1)/(n-2) contingencies
- The maximum fault clearing time for maintaining the stability will be determined and studied as per specified norms
- Identification of voltage sensitive nodes.

5. SHORT CIRCUIT STUDIES

Short circuit studies are performed to determine the magnitude of the fault currents flowing throughout the power system, needed for the purpose of determining the fault duty on circuit breaker and other equipment. The short circuit information can also be used to select fuses, breakers and switchgear ratings in addition to protective relay settings. These studies are generally carried out for the following cases:

(i) Single-phase faults (least severe but more frequent)

(ii) Two phase faults

(iii) Three-phase faults (most severe but less frequent).

5.1 Outcome of Short Circuit Studies

The Short Circuit studies gives the following information:

(i) Total fault currents (either phase quantities or sequence quantities) at the specified bus in the network at which the fault is applied

(ii) Fault current (either phase quantities or sequence quantities) through each of the power system component connected to the faulted bus

(iii) Pre fault bus voltages.

6. TO CONDUCT PLANNING STUDIES, THE FOLLOWING DATA IS REQUIRED AND TO BE ARRANGED AS PER THE SIMULATION PROGRAMME PROPOSED TO BE USED

Transmission Line Data

The transmission lines will be represented as PI circuits with lumped positive sequence resistance, reactance and susceptance associated with their corresponding line lengths.

- Line length (km)
- Positive and zero sequence resistance, reactance, susceptances (ohms/km & mhos/km or pu/km)
- No of circuits (single circuit or double circuit)
- Thermal rating of conductors used.

Transformer Data

All transformers will be modeled as two winding transformers with their associated winding resistance and reactance with inclusion of load tap changer. Generator transformers will be modeled with vector group YD11.

- No of transformers
- Two winding/three winding
- Voltage rating
- MVA rating
- Leakage resistance and reactance
- Connectivity (delta/star, star/star –grounded etc)
- Tap positions indicating the side on which it is provided
- Nominal tap
- Minimum/Maximum tap position
- Saturation characteristic.

Generator Data

All synchronous machines will be represented as PV buses i.e., with constant voltage and constant active power generation. The reactive power production and absorption will be specified by their Qmax and Qmin values.

- Voltage rating
- MVA rating
- Reactances (Xd, Xd′, Xd″, Xq, Xq′, Xq″, stator resistance and reactance)
- Time Constants (Td, Tdo, Tdo″, Tq, Tqo, Tqo″)
- Inertia constant
- Reactive capability curve
- AVR block diagram with parameters (gains & time constants, limiter values)
- Governor block diagram with parameters (gains & time constants, limiter values)
- Neutral Grounding Resistor.

Shunt Reactor Data

Shunt Reactors either bus or line reactors need to be considered appropriately.

- Voltage rating
- MVAr rating
- Neutral Grounding Reactor MVAR & voltage rating
- Non-linear characteristic.

Shunt Capacitor Data

Shunt capacitors need to be considered at 132 kV or at 33 kV.

- Voltage rating
- MVAr rating.

Load Data

Load modeling is an important aspect. Loads can be represented as: (i) constant MW, MVAr (ii) Voltage dependent and (iii) Frequency dependent.

- MW rating
- MVAr rating
- No. of loads (if more than one)
- Voltage kV rating.

Interstate Line Flows

- MW (Import/Export
- MVAr ((Import/Export).

SECTION 2: POWER SYSTEM MODELING ASPECTS

A power system model consisting of single machine connected to infinite bus, and SVC located in the middle of the line is considered for studying the modeling aspects. System modeling is studied in two aspects: (i) Linear system model and (ii) Non-linear system model. The details are discussed in the following sections.

1. LINEAR MODELING

To understand the power system performance, the original non-linear equations of the power system model under study is to be linearized around an operating point and arrange in standard state variable form. This would be convenient to analyze the stability study by evaluating the eigenvalues of the system state matrix. Also, this modeling can be used for identifying the controller parameters by obtaining the parameter stability plane.

The non-linear power system model equations referring to Fig. 1 are given in Appendix I, which are linearized and arranged in the following form:

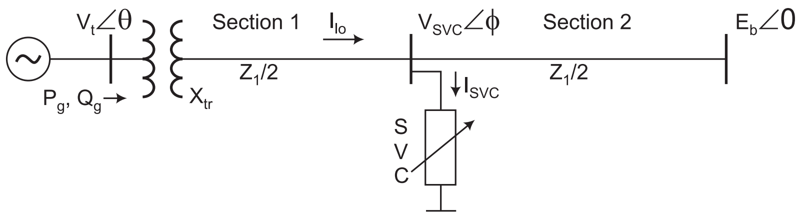

FIG. 1 SMIB POWER SYSTEM MODEL WITH SVC AT MIDDLE OF THE LINE

$$[P]\begin{bmatrix}\dot{X}_1\\ Z_1\end{bmatrix} = [Q]\,X_1 + [R]\,U_1 \tag{1}$$

This equation can be partitioned as

$$pX_1 = A_1X_1 + B_1U_1$$
$$Z_1 = C_1\,X_1 \tag{2}$$

where A_1 is the system matrix (without supplementary control to SVC). The eigenvalues of which denotes the stability of the system. X_1 is the state vector, Z_1 is the output vector and U_1 is the control vector. P matrix contains the elements of coefficients of derivatives of state variables and coefficients of output variables. Q matrix contains elements of coefficients of state variables. R matrix contains the elements of control variables. The significance of the vector Z_1 is that the output variables can be expressed in terms of state variables. This type of formulation also ensures correctness in modeling. The sum state variables and algebraic variable equals total number of equations.

Another advantage of this type of modeling is addition of new controls can be augmented systematically.

The supplementary controller equations are derived in the following form referring to Fig. 2.

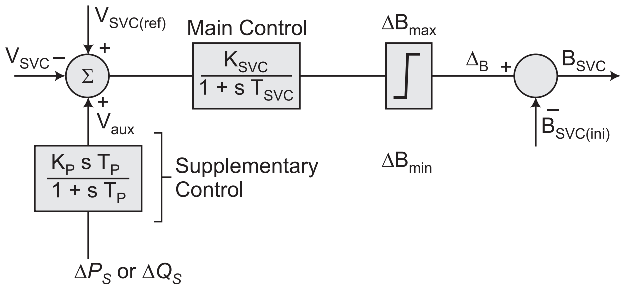

FIG. 2 BLOCK DIAGRAM OF SVC WITH AUXILIARY CONTROL

$$pZ_2 = P_2 Z_2 + N_2 Y_2$$

$$U_1 = H_2 Z_2 + G_2 Y_2 \quad (3)$$

To obtain the complete system equations, the supplementary control equations (3) are augmented to the basic system equation (2); which will be of the following form:

$$\dot{X} = AX \quad (4)$$

Eigen values of 'A' matrix are obtained, with varying auxiliary control parameters (ACP).

2. NON-LINEAR MODELING

The linear model simulation of the power system gives general guideline and idea about the behavior of the power system. The power system is non-linear, and its operating point always keeps changing. Hence, the actual performance evaluation needs to evaluate through non-linear simulation. Mathematically, it amounts to solving of differential and algebraic equations simultaneously. Non-linear simulations takes account of limits on variables, while in linear model simulation, this is not possible.

System Equation:

2.1 Machine Equations

The third order machine model is considered, which is sufficient to understand the phenomena. The following are the non-linear system equations referring to Fig. 3, used for time simulation studies.

$$p\delta = \omega b\ (\omega - 1)$$

$$p\omega = (Pm - Pe)/M$$

$$pEq' = \{Efd - [Eq' + (Xd - Xd')\ Id\}/Tdo'$$

The generator electrical power output

$$Pe = V_D I_D + V_Q I_Q$$

The transformation of machine d and q quantities to network reference frame D, Q for both currents and voltages are as follows:

$$\begin{pmatrix} (\ )_d \\ (\ )_q \end{pmatrix} = \begin{pmatrix} \cos\delta & \sin\delta \\ -\sin\delta & \cos\delta \end{pmatrix} \begin{pmatrix} (\ )_D \\ (\ )_Q \end{pmatrix}$$

Algebraically the machine currents and bus voltages are related by:

$$I_q = V_d/X_q; \quad I_d = [(E'_q - V_q)/X'_d];$$

$$V_d = X_q I_q; \quad V_q = E'_q - X'_d I_d.$$

2.2 Excitation System

The effect of excitation system (IEEE Type 1) shown in Fig. 4 is included in the SMIB system analysis as given below:

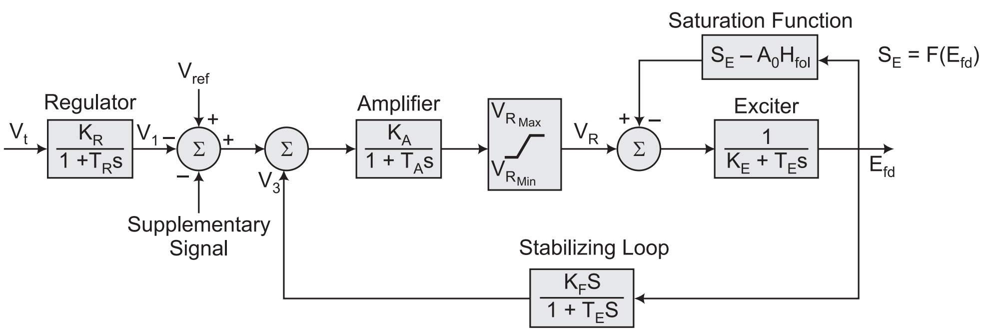

FIG. 3 IEEE TYPE1 EXCITATION SYSTEM

$$pE_{fd} = -[(S_e + K_E)/T_E]\ (E_{fd} - E_{fd0}) + (1/T_E)\ V_R$$

$$pV_1 = (K_R/T_R)\ V_t - (1/T_R)\ V_1$$

$$pV_3 = -\ [(K_F/T_E\ T_F)]\ (S_e + K_E)\ (E_{fd} - E_{fd0}) - (1/T_F)\ V_3 + [(K_F/T_E\ T_F)]\ V_R$$

$$pV_R = -(K_A/T_A)\ V_1 - (K_A/T_A)\ V_3 - (1/T_A)\ V_R + (K_A/T_A)\ (V_{ref} + \text{Supplementary Signal})$$

2.3 Power System Stabilizer

The supplementary signal input to the exciter is the output from Power system stabilizer (Fig. 4).

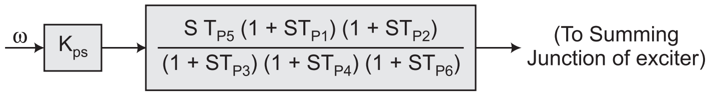

FIG. 4 PSS BLOCK DIAGRAM FOR GENERATOR SPEED DEVIATION SIGNAL

2.4 Static VAr Compensator (SVC)

The following equations are derived referring to Fig. 1.

SVC current and voltage are related by:

$$I_{SD} + j\, I_{SQ} = j\, B_{SVC}\, (V_{SD} + j\, V_{SQ})$$

The current balancing equation at SVC bus:

$$[(I_D + jI_Q) - (I_{SD} + j\, I_{SQ})] = [(V_{SD} + j\, V_{SQ}) - (V_{\infty D} + j\, V_{\infty Q})]\, (G_2 + j\, B_2)$$

The expression for power entering at the SVC bus is given below. This can be useful for realizing the supplementary signal (active or reactive power) to SVC.

$$P_s - j\, Q_s = (V_{SD} - j\, V_{SQ})\, (I_D + j\, I_Q)$$

SVC bus voltage is given by: $V_s = V_{SD} + j\, V_{SQ}$

SVC Dynamic equations

For the purpose of simplicity similar main loop control and auxiliary control is assumed. SVC dynamic equations for main control can be obtained as follows (referring to Fig. 2):

$$pB_{svc} = (K_{svc}/T_{svc})\, (V_{svcref} - V_{svc} + V_{aux}) - (1/T_{svc})\, B_{svc}$$

Modeling of supplementary control for SVCs

Supplementary control loop equations for SVC (Fig. 2):

$$pV_{aux} = (1/T_p)\, V_{aux} + (K_p/T_p)\, (\Delta P_s)$$

$$V_{aux} = -\, V_{aux} + K_p\, (\Delta P_s)$$

ΔP_s is to be replaced with ΔQ_s for reactive power signal. ΔP_s, ΔQ_s is active and reactive power at SVC bus.

The system differential and algebraic equations are to be solved simultaneously. The Bsvc solution obtained will enter at the diagonal element in the network Jacobian matrix in every iteration. The solution obtained for V_{aux} will enter at the summing junction of SVC control system block diagram.

2.5 Steam Governor and Turbine Models

Control System Block Diagrams of Steam Governor and Turbine Models are shown in Fig. 5 and 6 respectively. The input to the governor model is speed of the machine and the output is gate opening, and this is given as input to turbine and the mechanical torque is the output. The mechanical torque can be converted to electrical, which is appearing in the machine equations, thus the loop is closed.

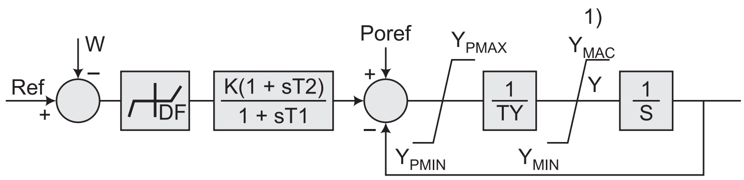

FIG. 5 BLOCK DIAGRAM OF STEAM GOVERNOR MODEL

ω: Speed of the machine

Y: Gate opening

K: Effective system speed governing gain

T_1, T_2: Time constants of governor

TY: Valve servo motor time constant

YPmin, YPmax: Valve servo rate limits

Y_{max}, Y_{min}: Valve position limits

POREF: Initial value of preprocessor

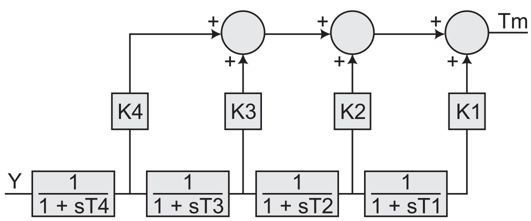

FIG. 6 BLOCK DIAGRAM OF STEAM TURBINE MODEL

K_1 to K_4: Gains of individual masses (sum of K_1 to K_4 = 1) and

T_1 to T_4: Time constants of individual masses

Y: Gate Opening

T_m: Mechanical Torque

It is important to make sure that, the control system block diagrams input and output variables are properly considered and finally a closed loop is established.

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PERFORMANCE EVALUATION OF TCSC CONTROL AND PROTECTION EQUIPMENT USING RTDS

M. ARUNACHALAM[1]

1. INTRODUCTION

In India the demand for electrical power is increasing at a rapid pace and it is becoming important to make the transmission system more effective. Flexible AC Transmission Systems (FACTS) are being employed more and more in present scenario to enhance the capability of the transmission system. TCSC is an important FACTS device that enhances the power delivery capability and improves the system stability. India's first series compensation scheme on 400KV ac line is installed at Ballabhgarh substation of Power Grid Corporation of India Limited (PGCIL) on the Kanpur-Ballabhgarh 400km long single circuit ac line. The project is implemented in two phases. In phase-I, Fixed Series Compensation (FSC) has been installed.

The FSC consists of two capacitor banks of 27% and 8% providing 35% compensation to the line. The FSC scheme is already in operation. In phase-II, the 8% compensation is made variable up to 20% by TCSC, which is formed by parallel connection of TCR. The variable portion of the phase-II was test commissioned and is being considered for putting in to continuous operation.

Thyristor valves and control system for TCSC are developed at Electronic Division, BHEL, Bangalore, India. The control system philosophy is developed in association with Indian Institute of Technology (IIT), Mumbai, India. The control system block diagram scheme has been arrived at after rigorous digital simulation studies in MATLAB. The developed scheme is implemented in the control panel using high-speed processor based hardware. As the controller is being developed for the first time, the system very complex and the limited time to commission the system,made it imperative to test and tune the controller using a real time simulator. The Real Time Digital Simulator (RTDS) at Central Power Research Institute (CPRI), Bangalore, was used to carry out this performance verification studies and tuning of the controller as per IEEE standards [1].

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*The content of this paper was originally presented at the 15th Power System Computation Conference (PSCC), Liège, Belgium, August 2006. This paper was co-authored with Dr. GhammandiLal, Mr. C. G. Rajiv of BHEL and Mr. M. M. Babu Narayanan of CPRI, India. The work reported is first of the kind carried out in India based on indigenous capabilities.

After production checks at BHEL works, the TCSC controller was interfaced to RTDS. Studies in RTDS were performed in stages. Initially, a simplified circuit consisting of the Kanpur-Ballabhgarh line with both ends represented by Thevenin equivalent source and impedance was considered. The transient response of the controller was studied for step changes in TCSC impedance and line current. In the second phase of the studies, the northern region power system was represented and various contingencies were simulated. The performance of the controller in damping the power swing oscillation in the Kanpur-Ballabhgarh line was demonstrated.

The important results of RTDS studies have been compared with the MATLAB digital simulation results. Both the results have a close agreement. The RTDS studies were helpful in carrying out the commissioning tests at site, as the open loop and closed loop tests were conducted very smoothly. The controller when tested on the RTDS had demonstrated a steady state low frequency oscillation when a voltage based damping controller was used or a current based controller with large gain was used. This was confirmed during field trials.

As a part of the visiting professor program under INAE DVP scheme, Dr M Arunachalam has presented and discussed this paper with the staff and students of School of Electrical and Electronics Engineering of Vellore Institute of Technology (VIT) University, Vellore, India.

2. THE SYSTEM AND ITS REPRESENTATION

2.1 The System under Study

The TCSC is installed at the Ballabhgarh end of the Kanpur-Ballabhgarh 400kV line. The range of variable compensation is 8%-20 % of the line reactance. Figure 1 shows the single line diagram of the TCSC scheme.

The major parameters of the system under study are:

Kanpur-Ballabhgarh 400 kV transmission line (400 km):

Positive sequence parameters –

L = 1.044 mH/km, C = 16 nF/km, R = 0.0296 Ω/km Zero sequence parameters –

L = 3.259 mH/km, C = 9 nF/km, R = 0.2986 Ω/km Fixed portion Series Capacitor: C = 90.7 μF

TCSC: Fixed capacitor: C = 306 μF, TCR: L = 4.4 mH, Q = 50

The NREB system comprises of the following elements:

(a) 87 Generating Stations: 312 generating units with their unit transformers.
(b) 1003 Lines + Transformers (excluding generator transformers).
(c) 404 high voltage nodes (132 kV and above) and 312 generator terminal nodes.
(d) One HVDC bipolar link (Rihand - Dadri) – rated total capacity 1500 MW.
(e) Two “Back to Back” HVDC links (Vindhyachal and Sasaram).
(f) One SVC at Kanpur rated at 280 MVAR.
(g) TCSC (27% fixed 8%-20% variable) on the Kanpur Ballabhgarh Line.

As this is a complex network, for RTDS testing purpose a reduced equivalent representation of the system as described in section 2.3 was used.

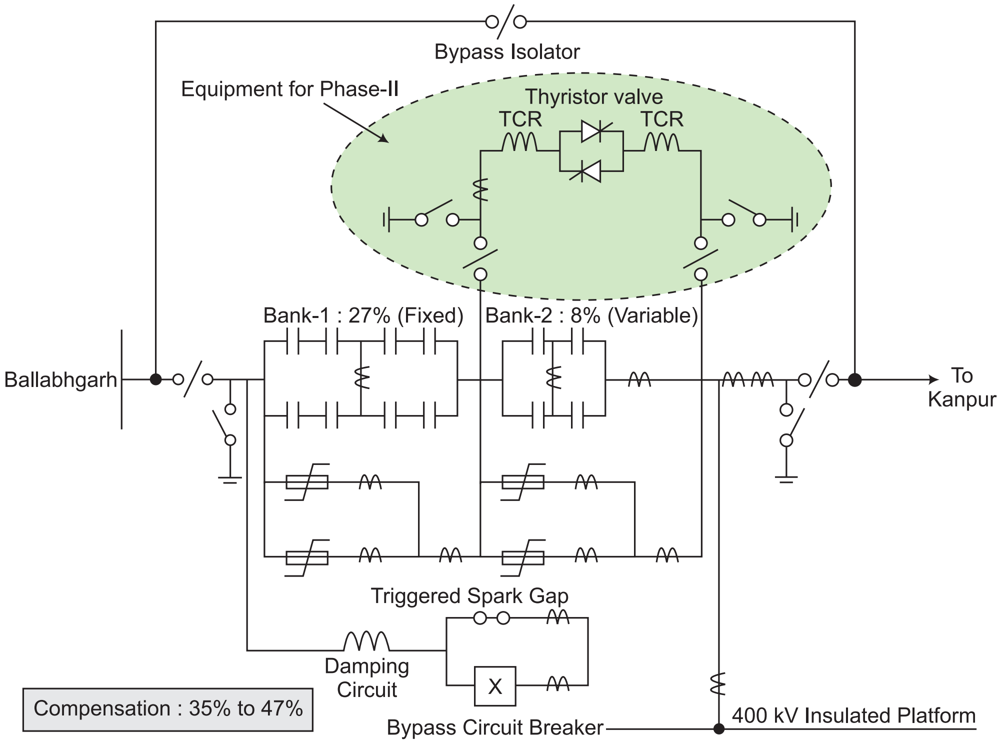

FIG. 1 SINGLE LINE DIAGRAM OF THE TCSC SCHEME

2.2 The System Representation for the First Phase

The TCSC was modeled in RTDS with its capacitors, MOVs, spark gap, by pass breaker and TCR. The TCR was modeled with the reactor and the thyristor valve with its snubber circuits and over voltage protec-tion. The fixed series compensation portion was also modeled.

For the first phase of the study, the following parameters were considered to represent the transmission line.

Thevenin resistance/inductance at Kanpur: 0.1 Ω, 0.043 H Ballabhgarh: 0.1 Ω, 0.026 H

Quiescent phase angle between the two ends: 35°. Quiescent voltage magnitudes at both ends: 400 kV line-line rms.

The transmission line, with sources at both ends and voltage and angles adjusted, to achieve the requisite power flow was used. A simplified representation of the transmission line, FSC and TCSC with its RTDS models as shown in Fig. 2.

2.3 The System Representation for the Second Phase

As mentioned earlier the size of the NREB system is large and it was not possible to represent the entire system in the RTDS due to its limitations. Hence a reduced equivalent of the system given by the utility as shown in Fig. 3 was considered for the second phase of the study.

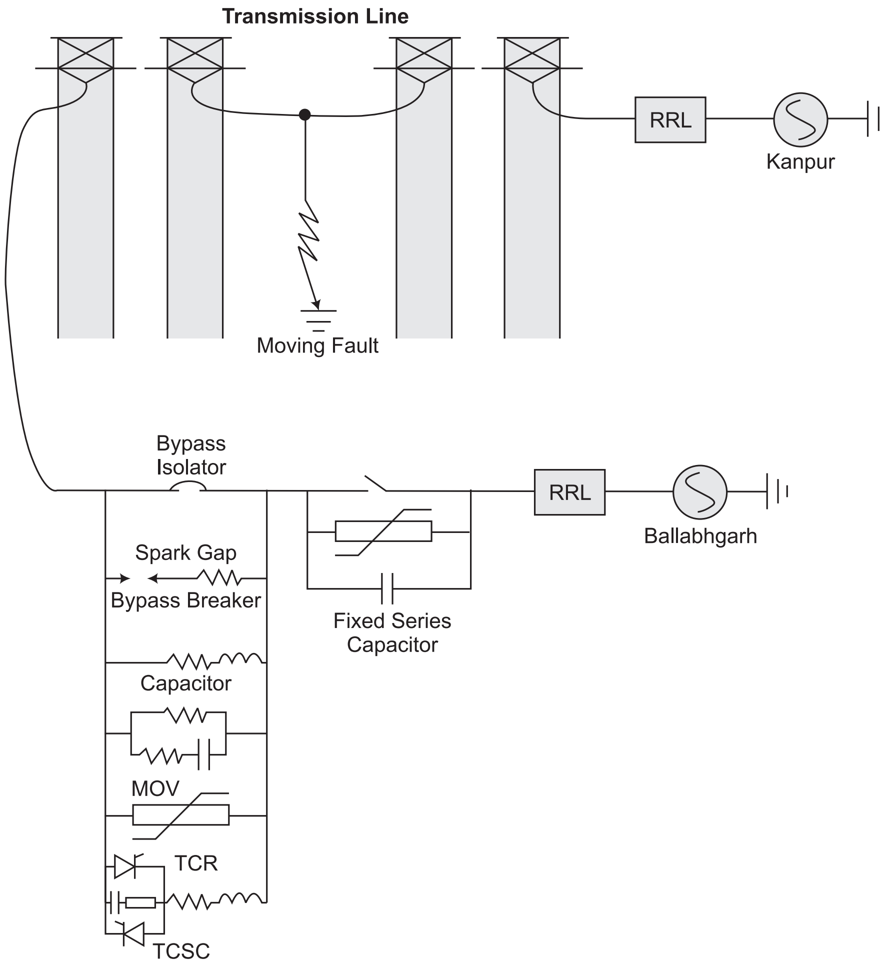

FIG. 2 SIMPLIFIED REPRESENTATION OF THE LINE, FSC AND TCSC RTDS MODELS

The reduced network comprised of the following elements:

(a) 14 infinite sources behind a series impedance.
(b) 22 nos of 400 kV lines.
(c) 11 nos of 220 kV lines.
(d) 10 nos of fictitious line were modeled as series impedance between buses.
(e) One HVDC bipolar link (Rihand - Dadri) – rated total capacity 1500 MW.
(f) One SVC at Kanpur rated at 280 MVAR.
(g) TCSC (27% fixed 8%-20% variable) on the Kanpur Ballabhgarh Line.

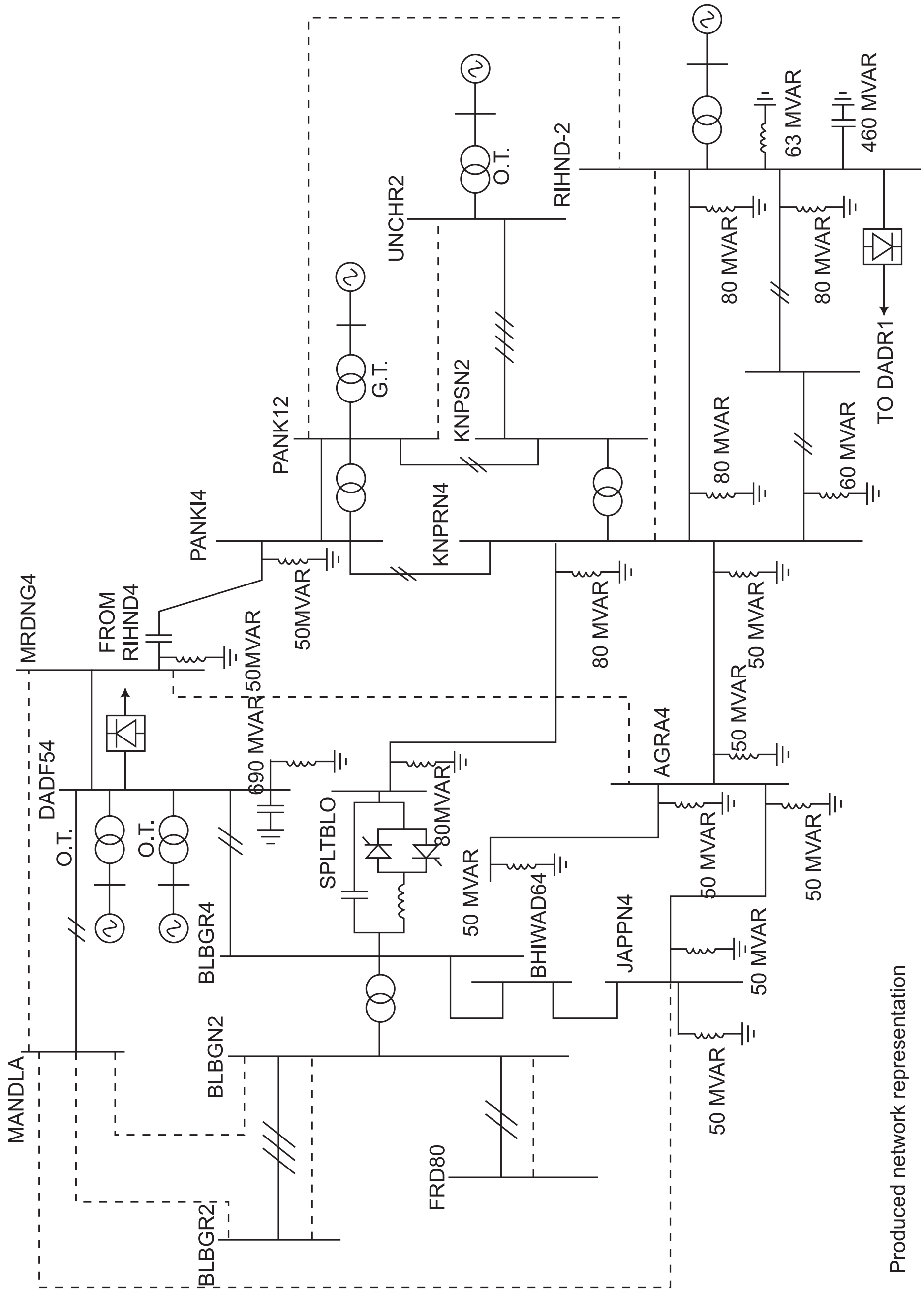

FIG. 3. REDUCED NETWORK REPRESENTATION

3. TCSC CONTROL AND PROTECTION AND INTERFACE WITH RTDS

3.1 Control Structure

The structure of the controller can be divided into the four levels as follows.

3.1.1 Master control

This level comprises of the mode selection (cur-rent/reactance), open/closed loop selection, voltage and current measurement and interlocking. The required reactance/current level setting is also carried out at this level.

3.1.2 Sub-segment control

At this level of control depending on the system requirements the Thyristors are blocked, bypassed or put in Vernier Mode. The capacitor overvoltage protection, TCR over current protection, damping control and firing angle control are also carried out.

3.1.3 Base electronics and thyristor monitoring

This comprises of the interface of the firing pulses to the thyristor valves and its health monitoring.

3.1.4 Thyristor control unit

This level comprises of the electronics to trigger the Thyristor and send feedback to the thyristor monitoring system.

As the controller under test comprised of only the master control and the sub-segment control, the functions of Base Electronics and Thyristor control units were modeled into the RTDS.

3.2 Block Diagram of the TCSC and its control system

Figure 4 gives a block diagram of the TCSC and its controls system.

Abbreviations used in Fig. 4 which gives a brief outline of the TCSC are: I_{TCR} - Line current, V_C - Line voltage, MOV- Metal Oxide Varistor, C- Capacitor, V_C – Capacitor Voltage, L_{TCR} – Thyristor Controlled Reactor, I_{TCR} – Thyristor Controlled Reactor Current, C - Firing angle, X – impedance, TSR –Thyristor Switched Reactor, TVM – Thyristors in Vernier Mode, TBM – Thyristors in Blocked Mode, I_M – Measured line cur-rent, I_{ref} – Reference line current, PI – Proportional Integral, X_{order} – Ordered impedance, X_{Manual} – Openloop impedance setting, X_{psdc} – Impedance modulated by the damping controller.

3.3 Interfaces to the RTDS

The line voltage and line current inputs from the RTDS were scaled down and given as voltage signals to the controller. The analog signals, TCR current, Capacitor voltage and fault to platform current were fed as scaled voltage signals to the controller. The digital inputs were given as opto-isolated inputs to the controller.

The firing pulses from the controller were given as digital inputs at 5V level to the RTDS. The other signals like “Block” and “Bypass” were given through optoisolated inputs to the RTDS.

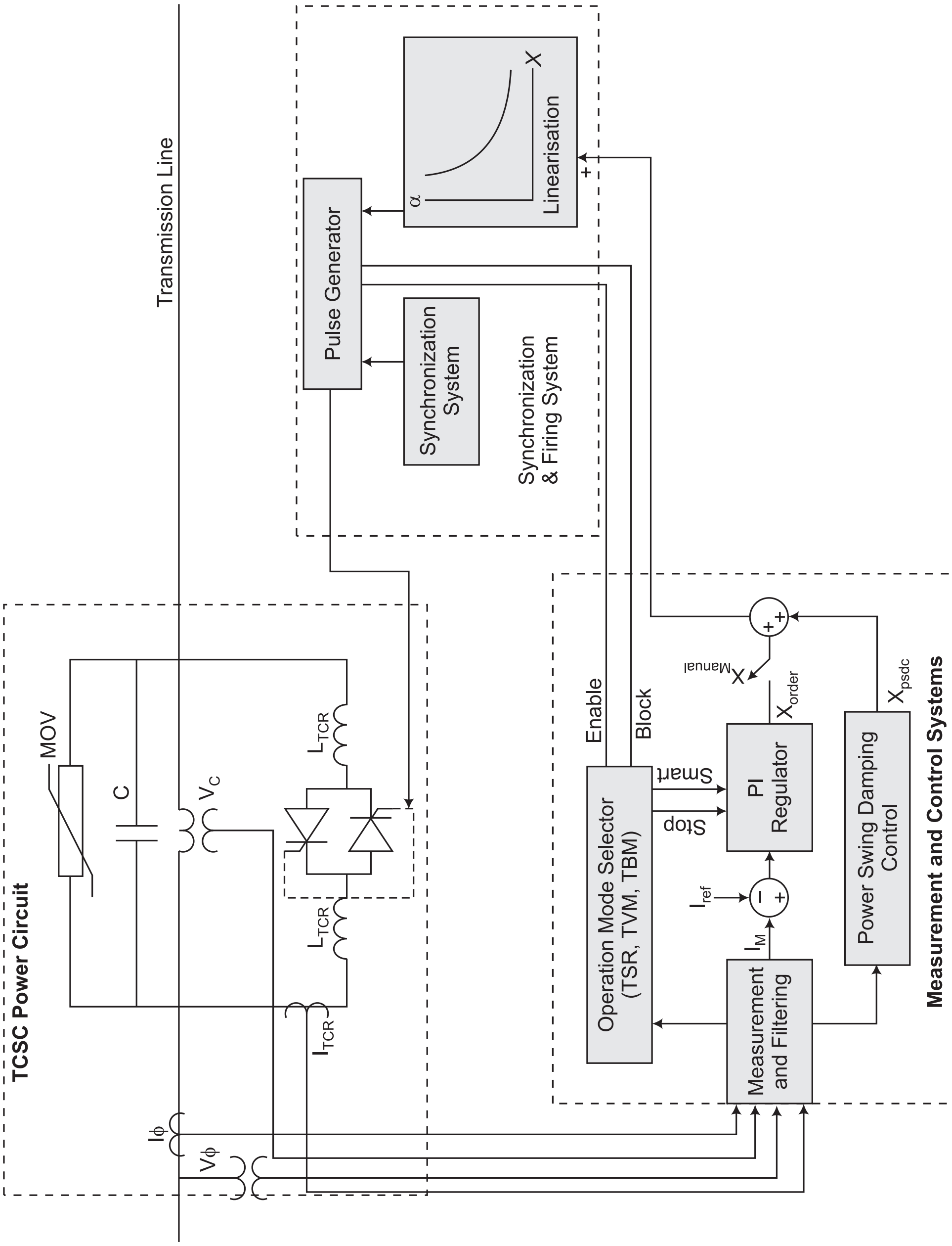

FIG. 4 BLOCK SCHEMATIC OF THE TCSC AND ITS CONTROL SYSTEM

3.4 Control and Protection Features

The following are the main features provided in the controller.

3.4.1 Reactance scheduler

The reactance scheduling can be done by the operator depending on the network requirements. The default value is 12.5 W working at a boost factor of 1.2, though the operator can choose a value in the range of 10.4 W to 25 W i.e., a boost factor of 1 to 2.5. The reactance scheduler is a slow controller that adjusts the firing angle to achieve the set reactance level in steady state. This controller is overridden by other faster controllers like the damping controller and voltage and current limiters.

3.4.2 Current (power) scheduler

The reactance-scheduling mode is the default mode of operation but an operator can select a current or power scheduler mode depending on the system requirements. The current or power scheduler mode is similar to the reactance scheduler. It will be active only if the reactance controller is disabled and the current control activated. The controller permits a current set-ting in the range of 150A to 1200A. The controller will change the firing angle to achieve this within its range. In case of overload the limiters will come into action.

3.4.3 Power swing oscillation damping control

The power swing oscillation-damping controller is a fast controller that modulates the output of the scheduler to damp out the power swing oscillations detected. The damping controller was tested for two cases of input signals (i) line current and (ii) line voltage. The line current based damping controller calculates the drop in voltage across the transmission line using the line current as an input whereas the line voltage based damping controller uses the measured line voltage directly.

3.4.4 SSR mitigation

Studies have revealed [2] that the TCSC working in the constant impedance mode with nominal firing angle is inductive in the SSR frequency range. Hence, no additional SSR mitigation controller was envisaged.

3.4.5 Capacitor overvoltage control

The TCSC can be operated at maximum boost continuously only for a line current of about 600A, but for higher line currents it can operate at maximum boost only for a short duration. The short time voltage rating of the capacitor is taken into consideration and time dependent voltage limiter is incorporated to reduce the boost automatically.

3.4.6 TCR over-current control

Similar to the capacitor's voltage rating, the TCR also has a short time current rating. A time dependent over current limiter is incorporated to reduce the boost automatically.

3.4.7 TSR mode on internal line faults

The controller detects the internal line faults from the amplitude of the line current and sets the TCSC into the TSR mode.

3.4.8 Open loop control

The open loop controller is provided only for checking the controller in the manual mode during *testing and trials.*

3.4.9 Thyristor monitoring system

The thyristor valve comprises of a number of thyristors in series. The thyristor monitoring system continuously monitors all the thyristor levels of the valves. Alarms and trip is generated based on the number of failures exceeding the pre-defined number of thyristor levels.

3.4.10 Valve cooling control

Deionized water is circulated in the thyristor valve to cool the thyristors and the snubber resistors.

The controller controls the pumps and heat exchangers of the cooling system. It also monitors the water temperature, flow and conductivity of the cooling system**.** Depending on the healthiness of the various cooling system parameters, changeover of pumps or requisite alarms and trips are initiated.

3.4.11 Self-diagnostics

The controller has self- diagnostic features built-in. It continuously monitors its own healthiness and a trip is generated in the event of its hardware failure.

4. TESTING AND RESULTS

4.1 First Phase of Testing

The first phase of testing was carried out using the simplified network described earlier. The following studies were carried out with this simplified network.

4.1.1 Open loop or manual mode checking

The open loop or manual mode was tested to ensure proper synchronization and interfacing to the RTDS. The firing angle was manually increased and decreased to result in the desired increase and decrease in boost.

4.1.2 Impedance control mode

In the impedance control mode, step changes were given to increase and decrease the boost. The set impedance level was changed from 12.5 Ω to 26 Ω and back from 26 Ω to 12.5 Ω, as shown in Fig. 5.

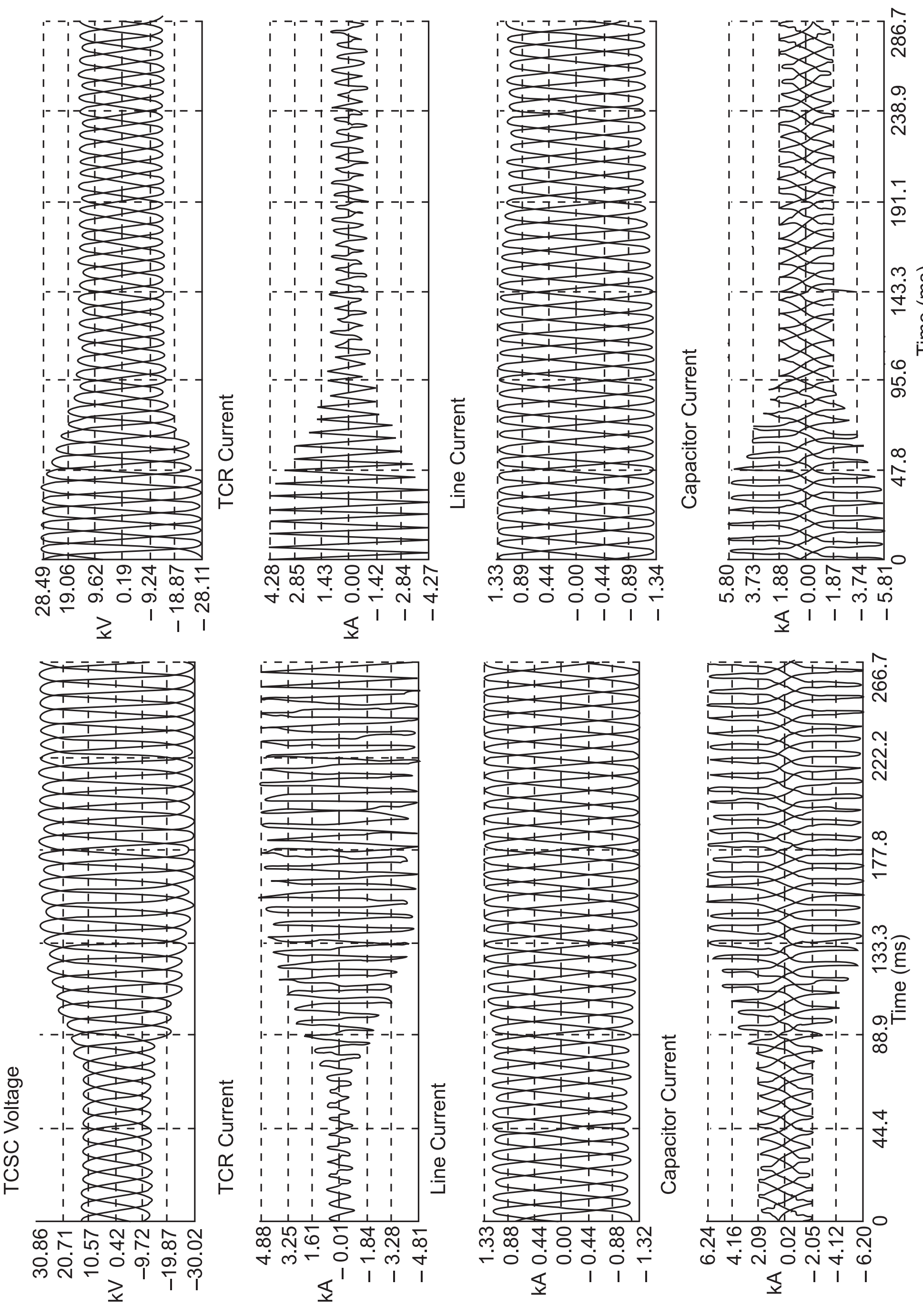

FIG. 5 STEP CHANGE (INCREASE /DECREASE) IN THE IMPEDANCE SETTING

4.1.3 Current control mode

In the current control mode, step changes from 700A to 800A and back from 800A to 700A, as shown in Fig. 6, were given to increase and decrease the boost. As the current scheduler is a slow controller the response times were kept at around 3 seconds, the response was smooth and did not cause any system disturbance. As response time is large, the Fig. 6 show only an envelope of the waveforms.

4.1.4 Frequency compensation

The frequency compensation provided in the controller was tested by gradually changing the system frequency from 47Hz to 53Hz. The controller did not demonstrate any abnormality and found to be working satisfactorily.

4.1.5 Capacitor over voltage and TCR overcurrent protection

For continuous operation, the entire impedance range of 12.5 Ω to 26 Ω of the TCSC can be used only for a line current of less than 600A. But for a line current of greater than 600A will result in an over voltage across the capacitor at higher impedance values. Hence an automatic time dependent voltage-limiting feature is provided in the controller. This feature was checked by increasing the line current and creating an overvoltage across the capacitor. It was demonstrated that firing angle was automatically varied to reduce the over voltage.

Similarly, operation at line currents greater than 600A and higher values of TCSC impedance also results in an over current in the TCR. The over current needs to be limited depending on the capability of the TCR. An over current was created in the thyristor-controlled reactor by increasing the line current and the time dependent current limiting feature was checked.

At the installation, the TCSC voltage and the TCR current signals to the controller are obtained by means of an Optically Powered Data Link (OPDL) with a voltage divider and a CT kept on the 400 kV platform.

4.1.6 Internal line faults

Fault on the Kanpur–Ballabhgarh transmission line are considered as internal line faults. In case of any fault on this line, the Thyristor switched reactor (TSR) mode should be activated. It was demonstrated that for internal line faults the TSR mode was successfully enabled helping in reducing the stress on the MOV as shown in Fig. 7.

4.2 The Second Phase of Testing

The second phase of testing was carried out using the reduced network described earlier. The studies carried out in the first phase were repeated to verify the performance. The following system disturbances were carried out with this reduced network.

4.2.1 External line faults

An external line fault refers to any fault on any transmission line other than the Kanpur–Ballabhgarh transmission line. In case of external faults, the Thyristor switched reactor (TSR) mode should not

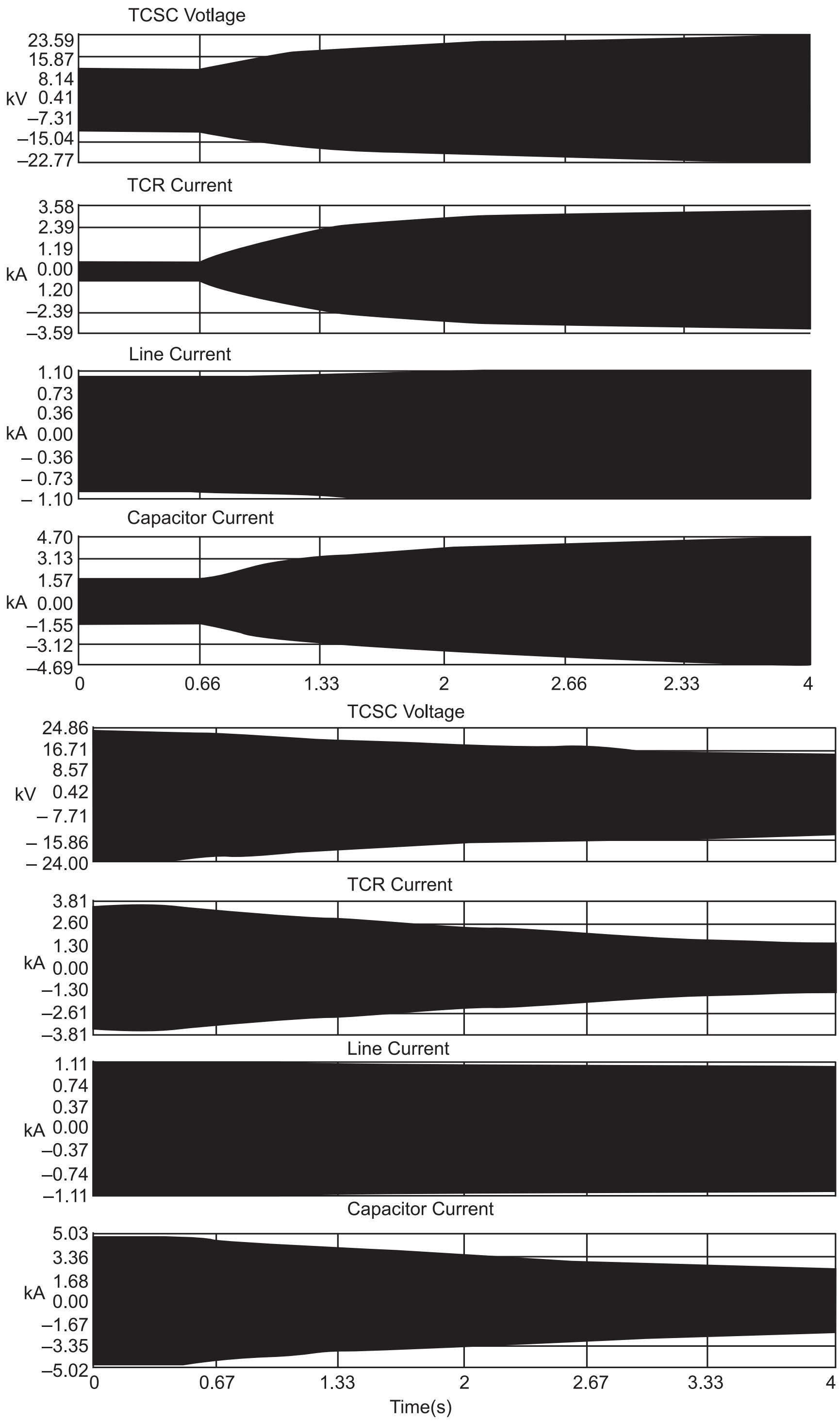

FIG. 6 STEP CHANGE (INCREASE/DECREASE) IN LINE CURRENT

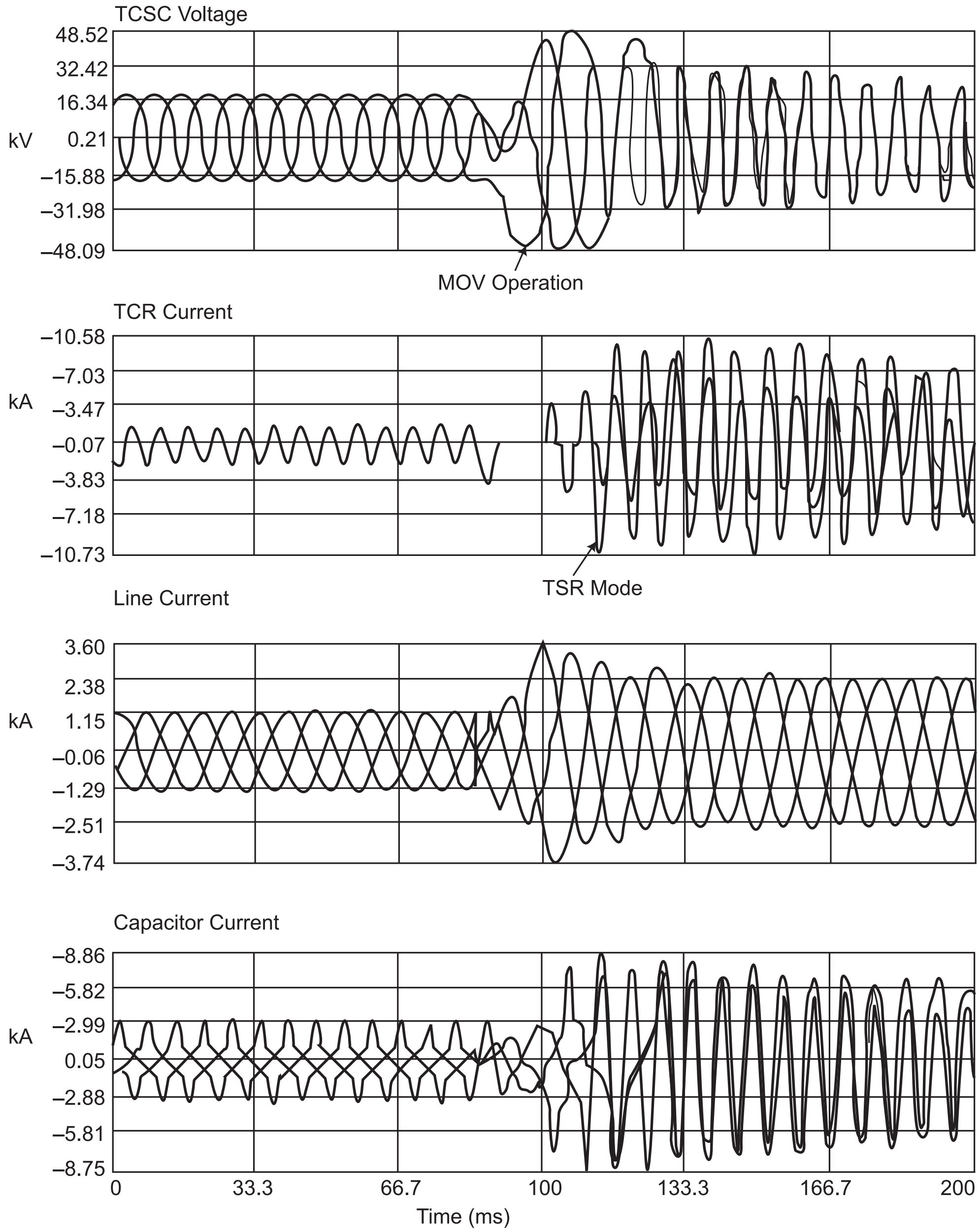

FIG. 7 THREE PHASE TO GROUND FAULT ON KANPUR–BALLABHGARH TRANSMISSION LINE

be activated. This feature was successfully tested by simulating faults like outage of the HVDC line and outage of the neighboring lines like the Panki-Muradnagar line.

4.2.2 Power swing oscillations

An outage of any major parallel transmission line or an outage of the HVDC line results in a power swing. The effectiveness of the damping function was checked. In the MATLAB studies [3], [4] conducted primarily, two signals were considered, (i) the line current, from which the voltage drop in the line was calculated, and (ii) the line voltage, for the damping controller, as shown in Fig. 8.

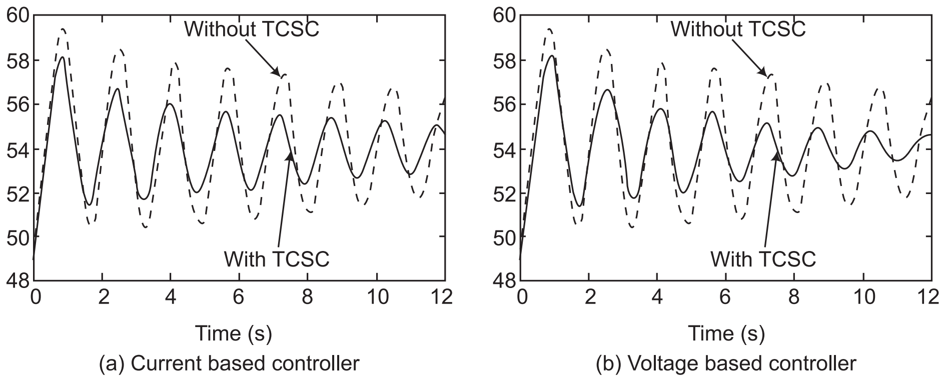

FIG. 8 DAMPING OF OUTAGE OF HVDC LINE ON MATLAB

The MATLAB studies had shown that the voltage based damping controller provided better damping but it introduced a low frequency oscillation on steady state.

It was confirmed during RTDS testing that though the voltage based damping controller yielded better damping, it also created a disturbance in the steady state as shown in Fig. 9(a). This result concurred with the MATLAB simulation results.

The current based damping controller provided satisfactory damping without disturbances in steady state. This is clear from Fig. 9(b). However, in this case also, a disturbance in the form of a low frequency oscillation was noticed under steady state with larger values of gain.

5. CONCLUSIONS

The TCSC controller was tested for its performance under normal system conditions as well as during system disturbances. Impedance control mode, current control mode, changing operating modes, open loop, closed loop operation and frequency compensation were checked, and the response found satisfactory. The capacitor over voltage and TCR over current protection features were successfully tested. Internal and external line faults were created and the controller behaved as desired. The damping controller with voltage and current based damping were studied and the results were in close concurrence with MATLAB simulation results.

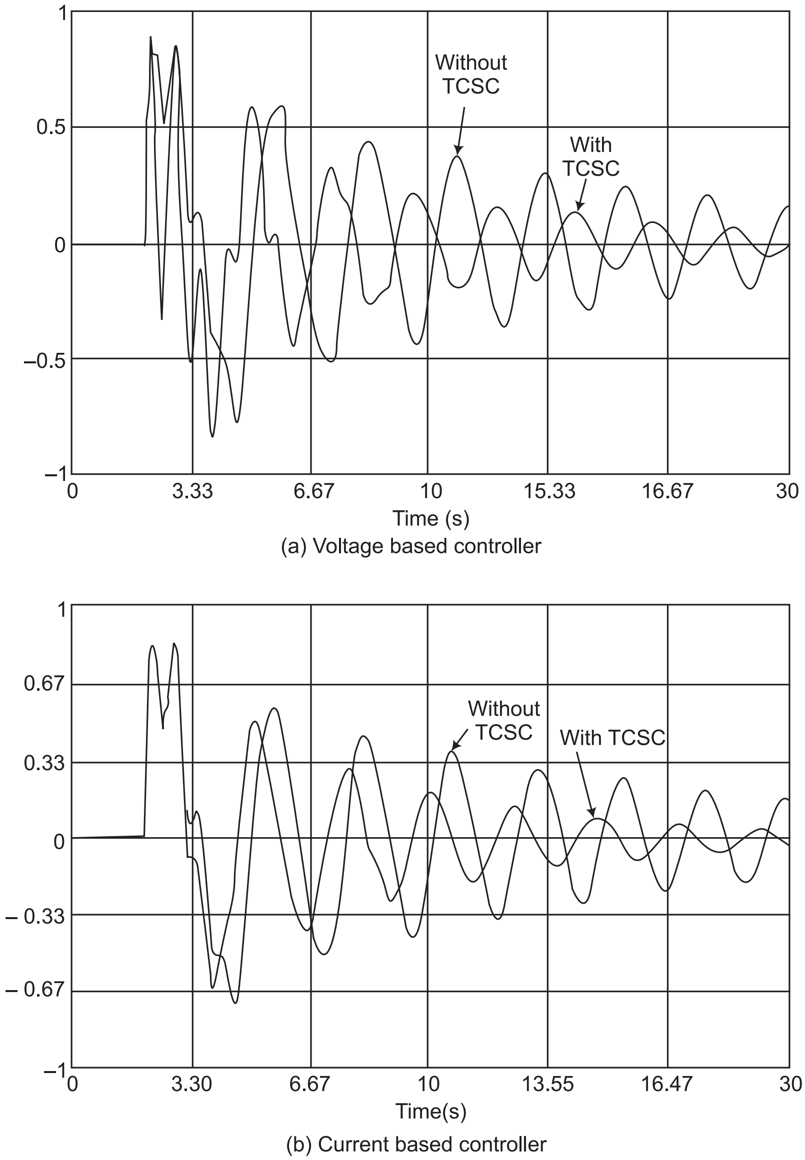

FIG. 9 DAMPING OF OUTAGE OF HVDC LINE ON RTDS

Steady state commissioning tests of the TCSC have been carried out in the field. The controller's steady performance at site is in concurrence with the RTDS studies. It was also noticed at site that the increase in gain of the line current based damping controller affects the controller's steady state performance in the form of a low frequency oscillation

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ELECTRONICS AND COMMUNICATION ENGINEERING

Current Trends in Engineering Practice Vol. III
Editor: Sneh Anand

SPREAD SPECTRUM AND MULTIUSER RADIO COMMUNICATION TECHNIQUES

D. JOHN[1]

1. INTRODUCTION

When secure communication is envisaged or when there is a requirement to reject interference a signaling technique known collectively as 'spread spectrum modulation' is employed. Spread spectrum modulation may be defined in two parts. 1 Spread spectrum is a means of transmission in which the data transmitted occupies a band width in excess of the minimum bandwidth necessary to transmit it 2. It is accomplished before transmission through the use of a code that is independent of the data being transmitted. The same code is used in the receiver to despread the received signal and recover the data. Other modulations such as frequency modulation and pulse code modulation satisfy part 1 of the definition but they are not spread spectrum because they do not satisfy part two of the definition.

Resistance to interference is a unique characteristic of spread-spectrum modulation. It can be used to provide multipath rejection in a ground based mobile-radio environment. Another application is in multiple-access communication in which a number of independent users are required to share a common channel without an external synchronizing mechanism. The example can again be a ground based radio environment involving mobiles that must communicate with a central station.

There are two kinds of spread spectrum modulation techniques; they are direct sequence spread spectrum (DS/SS) and frequency-hop spread spectrum. In direct sequence spread spectrum technique, two stages of modulation are used. The data is first modulated with the pseudo random spreading code and it becomes a wideband signal. Subsequently this wideband signal undergoes a second modulation which is phase shift keying. In the frequency-hop spread spectrum technique on the other hand, the spectrum of a data modulated carrier is widened by changing the carrier frequency in a pseudo random manner.

Code division multiple access (CDMA) used in wireless communication and discussed here subsequently is based on spread spectrum techniques.

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2. PSEUDO NOISE SEQUENCE

Pseudo-random noise (PN) sequence is a periodic binary sequence with a noise-like waveform. The PN sequence is usually generated using a feedback shift register that consists of *m* flip-flops, forming a shift register and a logic circuit connected to it providing multi-loop feedback. The flip-flops in the shift register are regulated by a single timing clock. If the logic circuit consists entirely of modulo-2 adders, the feedback shift register is said to be linear. In such a case, the zero state i.e., the state for which all the flip-flops are in state zero, is not permitted.

The maximum possible length (number of bits, N) of the PN sequence, produced at the output of a linear feedback shift register, consisting of m flip-flops is given by $N = 2^m - 1$; such a sequence is called maximal-length sequence. The feedback logic for a desired period/length N, can be found in the theory of error controlled codes. To simplify the matter, tables are available in literature giving the necessary feedback logic for varying shift register length, m.

The autocorrelation function of a maximal-length sequence is periodic and binary valued. This property is called the 'correlation property'. Let binary symbols 0 and 1 of the sequence be denoted by levels -1 and $+1$, respectively. Let $c(t)$ denote the resulting waveform of the maximal-length sequence. The period of the waveform $T_b = NT_c$ is where T_c is the duration assigned to symbol 1 or 0 of the maximal-length sequence.

By definition, the autocorrelation function of a periodic signal $c(t)$ of period T_b is

$$R_c(\tau) = \frac{1}{T_b} \int_{-T_b/2}^{T_b/2} c(t)\, c(t - \tau)\, dt$$

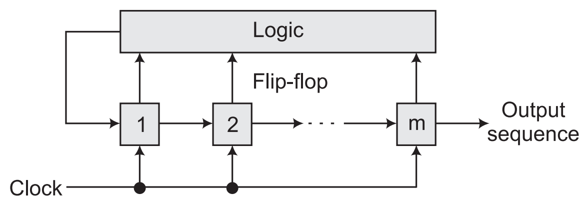

FIG. 1 FEEDBACK SHIFT REGISTER

Maximal-length sequences have many of the properties possessed by a truly random binary sequence. A random binary sequence is a sequence in which the presence of binary symbol 1 or 0 is equally probable. It may be noted that longer the PN sequence, the closer its spectrum will be to that of random binary sequence and hence desirable. However this imposes practical limitations as can be envisaged easily.

3. MECHANISM OF SPREAD SPECTRUM TECHNIQUE

An important function of spread spectrum (SS) modulation is protection against jamming wave form. This is achieved by purposely making information bearing signal occupy a bandwidth far in excess of the minimum bandwidth required to transmit it. This has the effect of making the signal assume a noise like appearance so as to blend in the background. This enables the signal to propagate through the channel undetected. Therefore spreading spectrum can be considered as a method of “camouflaging” the information bearing signal.

Let (b_k) denote the binary data sequence (information bearing data signal) and (c_k) denote a pseudo-noise (PN) sequence (PN signal). Let the waveforms $b(t)$ and $c(t)$ denote their respective polar nonreturn-to-zero representations in terms of two levels equal in amplitude and opposite in polarity, namely, ±1. The SS modulation is obtained by applying these two signals to a product modulator or a multiplier. We know from Fourier transform theory that multiplication of two signals produces a signal whose spectrum equals to the convolution of the spectra of the two component signals. Thus if $b(t)$ is a narrow band signal and PN signal $c(t)$ is wideband, then the spectrum of modulated signal $m(t)$, is nearly same as the wideband PN signal. In other words in our present application, the PN sequence performs the role of a spreading code. The transmitted signal is

$$m(t) = c(t)\ b(t)$$

Now at the other end the received signal $r(t)$ consists of transmitted signal $m(t)$ plus additive interference denoted by $i(t)$. The received signal can be written as follows.

$$r(t) = m(t) - i(t) = c(t)\ b(t) - i(t)$$

To recover the original message signal $b(t)$, the receiver signal $r(t)$ is applied to a demodulator consisting multiplier followed by an integrator and a decision device. The multiplier is supplied with a locally generated PN sequence that is an exact replica of that used in the transmitter. The receiver operates in perfect synchronization with the transmitter, which means that the PN sequence in the receiver is lined up exactly with that in the transmitter. The multiplier output in the receiver therefore is as follows.

$$z(t) = c(t)\ r(t) = c^2(t)\ b(t) + c(t)\ i(t)$$

The PN signal $c(t)$ alternates between -1 and $+1$ and the alternation is destroyed when it is squired; hence,

$$c^2(t) = 1 \text{ for all } t$$

Therefore, we have

$$z(t) = b(t) - c(t)\ i(t).$$

It may be noted that the interference is spread by the spreading code and when the signal is filtered by a narrow band filter that allows the data signal, the contribution of the interference in that narrow band becomes insignificant. Thus the data signal is recovered at the output.

4. DIRECT-SEQUENCE SPREAD SPECTRUM WITH COHERENT BINARY PHASE SHIFT KEYING

The spread spectrum technique described above is referred to as direct sequence spread spectrum. In order to transmit the data that has been spread in spectrum by the PN code over a radio channel, we may incorporate coherent binary PSK. In the transmitter, the incoming data sequence is first converted to a polar NRZ waveform, which in turn undergoes two stages of modulation.

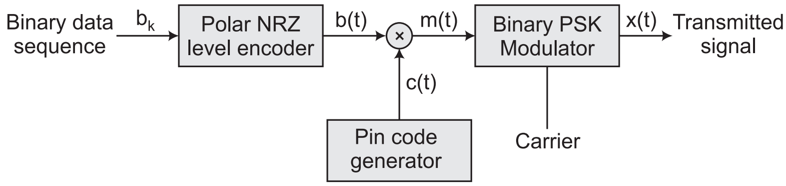

FIG. 2. DIRECT SEQUENCE SPREAD SPECTRUM COHERENT PSK TRANSMITTER

The first is a product modulator where the NRZ waveform is multiplied by the PN code. The second stage consists of a binary PSK modulator that uses a stable carrier frequency. The transmitted signal is thus a direct sequence spread spectrum binary phase shift keyed (DS/BPSK) signal.

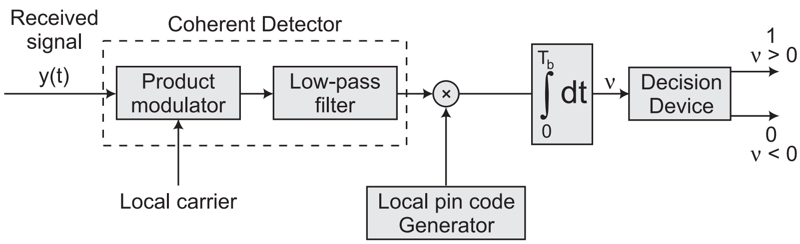

FIG. 3 DIRECT SEQUENCE SPREAD SPECTRUM COHERENT PSK RECEIVER

The receiver consists of two stages of demodulation. The first is PSK demodulation using a locally generated coherent carrier in a signal multiplier follower by a low pass filter (LPF). The second demodulation performs spectrum despreading by multiplying the LPF output by locally generated replica of the original PN code. This signal is integrated over a bit interval and then a decision device recovers the bit stream.

The locally generated PN code must be synchronized to the PN code of the received signal for proper operation of the receiver. Synchronization consists of two parts: acquisition and tracking. In acquisition the two codes are aligned within a fraction of the chip ('bit' of the PN code) in as short a time as possible. This is done by measuring the correlation between the two codes and taking appropriate decision based on it. Tracking is accomplished by phase lock technique.

5. PROCESSING GAIN

Processing gain (PG) of the spread spectrum is the improvement in signal-to-noise ratio obtained by the use of spread spectrum. It is the ratio of bit duration to chip duration. The processing gain and the spread factor N (length of the PN code) are both equal to the ratio T_b/T_c. Thus longer the

PN code, or correspondingly, smaller the chip time, the larger will be the processing gain. The ability of direct sequence spread spectrum (DS/SS) to combat the effect of jammers is determined by the processing gain of the system.

6. FREQUENCY HOP SPREAD SPECTRUM

In DS spread spectrum systems the PN code achieves instantaneous spreading of transmission bandwidth. In order to counter the effects of certain jamming situations, narrowing the chip duration to increase the processing gain will encounter physical device limitations. Hence other techniques are employed. One alternative is to force the jammer to cover a wider spectrum by randomly hopping the data modulated carrier from one frequency to another. In this case the spectrum of the signal is spread sequentially rather than instantaneously as in the direct sequence case. This type of spread spectrum is called frequency-hop (FH) spread spectrum. A common modulation format for FH system is that of M-ary frequency shift keying (MFSK). The combination of these two techniques is simply referred to FH/MFSK.

Since the frequency hopping does not cover the spread spectrum instantaneously, we need to consider the rate at which the hops occur. In this context we have two basic characterization of frequency hopping. In slow frequency hopping, the symbol rate of MFSK is an integer multiple of the hop rate. That is, several symbols are transmitted in one frequency hop. In fast frequency hopping, hop rate is an integer multiple of MFSK symbol rate. That is, carrier frequency will change several times during the transmission of one symbol.

In an FH/MFSK transmitter, the data is first MFSK modulated. This modulated wave and the output from a digital frequency synthesizer are then applied to a mixer that consists of a multiplier followed by a band pass filter. The filter is designed to select the sum frequency component resulting from the multiplication process as the FH/MFSK signal for transmission.

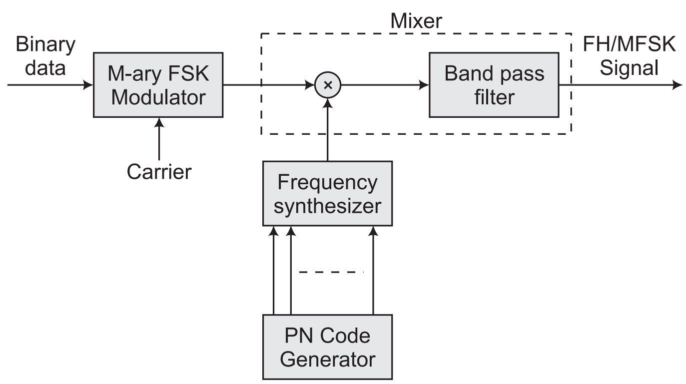

FIG. 4 FREQUENCY-HOP SPREAD SPECTRUM M-ARY FSK TRANSMITTER

The frequency synthesizer is driven by a PN sequence generator. In particular, the successive *k*-bit segments of the PN sequence drive the frequency synthesizer, which enables the carrier frequency to hop over 2^k distinct values. Even though on a single hop, for any one value of 2^k, the band width of the signal is the same as that for a conventional MFSK, for a complete range of 2^k frequency hops, the signal occupies a much larger bandwidth. Indeed with today's technology, bandwidth of the order of several GHz is attainable.

In the receiver the frequency hopping is first removed by mixing (down converting) the received signal with the output of the local frequency synthesizer that is synchronously controlled in the same manner as that in the transmitter. The resulting output is then band pass filtered and subsequently processed by a noncoherent M-ary FSK detector. To implement this M-ary detector, we may use a bank of M noncoherent matched filter, each of which is matched to one of the MFSK tones. An estimate of the original symbol transmitted is obtained by selecting the largest filter output.

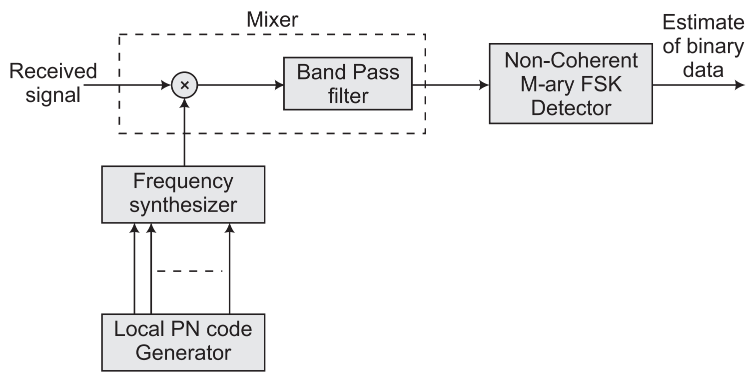

FIG. 5 FREQUENCY-HOP SPREAD SPECTRUM M-ARY FSK RECEIVER

An individual FH/MFSK tone of shortest duration is referred to as chip; this terminology should not be confused with that used describing DS/BPSK. The chip rate, R_c, for an FH/MFSK system is defined by $R_C = \max(R_h, R_s)$ Where R_h is the hop rate and R_s is the symbol rate.

7. TDMA AND CDMA IN WIRELESS COMMUNICATION SYSTEMS

In wireless communication, for the user to talk and listen simultaneously, two separate frequency bands are provided. One band, for the forward link from base station to a mobile and another band, for the reverse link from the mobile to base station are provided. This is called frequency division duplexing (FDD) and is an integral part of the two widely used wireless communication systems.

The first of these systems, namely, GSM, uses TDMA (Time Division Multiple Access). In a TDMA system each subscriber is permitted to access the radio channel during a set of predetermined time slots during which that particular subscriber will have full use of a channel. Consequently, data are transmitted in bursts. The basic GSM frame is composed of eight 577 μs slots. The 1 bit flag preceding each data burst of 57 bits is used to identify whether the data bits are digitized speech or some other information bearing signal. The 3 tail bits, all logical zeros, are used in convolution decoding of the channel-encoded data bits. The 26 bit training sequence in the middle of the time slot is used for channel equalization. Finally the guard time, occupying 8.25 bits, is included at the end of each slot to prevent data bursts received at the base station from the mobile from overlapping with each other; this is achieved by transmitting no signal at all during the guard time. With each slot consisting of 156.25 bits of which 40.25 bits are overhead (ignoring the 2 flag bits), the frame efficiency of GSM is 74.24%.

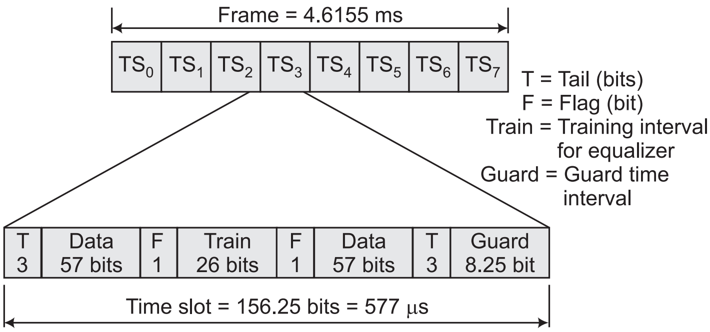

FIG. 6 FRAME STRUCTURE OF THE GSM WIRELESS COMMUNICATION SYSTEM

The second wireless communication system IS-95 uses CDMA (Code Division Multiple Access). In CDMA, each subscriber is assigned a distinct spreading code (PN sequence), thereby permitting the subscriber full access to the channel all of the time. Here we have a new form of interference called multiple access interference, which arises because of the deviation of the spreading codes from perfect orthogonality. Also near-far problem occurs in this system due to mobile units not having equal power at the base station. In this situation the strongest received signal from a mobile user captures the demodulation process at the base station to the detriment of the other users. To overcome this near-far problem power control is used at the base station. The base station maintains the control over the power level of the signal transmitted from every mobile being served by the base station. Another advantage of this kind of power control, in CDMA system, is the capability of the base station to maximize the system capacity while ensuring the acceptable level of interference for reliable service.

Channel data rates are very high in CDMA systems. Consequently the, chip duration is very short and usually much less than the channel delay spread. Since PN sequences have low autocorrelation, multi-path signal which is delayed by more than a chip will appear as noise. The RAKE receiver configuration is incorporated in the receiver design in order to improve reception by collecting time delayed versions of the required signal.

8. SOURCE CODING OF SPEECH FOR WIRELESS COMMUNICATIONS

In multiuser digital wireless communication systems it is essential to use the channel bandwidth efficiently. What ever may be the type of access scheme, TDMA or CDMA employed, the system uses speech coding to remove almost all of the natural redundancy in speech, while maintaining a high quality of speech on decoding. The common approach is to use source coding which in one form or other exploits the linear predictive coding (LPC) of speech.

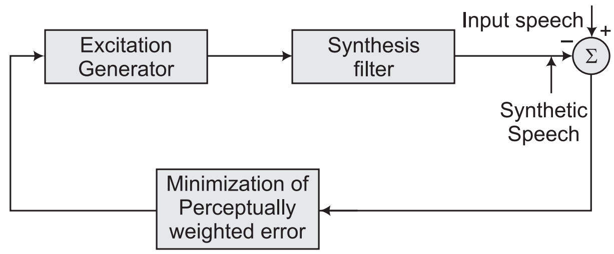

FIG. 7 MULTI-PULSE EXITED LINEAR PREDICTIVE ENCODER

There are two different techniques for speech coding: multi-pulse excited LPC (MPE-LPC) is used in GSM (TDMA system) and code excited LPC (CELP) is used in IS-95 (CDMA system). The multi-pulse excited LPC operates at a bit rate of 13 kbps while maintaining high-quality speech. The code excited LPC commonly referred to as CELP.

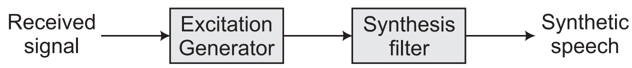

FIG. 8 MULTI-PULSE EXITED LINEAR PREDICTIVE DECODER

In the case of multi-pulse excited LPC, the encoder includes a replica of the decoder in the design. Weighted error between the original speech and the synthesized speech is used to optimize the amplitude and position of the pulses used in excitation with an aim to minimize the error. The quantized filter parameters and quantized excitation of the encoder are transmitted to the decoder. The decoder, located in the receiver, consists simply of two parts: excitation generator and synthesis filter, as shown. These two parts are identical to the corresponding ones in the encoder. The function of the decoder is to use the received signal to produce a synthetic version of the original speech signal. This is achieved by passing the decoded excitation through the synthesis filter whose parameters are set equal to those in the encoder.

The CELP (code excited LPC) uses a predetermined codebook of stochastic (zero-mean Gaussian) vectors as the source of excitation for the synthesis filter. The synthesis filter itself consists of two all-pole filters connected in cascade, one of which performs short-term prediction and the other performs long-term prediction. The free parameters of the synthesis filter are computed first, using the actual speech samples as input. Next, the choice of a particular vector (code) stored in the excitation codebook is made and the gain factor G shown in the figure below is optimized by minimizing the average power of the perceptually weighted error between the original speech and synthesized speech(i.e., output of the synthesis filter). The address of the code selected and the corresponding quantized gain factor, together with quantized filter parameter are the transmitted signal.

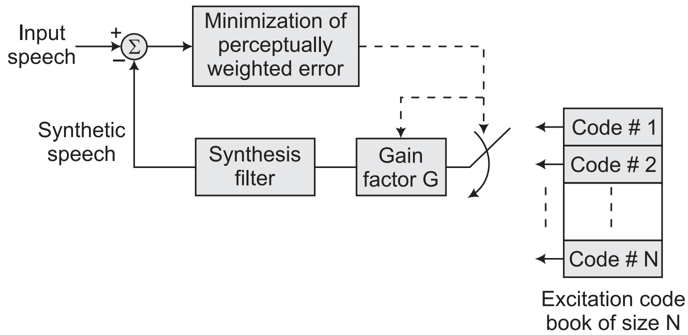

FIG. 9 ENCODER OF THE CODE-EXCITED LINEAR PREDICTIVE CODEC (CELP)

An identical copy of the codebook is made available to the decoder and likewise for the synthesis filter. Hence, given the received signal, the decoder is enabled to parameterize its own synthesis filter and determine the appropriate excitation for the synthesis filter, thereby producing a synthetic version of the original speech signal. CELP is capable of producing good quality speech at a bit rate of 8 kbps. Nevertheless, computational complexity is intensive for CELP and real-time implementation has been made possible because of the advances in digital signal processing and VLSI technology.

9. CONCLUSION

Direct sequence phase shift keying (DS/PSK) and frequency-hop M-ary frequency shift-keying (FH/MFSK) represent two principal categories of spread-spectrum communications. Both of them rely on the use of a pseudo-noise (PN) sequence, which is applied differently in the two categories. In DS/PSK system, the PN sequence makes the transmitted signal assume a noise like appearance by spreading its spectrum over a broad range of frequencies simultaneously. On the other hand, in FH/MFSK system, the PN sequence makes the carrier hop over a number of frequencies in a pseudo-random manner, with the result the spectrum of the transmitted signal is spread in a sequential manner. There are two widely used multiuser wireless communication systems. The first of these systems, namely, GSM, uses TDMA and the second is a CDMA system in which a subscriber is assigned a distinct spreading code (PN sequence) thus permitting the subscriber full access to the channel all the time. The codes assigned to the various users of the channel are orthogonal to each other. In wireless communication channel band width is a precious resource, the conservation of which necessitates the use of spectrally efficient speech coding techniques to produce toll-quality digitized speech at data rates that are a small fraction of the PCM rate. The preferred approach is to use spectrally efficient source coding techniques such as LPC and CELP.

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Current Trends in Engineering Practice Vol. III
Editor: Sneh Anand

SPACE LINKS

D. JOHN[1]

1. INTRODUCTION

The space link relates the power transmitted from one end to the power received at the other end so that the message is transmitted through the intervening space with acceptable fidelity. The link calculations are made to arrive at the minimum power needed to transmit the information successfully to the receiver. As we are only considering radio links the word 'radio' is generally not used in the discussions.

For communications with satellite two links are involved and they work in tandem. The link from the ground to the satellite is called the 'uplink' and that from the satellite to the ground station is called the 'down link'. Each component of the link has its individual characteristics. For example, when the destination user terminal is a VSAT with small antenna, the received carrier level will be small and the 'satellite-to-user terminal' link becomes critical in the overall link. A system designer optimizes the overall link taking into consideration the characteristics of each component of the link. Sometimes when optimizing the link with stringent communication requirements one may encounter unacceptable demands on satellite resources or earth station in terms of size, cost and complexity. A link design endeavors to achieve the objective by judicious choice of the various link parameters.

2. DECIBELS

Decibel quantities are used in Link calculations due to their inherent advantages. The various quantities are added and subtracted instead of multiplying and dividing them when doing the calculations.

A power ratio is expressed in decibels and abbreviated dB.

The power ratio $\frac{P_1}{P_2}$ is expressed in dB as below.

$$10 \log \frac{P_1}{P_2} \text{ dB} \qquad \text{Here the base is 10}$$

[1]Former Deputy Director, ISRO HQ, Bangalore

Power expressed relative to 1W is denoted as dBW and that related to 1mW is denoted as dBm.

For example 50 W is expressed in decibel related to 1 W is 17 dBW and the same expressed in decibel related to 1 mW is 47 dBm.

By definition the ratio of voltages $\frac{V_1}{V_2}$ is expressed in decibels as

$$20 \log \frac{V_1}{V_2} \text{ dB}$$

The multiplication factor of 20 comes about because power is proportional to square of voltage. When reference is 1V the ratio is denoted as dBV and when the reference is 1 μV the ratio is denoted as dBμV.

For example, 0.5 V is expressed in decibels as −6 dBV when reference is 1 V. The same voltage level is expressed as 114 dBμV relative to 1μV.

Other than voltage and current, all other decibel like quantities are taken as 10log (-).

2.1 Example

(a) 10 kHz = 10 log (10×10^3) = 40 dBHz

(Expressed in decibel relative to 1 Hz)

(b) Boltzmann's Constant k = 1.38×10^{-23} Joule/°K

Expressed in decibel relative to 1 Joule/°K

k = 10 log 1.38×10^{-23} = −228.6 dB J/°K

We know 1 Joule = 1 W Sec

i.e. k = −228.6 dBW Sec/°K This term is used to calculate Noise power and is simply known as dBW/°K.

Hence k = −228.6 dBW/°K

or k = −198.6 dBm/°K

Note: For convenience let us use Square bracket, [~] to denote decibel quantity. A ratio x in decibel is thus [x] = 10 log x.

3. TRANSMISSION EQUATION

The transmission equation is fundamental to the design of a communication link. The equation relates the received RF signal power at the destination to the RF power transmitted by the source, the transmission frequency and the transmitter-to-receiver distance. The level of the received signal power governs the quality of the message delivered to the destination and its estimation is therefore important to the link design.

Consider an isotropic radiator. The power transmitter from such a source spreads uniformly outwards on and expanding sphere. At any distance *R*, the transmitted power is therefore uniformly spread over the area of a sphere of radius *R*. The received power flux density expressed as power per unit area at a distance *R* from the source is given by:

$P_{ED} = \frac{P_S}{4\pi R^2}$ W/m^2 where P_S = Transmitted power in Watts from the isotropic source, $4\pi R^2$ = Surface area of a sphere of radius R.

When the isotropic radiator is replaced by an antenna of gain G_S, the power flux density in the direction of antenna boresight is increased by G_S

$$P_{ED} = \frac{P_S G_S}{4\pi R^2} \text{ W/m}^2 \tag{1}$$

The product $P_S\, G_S$ is known as effective isotropic radiated power (EIRP) of the transmitter.

Equation (1) expressed in decibels:

$$[P_{FD}] = [P_S G_S] - [4\pi R^2]$$

i.e.

$$[P_{FD}] = [\text{EIRP}] - [4\pi R^2] \tag{1.1}$$

The received power C at a distance R with an antenna of area A_d m^2 and gain G_d is therefore

$$C = P_{ED}\, A_d \text{ Watts} \tag{2}$$

We know the gain of the antenna $G_d = \frac{4\pi A_d}{\lambda^2}$

Therefore

$$A_d = \frac{G_d \lambda^2}{4\pi} \tag{3}$$

Substituting P_{ED} and A_d in (2), power received $C = P_S G_S G_d \left(\frac{\lambda^2}{4\pi R}\right)^2$ (4)

Expressing in dB we have

$$[C] = [P_S] + [G_S] + [G_d] - \left[\left(\frac{4\pi R}{\lambda}\right)^2\right] \tag{5}$$

The term $\left[\left(\frac{4\pi R}{\lambda}\right)^2\right]$ is known as **free space path loss**. Expression Eq. (5) or (4) is commonly known as **transmission equation**.

Equation (5) can be rewritten as

$$[C] = [\text{EIRP}] + [G_d] - \left[\left(\frac{4\pi R}{\lambda}\right)^2\right]. \tag{6}$$

From this expression it is seen that for a fixed EIRP the received power remains the same when the frequency is increased. When the frequency is increased, the increase in free space path loss is exactly compensated by the increase in receive antenna gain. If however the power transmitted by the source is kept the same, the received power increases with frequency since the transmit antenna gain also increases with frequency. Therefore as we go higher in frequency, like from C band to Ku band transmission, smaller low cost antennas at the user terminals can be used as in the case of corporate VSAT or domestic DTH reception.

4. TRANSMISSION LOSSES

The EIRP can be thought of as the power input at one end of the transmission link and it is required to find the received power at the other end. Losses will occur along the way some of which are constant, other losses are variable and can only be estimated from statistical data and some others are dependent on weather conditions especially on rainfall. The first step is to determine the losses for clear weather or clear sky conditions. These calculations take into account the losses including those calculated on statistical basis which do not vary significantly with time.

Losses which are weather related and other losses which fluctuate with time are then allowed for, by introducing appropriate fade margins into the transmission equation.

The free space path loss [FSL] resulting from the spreading of the signal in space is a major component and is obtained as shown above.

Losses occur in the connection between the receive antenna and the receiver proper. Such losses will occur in wave guides/cables, filters and couplers. These will be termed as receiver feeder losses [RFL]. Similar losses occur in the filters, couplers and wave guides/cables of the high power amplifier output and is called transmit feeder loss [TFL]. The [EIRP] is specified after subtracting in dB these losses from the power at the source.

When a satellite link is established the ideal situation is to have the earth station and satellite antennas aligned along their bore-sight. In the actual case they off-point. The loss due to this off-pointing is called off-axis loss. In addition to pointing losses, losses may result at the antenna from misalignment of the polarization direction. (This is in addition to polarization losses due to depolarization in the free space between transmission and reception ends.) The polarization misalignment losses are usually small and antenna misalignment losses denoted by [AML] usually includes this.

Atmospheric gases result in losses by absorption. This loss is prominent at low elevation angles. These losses usually amount to a fraction of a decibel and denoted by [AA].

Polarization losses due to depolarization in the free space between transmission and reception, caused by ionosphere, ice crystals in the upper atmosphere and rain is to be considered. However in the case of clear sky calculation only the effect due to ionosphere is to be taken in to account. The ionosphere rotates the E vector as the wave passes through and it is called Faraday rotation. The polarization loss due to ionosphere is denoted by [PL] and is equal to 20 log (cos θ_F). Here θ_F is the angle of Faraday rotation of the E vector. Faraday rotation is encountered only in the case of linear polarization, for circular polarization there is no signal loss due to E vector rotation.

Having identified the losses, the power at the receiver maybe calculated simply as [EIRP] – [LOSSES] + [G_R], where the last quantity is the receiver antenna gain. Note that decibel addition must be used. The losses for clear sky conditions are

$$[\text{LOSSES}] = [\text{FSL}] + [\text{RFL}] + [\text{AML}] + [\text{AA}] + [\text{PL}] \tag{7}$$

The decibel equation for received power is then:

$$[C] = [\text{EIRP}] + [G_R] - [\text{LOSSES}] \tag{7.1}$$

Equation (7.1) is the basic **link power budget equation**.

5. SYSTEM NOISE

The received power in a satellite link is very small, of the order of pico-watts. This by itself would not be a problem because amplification could be used to bring the signal strength up to an acceptable level. However electrical noise is always present at the input. Unless the signal is significantly greater than the noise, amplification will be of no help because it will amplify signal and noise to the same extent. In fact, the situation will be worsened by the noise added by the amplifier.

The major source of electrical noise in equipment is that which arises from the random thermal motion of electron in various resistive and active devices in the receiver. **Thermal noise** is also generated in the lossy components of antenna and thermal-like noise is picked up by antennas as radiation. The available noise power from a thermal noise source is given by $P_N = kT_N B_N$ where T_N is known as equivalent noise temperature, B_N is the equivalent noise bandwidths and k is Boltzmann's constant. With temperature in Kelvin and bandwidth in Hertz the noise power will be in watts.

The main characteristic of thermal noise is that it has a flat frequency spectrum; that is the noise power per unit bandwidth is constant. The noise power per unit bandwidth is termed the "noise power spectral density". This is denoted by N_0.

$$N_0 = \frac{P_N}{B_N} = kT_N \text{ Joules} \tag{8}$$

The noise temperature is directly related to the physical temperature of the noise source but is not always equal to it. The noise temperatures of various sources which are connected together in a circuit (in tandem like in a receiver chain), referred to a point in that circuit, can be added directly to give the total noise at that point.

In addition to these thermal noise sources, intermodulation distortion in high power amplifiers can result in signal products which appear as noise and in fact is referred to as **intermodulation noise**.

In dual polarization system, **depolarization** causes cross-polar coupling resulting in **interference** and this is also accounted as noise. The interference is estimated from cross polar isolation XPI given by:

$$\text{XPI} = 20 \log \frac{|E_{11}|}{|E_{21}|}$$

Where, E_{11} = received co-polarized electric field strength

E_{21} = cross-polar component.

6. ANTENNA NOISE

Antenna noise can be broadly classified into two groups: Noise originating from the antenna losses and "sky noise"

Sky noise is a term used to describe microwave radiation which is present throughout the universe and which appears to originate from matter in any form at finite temperatures. Such radiation in fact covers a wider spectrum than the microwave spectrum. The noise temperature is about 3°K at frequencies between about 1 and 10 GHz. This represents the residual background radiation in the universe.

Any absorptive loss mechanism generates thermal noise, there being a direct connection between the loss and the effective noise temperature. Rainfall introduces attenuation and therefore it degrades transmission in two ways: it attenuates the signal and it introduces noise. The detrimental effects of rain are much worse at Ku-band frequencies than at C-band.

Satellite antennas are generally pointed towards earth and therefore they receive the full thermal radiation from it. In this case, the equivalent noise temperature of the antenna, excluding antenna losses is approximately 290°K.

Antenna losses add to noise received as radiation and the total antenna noise temperature is the sum of the equivalent of the noise temperatures of all these sources. For large ground based C-band antennas the total noise temperature is typically about 60°K and for Ku-band about 80°K under clear-sky conditions. **Note** that these values do not apply to any specific situation and are quoted merely to give some idea of the magnitudes involved.

7. AMPLIFIER NOISE TEMPERATURE

Let us consider the antenna connected to the low noise amplifier (LNA) of the receiver. The available power gain of the amplifier is denoted as G and the noise power output as $N_{0,\text{out}}$. Here we consider the noise power per unit bandwidth, which is simply noise energy in joules. The input noise energy coming from the antenna is

$$N_{0,\text{ant}} = kT_{\text{ant}}$$

The output noise energy $N_{0,\text{out}}$ will be $GN_{0,\text{ant}}$ plus the contribution made by the amplifier. All the amplifier noise, wherever it occurs in the amplifier may be referred to the input in terms of an equivalent input noise temperature for the amplifier T_e. This allows the output noise to be written as

$$N_{0,\text{out}} = Gk(T_{\text{ant}} - T_e)$$

The total noise referred to the input is simply $N_{0,\text{out}}/G$,

or
$$N_{0,\text{in}} = k(T_{\text{ant}} - T_e)$$

This means the noise temperature of the antenna and the amplifier are directly added to get the noise temperature referred to the input of the receiver.

8. AMPLIFIERS IN CASCADE

When two amplifiers with gains equal to G_1 and G_2 respectively are cascaded, the overall gain is $G = G_1G_2$.

The noise energy of amplifier-2 referred to its own input is simply kT_{e2}. The noise input to amplifier-2 from the preceding stages is $G_1k(T_{ant} - T_{e1})$ and thus the total noise energy referred to noise amplifier-2 input is

$$N_{0,2} = G_1k(T_{ant} - T_{e1}) - kT_{e2}$$

The noise energy may be referred to amplifier-1 input by dividing by the gain of amplifier-1:

$$N_{0,1} = k\left(T_{ant} + T_{e1} + \frac{T_{e2}}{G_1}\right)$$

A system noise temperature may now be defined as T_S by

$$N_{0,1} = kT_S$$

And hence it will be seen that $T_S = T_{ant} + T_{e1} + \frac{T_{e2}}{G_1}$.

This is an important result. It shows that noise temperature of the second stage is divided by the gain of the first stage when referred to the system input. Hence in order to keep the system noise temperature low the first stage (LNA) should have high gain as well as low noise temperature.

In the most general case when number of stages are cascaded the system noise temperature is given by:

$$T_S = T_{ant} + T_{e1} + \frac{T_{e2}}{G_1} + \frac{T_{e3}}{G_1G_2} + \ldots \tag{9}$$

9. NOISE FIGURE

An alternate way of representing amplifier noise is **'Noise Factor'** and it is defined as the ratio of the signal to noise power ratio at the input to the output. The noise factor expressed in dB is called **'Noise Figure'** From the definition noise factor is given by:

$$F = \frac{C_{in}/N_{in}}{C_{out}/N_{out}} \tag{10}$$

In defining the noise factor of an amplifier, the source is taken to be at room temperature, denoted by T_0 usually taken to be 290°K, then

$$F = \frac{N_{out}}{GkT_0B}$$

Where $G = C_{out}/C_{in}$, B = measurement bandwidth and N_{out} = output noise power

In terms of noise spectral density the above expression is rewritten as

$$F = \frac{N_{0,out}}{GkT_0}$$

i.e. $$N_{0,out} = FGkT_0$$

A simple relationship between **noise temperature** and **noise factor** can be derived. Let T_e be the noise temperature of an amplifier and let the source be at room temperature (T_0) as required by the definition of F.

The above equation can be rewritten as:

$$Gk(T_0 - T_e) = FGkT_0$$

or
$$T_e = T_0(F - 1). \quad (11)$$

This shows direct equivalence between noise factor and noise temperature. As a matter of convenience, in satellite receiving systems, **noise temperature is specified** for low noise amplifiers (LNA) or low noise block converters (LNBC) and **noise figure is specified** for the main receiver unit.

9.1 Noise Temperature of Absorptive Network

Consider an absorptive network that has a power loss L. The power loss is the ratio of input power to output power and will always be greater than unity. From the definition of noise temperature, the equivalent noise temperature of the attenuator can be shown to be:

$$T_L = T_0(L - 1) \quad (12)$$

This gives equivalent noise temperature of an attenuator referred to the input at the antenna when the antenna is used in the receiving mode. It is assumed that the attenuator is at room temperature. Comparison of equation 11 and 12 shows that

$$F = L$$

This shows that at room temperature the noise factor of a lossy network is equal to its power loss.

9.1.1 Some useful relations

Refer to the following Figure 1.

T_{ant} = Effective antenna temperature considering all external noise contributions assuming no Ohmic losses in antenna

T_L = Ambient temperature of the attenuator.

$T_R = T_0 (F - 1)$ where T_0 = 290°K

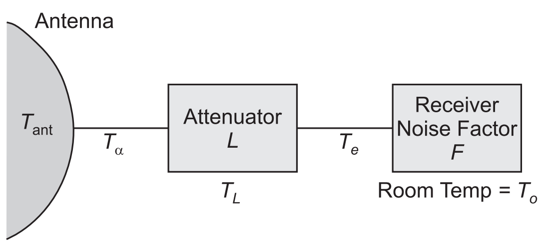

FIG. 1 ANTENNA CONNECTED TO THE RECEIVER BY A CABLE OF LOSS L

The useful relations are:

$$T_\alpha = T_{\text{ant}} - LT_R - (L - 1)T_L \tag{12.1}$$

$$T_e = T_R + \frac{T_{\text{ant}}}{L} + \frac{(L-1)T_L}{L}. \tag{12.2}$$

9.2 Noise Factor and Noise Temperature of Network in Series

When '*n*' amplifiers are cascaded, the equivalent noise temperature can be shown to be

$$T_e = T_1 + \frac{T_2}{G_1} + \frac{T_3}{G_1 G_2} + \ldots + \frac{T}{G_1 G_2 \ldots G_{n-1}} \tag{13}$$

Where F_n and G_n are respectively the effective noise temperature and the gain of the *n*th stage.

Substituting the equivalent noise factor in equation (13) the noise factor of *n* cascaded amplifiers is given as

$$F = F_1 + \left(\frac{F_2 - 1}{G_1}\right) + \left(\frac{F_3 - 1}{G_1 G_2}\right) + \ldots + \left(\frac{F_n - 1}{G_1 G_2 \ldots G_{n-1}}\right) \tag{14}$$

Where, F_n is the noise factor of the *n*th stage amplifier.

Equations (13) and (14) provide an important insight into the system noise behaviour of the system. Notice that noise contribution of the first stage is the largest, whereas the contributions from the succeeding stages are reduced successively as G_1, G_1G_2 etc.

Therefore every effort should be made to minimize the noise of the first stage of the receiver.

9.3 Overall System Noise Temperature

Consider a typical receiving system where the antenna feed is directly connected to the LNA of noise temperature T_{LNA} followed by the cable/wave guide of loss L and connected to the receiver with a noise factor F. Applying the results of the previous sections yields for the system noise temperature referred to the input,

$$T_S = T_{\text{ant}} + T_{LNA} + \frac{(L-1)T_0}{G_1} + \frac{L(\text{F} - 1)T_0}{G_1} \tag{15}$$

It is important to place LNA ahead of the cable to reduce the system noise temperature.

It can be shown that any loss, ahead of the first stage amplifier (LNA) directly adds to the noise figure of the first stage (LNA) in decibels.

10. CARRIER-TO-NOISE RATIO

A measure of the performance of a satellite link is the ratio of the carrier power to the noise power at the receiver input. The ratio is denoted by C/N (or CNR) which is equal to received power divided by noise power. In terms of decibels,

$$\left[\frac{C}{N}\right] = [\text{Received power}] - [\text{Noise power}]$$

Using the relations explained above it can be written,

$$\left[\frac{C}{N}\right] = [\text{EIRP}] + [G_R] - [\text{LOSSES}] - [k] - [T_S] - [B] \tag{16}$$

The G/T ratio is a key parameter in specifying the receiving system. The antenna gain $[G_R]$ and the system noise temperature $[T_S]$ in equation (16) can be combined as

$$[G/T] = [G_R] - [T_S]$$

The term $[G/T]$ is called the figure of merit of the receiving antenna (receiving system).

It is convenient to express Eq. (16) in terms of noise spectral density, N_0.

Hence

$$\left[\frac{C}{N_0}\right] = [\text{EIRP}] + \left[\frac{G}{T}\right] - [\text{LOSSES}] - [k] \text{ dBHz} \tag{17}$$

Note that the unit of the above is dBHz and this equation is widely used.

11. THE UPLINK

The uplink is the one in which the earth station is transmitting the signal and the satellite is receiving it. The above equation can be applied, but subscript U will be used to denote the uplink.

$$\left[\frac{C}{N_0}\right]_U = [\text{EIRP}]_U + \left[\frac{G}{T}\right]_U - [\text{LOSSES}]_U - [k] \text{ dBHz} \tag{18}$$

In equation (18) the values to be used are earth station EIRP, the satellite receiver feeder loss and satellite receiver G/T. The free space loss and other losses which are frequency dependent are calculated for the uplink frequency. The resulting carrier to noise spectral density ratio given by Eq. (18) is that which appears **at the satellite receiver**.

11.1 Saturation Flux Density

In some situations, the flux density appearing at the satellite receive antenna is specified.

Figure. 2 shows the TWTA (traveling wave tube amplifier) in a satellite transponder exhibiting power output saturation. The flux density required at the receiving antenna to produce saturation of the TWTA is termed the 'saturation flux density' (SFD).

Consider the Eq. (1.1) $[P_{FD}] = [\text{EIRP}] - [4\pi R^2]$

But we know $$[\text{FSL}] = \left[\left(\frac{4\pi R}{\lambda}\right)^2\right]$$

Hence $\left[\frac{\lambda^2}{4\pi}\right] + \left[\frac{1}{4\pi R^2}\right] = -\,[\text{FSL}]$ substituting this in Eq. (1.1), we have

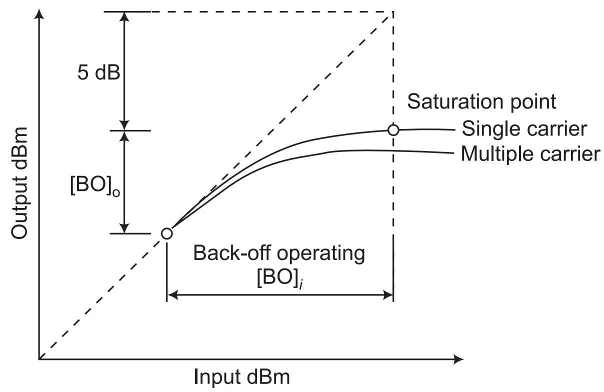

FIG. 2 OUTPUT POWER SATURATION OF SATELLITE TWTA

$$[P_{FD}] = [\text{EIRP}] - [\text{FSL}] - \left[\frac{\lambda^2}{4\pi}\right] \tag{19}$$

The term $\left[\frac{\lambda^2}{4\pi}\right]$ has the dimension of area and it is in fact the effective area of an isotropic antenna. Denoting this by $[A_0]$ we can rewrite Eq. (19) as

$$[\text{EIRP}] = [P_{FD}] + [A_0] + [\text{FSL}]$$

Considering other propagation losses such as atmospheric absorption loss, polarization loss, and antenna misalignment loss as earlier, we have,

$$[\text{EIRP}] = [P_{FD}] + [A_0] + [\text{FSL}] + [\text{AA}] + [\text{PL}] + [\text{AML}] \tag{20}$$

This gives the minimum EIRP required to be transmitted from the ground station, for clear sky conditions to get the given power flux density P_{FD} at the satellite receive antenna. Normally the saturation flux density SFD is specified. With saturation value denoted by $[P_{SFD}]$ the above equation is rewritten as,

$$[\text{EIRP}_S]_U = [P_{SFD}] + [A_0] + [\text{FSL}]_U + [\text{AA}]_U + [\text{PL}]_U + [\text{AML}]_U \tag{21}$$

11.2 Input Backoff

When a number of carriers are present simultaneously in a TWTA, the operating point must be backed off to a linear portion of the transfer characteristic to reduce the effect of intermodulation distortion.

When the SFD for a single carrier operation is known and the input backoff for multiple carrier operation referred to the single carrier saturation level is given, the earth station EIRP will have to be reduced by the specified backoff (BO).

Then $$[\text{EIRP}]_U = [\text{EIRP}_S]_U - [\text{BO}]_i \tag{22}$$

Normally the input backoff is achieved through reduction of the earth station EIRP.

Equation (18) can be rewritten using Eqs. (7), (21) and (22) as below.

$$\left[\frac{C}{N_0}\right]_U = [P_{SFD}] + [A_0] + \left[\frac{G}{T}\right]_U - k - [\text{RFL}] - [\text{BO}]_i \tag{23}$$

Equation (23) is for clear sky condition.

12. DOWN LINK

The down link is the one in which the satellite is transmitting the signal and the ground station is receiving it. Equation (18) can be applied but with the subscript changed to D.

12.1 Output Backoff

When input back off is employed a corresponding output backoff must be allowed for in the satellite EIRP. As is evident from the figure, output backoff is not linearly related to the input backoff. A rule of thumb used is to take the output backoff as a point on the curve which is 5 dB below the extrapolated linear portion as shown in the Fig. 2. Since the slope of the linear portion is 1, the relationship between the input and output backoff is

$$[\text{BO}]_o = [\text{BO}]_i - 5 \text{ dB}. \tag{24}$$

For example with an input backoff of 11 dB the output backoff becomes 6 dB. If the satellite EIRP for saturation condition is specified as $[\text{EIRP}_S]_D$ then,

$$[\text{EIRP}]_D = [\text{EIRP}_S]_D - [\text{BO}]_o \tag{25}$$

Then the downlink equation is given by

$$[C/N_0]_D = [\text{EIRP}_S]_D - [\text{BO}]_o + [G/T]_D - [\text{LOSSES}]_D - [k]. \tag{26}$$

13. RAIN EFFECT

Up to this point, calculations have been made for clear sky conditions. In C-band and especially in Ku band rainfall is the most significant cause of signal fading. Rainfall results in attenuation of radio waves by scattering and by absorption of energy from the wave. Rainfall results in attenuation of signal and an increase in noise temperature, degrading the CNR of the satellite in two ways.

In the uplink the increase in noise however is not a major factor because the satellite antenna is pointed towards a ‘hot’ earth, and this added to satellite receiver noise tends to mask the additional noise introduced by rain. What is important is the uplink carrier power reduced by the rain attenuation/rain fade. Usually charts are available to provide rain attenuation figures for various locations on earth for various percentage of rain duration.

In the down link rainfall degrades the ground station received CNR in two ways: by attenuating the carrier wave and by contributing the sky noise temperature.

13.1 Some Useful Relations for Rain Condition

1. $T_{\text{ant, Rain}} = \dfrac{T_{\text{Sky}} - (L_R - 1)T_r}{L_R}$
2. Down link CNR under rain is $\left(\dfrac{N}{C}\right)_{\text{Rain}} = \left(\dfrac{N}{C}\right)_{\text{Clear Sky}} \times \left(L_R + (L_R - 1)\,\dfrac{T_r}{T_{\text{Sks. Clear Sky}}}\right)$

All quantities in the above equations are not in dB

Where,

T_{Sky} = Clear sky temperature due to galactic noise, microwave background, and oxygen and water vapour losses.

T_r = Rain or tropospheric temperature normally = 290°K

L_R = Rain loss

$T_{\text{Sys. Clear Sky}}$ = Total receiving system noise temperature under clear sky condition.

14. INTERMODULATION NOISE

Intermodulation occurs when multiple carriers pass through any device with non linear characteristics. In satellite communication system intermodulation most commonly occurs in the TWTA/SSPA. Both amplitude and phase nonlinearities give rise to intermodulation products (IMP). The third-order IMP falls on the neighbouring carrier frequencies causing interference. When a large number of modulated carriers are present, the intermodulation products appear as a type of noise which is termed ‘intermodulation noise’.

15. INTERFERENCE

There are various sources of interference in a satellite communication system. These may be broadly classified as intra-system and inter-system interferences.

Intra-system interference: A number of sources can cause intra-system interference. Interference can be caused by coupling of orthogonally polarized signals in a dual polarized system. Interference can occur when the filters used for isolating adjacent satellite channels do not have sufficient roll-off characteristics. There are other miscellaneous intra-system interferences caused by signals traveling via multiple paths in satellites. Magnitude of these interferences is difficult to predict analytically. However with proper sub-system and system designs a link margin of 0.5 to 1 dB is adequate to compensate for intra-system interference.

Inter-system interference: Care must be exercised to minimize interference from and to other satellite and terrestrial systems during initial systems design. Procedures laid down by ITU are used to minimize inter-system interference in both the uplink and the down link.

A carrier may be impaired by unintended interference signals besides the ever present AWGN. The fundamental link equation can be generalized to include the effects of interference on both uplink and down links. To do so we have to make the assumption that all interference signals including the AWGN are statistically independent wide-sense stationary random processes of zero means.

When the interferences are non-Gaussian and none of them has a dominant effect, the joint probability density function approaches the Gaussian density function with zero means and variants equal to the sum of individual variances as stated by the 'Central Limit Theorem'. Their effect can be approximated like that of a single AWGN process which produces the same carrier-to-interference ratio.

16. TOTAL CARRIER-TO-NOISE RATIO

The total link carrier to noise ratio can be shown in terms of the uplink CNR and down link CNR as below:

$$\left(\frac{C}{N}\right)_T = \left\{\left(\frac{C}{N}\right)_U^{-1} + \left(\frac{C}{N}\right)_D^{-1}\right\}^{-1} \tag{27}$$

If we take into account $(C/I)_{UD}$, the carrier-to-intermodulation ratio of the total satellite link and $(C/N_i)_{UD}$, the carrier-to-sum of up and down link interference noises in the overall link, Eq. (27) can be rewritten by including these two terms as shown:

$$\left(\frac{C}{N}\right)_T = \left\{\left(\frac{C}{N}\right)_U^{-1} + \left(\frac{C}{N}\right)_D^{-1} + \left(\frac{C}{I}\right)_{UD}^{-1} + \left(\frac{C}{N_i}\right)_{UD}^{-1}\right\}^{-1} \tag{28}$$

For digital modulation the quantity E_b/N_0, the bit energy to noise density ratio can be computed from Eq. (27) or (28) knowing that $\frac{E_b}{N_0} = \frac{B}{R}\left(\frac{C}{N}\right)$ where R equal to bit rate and B equal to noise bandwidth. Equation (27) provides fundamental analysis of a satellite link where the satellite transponder is a frequency-translating repeater. In this type of satellite transponder uplink noise adds directly to the down link noise. From Eq. (27) we note that if uplink CNR is much greater than down link CNR then the total CNR is approximately equal to the down link CNR. In this case the satellite link is said to be down link limited. This is the common case in satellite communications.

Design of a satellite link, to establish a carrier-to-noise plus interference ratio, to meet specified performance criteria, is a complex task. The systems and applications of the link dictate the performance criteria. The system engineer must determine the earth station EIRP and G/T within the specified cost constraints to achieve the desired performance.

It is to be remembered that the other important parameters that dictate the link design are:

1. **For the earth station:** Geographical location that provides an estimate of rain fade, satellite look-angle, satellite EIRP in the direction of earth station and intermodulation noise.
2. **For the satellite:** Location of the satellite, G/T, transponder gain, EIRP and transponder type (transparent or regenerative).

3. **For the channel:** Operating frequency, path loss, link margin, modulation and coding, propagation characteristic that govern the link margin and inter system noise that affects the system noise budget.

17. SAMPLE LINK CALCULATIONS

Figure 3 shows the links of the satellite communication with all the parameters involved. Two cases using two different multiple access techniques and frequency bands are considered in the following examples to illustrate how the link calculations are done.

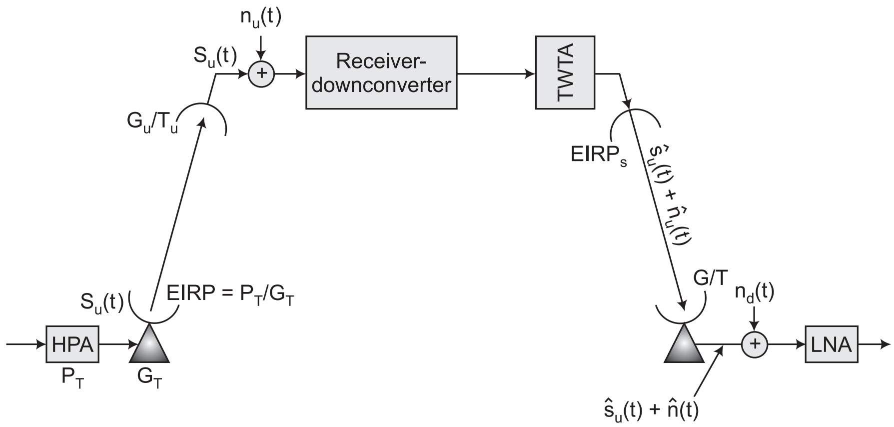

FIG. 3 BASIC SATELLITE LINK

Example 1 Consider a Ku band (14/12-GHz) satellite system operating in the single-carrier-per-transponder TDMA mode using QPSK carrier modulation.

The system parameters given are as below:

Carrier modulation parameters - Bit rate: 60 Mbps, Bit duration-bandwidth product: 0.6, Noise bandwidth: 36 MHz

Satellite parameters – Antenna G/T: 1.6 dB/°K, Satellite saturation EIRP: 44 dBW, TWTA input back-off: 0 dB, TWTA output back-off: 0 dB

Earth station parameters – Antenna diameter: 7 m, Transmit antenna gain at 14 GHz: 56.7 dB, Receive antenna gain at 12 GHz: 56.3 dB, Transmit power into antenna: 174 W, Maximum slant range for up and down links: 37,506 km, Antenna tracking loss: 1.2 dB (uplink) and 0.9 dB (down link), Receive system noise temperature: 160°K

Based on the above parameters and the equations given earlier here, link calculation is done to find out the overall performance of the communication system.

The uplink performance (14.25 GHz)

Ground station EIRP	80 dBW
Free space path loss	206.9 dB
Antenna tracking loss	1.2 dB

Satellite G/T	1.6 dB/°K
Boltzmann's constant	– 228.6 dBW/ °K-Hz
Noise bandwidth	75.6 dB-Hz
$(C/N)_u$	26.5 dB

The downlink performance (11.95 GHz)

Satellite EIRP	44 dBW
Free space path loss	205.5 dB
Antenna tracking loss	0.9 dB
Earth station G/T	34.3 dB/°K
Boltzmann's constant	– 228.6 dBW/ °K-Hz
Noise bandwidth	75.6 dB-Hz
$(C/N)_d$	24.9 dB
Total carrier to noise ratio	**22.6 dB**
Link E_b/N_0	**20.4 dB**

As can be seen, the overall link in the above example is neither uplink limited nor downlink limited.

Example 2 Now consider the case of a multiple-carriers-transponder operation for a C band (6/4 GHz) satellite system operating in the FDMA mode but using the same QPSK modulation.

The system parameters given are as below:

Carrier modulation parameters – Bit rate: 64 kbps, Bit duration-bandwidth product: 0.625, Noise bandwidth: 40 kHz

Satellite parameters – Antenna G/T: –7 dB/°K, Satellite saturation EIRP: 36 dBW, TWTA input back-off: 11 dB, TWTA output back-off: 6 dB, Number of carriers in the transponder bandwidth: 200, Power flux density at the satellite to saturate the transponder: –80 dBW/m^2

Earth station parameters - Saturation power flux density per carrier: –80 –10 log 200 = –103 dBW/m^2, Transmit antenna gain: 47 dB, Receive antenna gain: 44.5 dB, Earth station G/T: 22 dB/°K,

Maximum downlink slant range: 37,506 km.

Based on the above parameters link calculation is done to find out the overall performance of the communication system.

The uplink performance (6 GHz)

Saturation power flux density per carrier	–103 dBW/m^2
Gain of an ideal 1 m^2 antenna [$4\pi/\lambda^2$]	37 dB
Satellite G/T	–7 dB/°K
Boltzmann's constant	– 228.6 dBW/ °K-Hz
Noise bandwidth	46 dB-Hz
TWTA input backoff	11 dB
$(C/N)_u$	24.6 dB

The downlink performance (4 GHz)

Saturation EIRP per carrier (36-10log200)	13 dBW
Free space path loss	196 dB
Earth station G/T	22 dB/°K
Boltzmann's constant	– 228.6 dBW/ °K-Hz
Noise bandwidth	46 dB-Hz
TWTA output backoff	6 dB
$(C/N)_d$	15.6 dB
Total carrier to noise ratio	**15 dB**
Link E_b/N_0	**12.96 dB**

17.1 Explanation

It may be noted that in example 2, the satellite link is downlink limited unlike in the previous example. In example 2, the signal flux density at the satellite receive antenna to saturate the transponder output is given instead of power into the earth-station antenna. Therefore the uplink calculation is done differently without having the requirement to calculate the uplink free space path loss.

In example 1, the satellite transponder is operated in saturation mode since the satellite access technique employed is TDMA, consequently the input/output backoff of the satellite TWTA is 0 dB. In example 2, the transponder handles multi-carriers in FDMA and hence appropriate input and output back-offs are used.

18. CONCLUSION

Link calculations are done diligently when finalizing the design of the communication system. All parameters are considered carefully so that the system is optimized for the required performance. This article illustrates the design aspects of the communication link and the actual link calculations that are encountered in satellite communications.

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SATELLITE COMMUNICATION SERVICES AND APPLICATIONS

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1. INTRODUCTION

Satellite communication has played a very important roll in the world of communication over the years and covers many services and applications. It has been widely acknowledged that it is the only cost effective means of communication to reach remote areas and difficult to reach locations and can be implemented easily and quickly. The applications include many aspects touching human life, such as, entertainment, telecommunication, education, health, search and rescue, instructions and training, teleconferencing etc.

2. COMMUNICATION SATELLITE SERVICES

Communication satellite services are classified as below:

- Fixed satellite services (FSS)
- Broadcast satellite services (BSS)
- Mobile satellite services (MSS)

Fixed satellite services includes all of the radio communication services operated via INSAT, INTELSAT, EUTALSAT, PANAMSAT etc., and operates essentially to fixed earth stations. BSS covers direct broadcasting of TV and radio signals and includes direct broadcasting satellite (DBS) systems. This consists of much smaller earth stations on domestic premises together with fixed earth stations providing the uplink feeder to the satellite. MSS operates in the maritime mobile service, aeronautical mobile service, land mobile service via INMARSAT, plus a number of global and regional systems. INSAT system also includes BSS and MSS components in its communication applications.

2.1 Fixed Satellite Services

Fixed satellite services have mainly the following frequency bands:

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Frequency Band	*Downlink*	*Uplink*
C	3.4 - 4.2 and 4.5 - 4.8 GHz	5.725 - 7.075 GHz
Ku	10.7 - 11.7 GHz	12.75 - 13.25 and 14.0 - 14.5 GHz

For FSS the nature of the satellites and earth station equipment, modulation methods and interference aspects of the service can be very diverse. For example, we have mammoth 33 m diameter earth stations with large capacity and very small aperture terminals (VSATs) with antenna diameter of less than 1 m and capacity adequate for low-volume traffic.

The FSS applications, for example, provided by INSAT are, telecommunication i.e., speech circuits on trunk routes, TV broadcasting, business communication, radio networking, VSAT connectivity, meteorological data collection, disaster warning, Search and rescue, distance-education and telemedicine.

The services provided by INSAT include telecommunication circuits reaching remote inaccessible areas with digital technology. In recent times there has been a dramatic increase in corporate communications with VSATs. Introduction of digital TV has resulted in a more efficient way of using the communication satellite transponders. The cyclone warning system that works with INSAT provides advance information on impending disaster from approaching cyclones to the vulnerable areas.

2.2 Broadcast Satellite Services

Broadcast satellite services meet the requirements of television and radio broadcast via satellites. Digital broadcasting is an evolving technology. Satellite TV broadcasting has gained a place in the market already. The satellite television is available in many places with a wide choice of programs and this broadcast uses the FSS frequency band. On the other hand there is very little satellite sound broadcasting as dictated by the needs Former Deputy Director, ISRO HQ, Bangalore of the market. The digital audio broadcast (DAB) however uses the BSS frequency band, which is nominally the S band.

The main BSS frequency bands are as follows:

INSAT BSS operates with the downlink operates in S band (2550 – 2630 GHz) and uplink in C band (5850 - 5930 GHz). Two channels each having 40 MHz bandwidth have been operating for TV distribution and radio networking.

The frequency band 1452 – 1492 MHz has been allotted by ITU for use from 2007 in many countries for digital audio broadcast via satellite. However the US has adopted 2.3 GHz, and some countries have also accepted this as an option, in addition to the use of 1.5 GHz.

2.3 Mobile Satellite Services

Mobile satellite services in the beginning were considered primarily for maritime requirements. Those concerned with maritime and aeronautical communications have, since the first experiments in satellite communications, realized the potential benefits of the satellite communication to their respective communities. The arrival of cellular radio services has awakened interest in land mobile satellite services as well. Satellite mobile terminals are distributed over wide geographical areas hence mobile satellite services do not normally share the frequency bands used by fixed links.

INSAT MSS uses S band for communication with mobile terminals. Mobile uplink uses 2.67-2.69 GHz and downlink operates in 2.50-2.52 GHz. Under INSAT MSS two services are operating; one of them for two-way voice and data communication, using Type-A mobile terminal and the other for one-way reporting services using Type-C terminal. The reporting service is used for tracking vehicles and wagons on the move. This service employs 100 carriers with 10 kHz spacing in 2677.56-2678.56 MHz band. The rest of the uplink band and the downlink band are used for Type-A services. The fixed links between satellite and the base stations of the MSS Type-A and Type-C services, operate in the C band (FSS band).

The current MSS frequency allocations in the L band for earth to space transmission extends from 1626.5 MHz to 1660.5 MHz. The corresponding space to earth band extends from 1525 MHz to 1559 MHz. These bands are subdivided for Maritime Mobile Satellite service (MMSS), Aeronautical Mobile Satellite Service (AMSS) and Land Mobile Satellite Service (LMSS) such that duplex channels are paired with an offset frequency of 101.5 MHz. The co-primary allocations to the MSS, intended for use by the FPLMTS (Future Public Land Mobile Telecommunication System) is in the bands 1980-2010 and 2170-2200 MHz.

INMARSAT is an organization that has provided mobile communication throughout the world in a big way. When INMARSAT formed it was mandated to support services for maritime users alone. During the 1980s INMARSAT extended its field of interest to include aeronautical and land mobile systems. The INMARSAT space segment is deployed in the four ocean region configuration which was developed from the earlier three ocean region arrangement designed to support maritime services. The fourth generation satellites have been deployed in 2005.

From 1976 various INMARSAT terminals for mobile communication have been operating such as INMARSAT-A /B/C/M, INMARSAT-Aero and INMARSAT-D. INMARSAT-A provided circuit-switched telephony and telex services between PSTN and suitably equipped ships.

Majority of the services provided by INMARSAT-B system, which came into existence subsequently, are circuit-switched. This system provides low speed (300 bps) asynchronous data services and medium speed (9.6 kbps) data services in addition to telephony and telex. In addition to point-to-point services shore-to-ship broadcast telex services are provided for fleet management, safety-message distribution and network-management services. INMARSAT-C service supports a low-speed, store-and-forward, two-way message service for land and maritime applications. This system provides for individual ship, fleet and geographical-region addressing in its broadcast mode to satisfy the requirements of maritime safety functions. The system handling short-messages employs packet-switching techniques. INMARSAT-M system is designed to support circuit switched, medium quality telephony and full duplex medium-rate data services. This data service meets the requirement of CCITT group 3 facsimile. The system also supports distress calling facilities for maritime users. The system call set-up protocols used here are common to INMARSAT-B service making easy the introduction of INMARSAT-M system.

With the introduction of spot beam capability provided by the third generation satellites, a derivative of the INMARSAT-M, known as mini-M entered the service in the late 1996. These terminals, the land-mobile variant of which is about the size of a laptop computer, differ from full-M taking advantage of the higher gains of the satellite antennas.

The INMARSAT-Aero system as its name implies is designed to cater to the needs of aeronautical users. To ensure spectral efficiency the Doppler shift of about 1.5 kHz introduced by the aircraft motion is compensated appropriately. As with the INMARSAT-B and M systems, power control and voice activation are used to ensure maximum utilization of spacecraft power. Power control is very essential in the aeronautical system since the aircraft antenna is expected to exhibit gain variations of several dB over the specified coverage regions.

The INMARSAT-D introduced during 1996 is a messaging service. The initial system was one-way, but a D+ system provided an acknowledgement capability.

The Inmarsat M4 or Global Area Network (GAN) uses land portable terminals to provide on-demand voice, fax, and 64 kbps ISDN data services. GAN brings an ISDN environment to almost any remote location, and two GAN terminals can be multiplexed to achieve 128 kbps. The 3.1 kHz audio mode allows analog modem connections. A 2.4 kbps circuit-switched data mode exists for backwards compatibility. The Mobile Packet Data Service (MPDS) is an “always-on” internet/data service billed on the amount of data transferred instead of connection time. Typical applications of GAN include email, web surfing, transmitting large data files, real time or store & forward video, and secure communications. Most of the earth’s land masses are covered except for the polar caps with this system.

The Inmarsat Broadband Global Area Network (BGAN) was launched in December 2005. It is a powerful Inmarsat service providing data speeds up to 492 kbps and simultaneous voice and data calling capability. BGAN offers on-demand guaranteed data rate “streaming IP” services up to 256 kbps, as well as 64 kbps ISDN circuit-switched data for backwards compatibility with older GAN applications.

Today INMARSAT offers BGAN Link broadband data services for users who have a requirement for high volumes of standard IP data in one location providing data speeds up to half a megabit. It is suitable for companies working in a remote area. FleetBroadband is the maritime communications service offered, to provide broadband data and voice simultaneously through a compact antenna on global basis and it is capable of standard IP data rate upto 432 kbps for internet access. SwiftBroadband is the aeronautical communications service offered today and it is capable of meeting demand for bandwidth. It delivers high-quality voice and data communications through a single antenna to the whole aircraft, servicing cockpit, cabin and operational applications.

Iridium’s satellite network is the only truly global communications network established with a constellation of 66 LEO satellites and has coverage available including the Polar regions. The system provides voice, paging, 160-character two-way short text messaging (SMS), emergency 911 service (dial sequence 00-911) and internet access services to subscribers anywhere on the surface of the earth.

The latest Iridium hand held phone, 9505A is smaller, more power efficient and more water resistant than the original Iridium phone, the ‘Iridium 9500’. The internet access is 2400 bps (direct dial circuit switched). The bandwidth of Iridium 9505A is 2400 bps. Special free compression software (SkyFile) is available for most Windows platforms which boosts the effective compressed speed to 10,000 bps for many common highly compressible data types such as text-based email communication. The compression software enables the user to connect to the Internet directly through Iridium's gateway using a packet data service specifically designed to maintain the continuity of an internet access session even when the signal is temporarily lost. In the event of signal loss, the Iridium phone reconnects automatically and transparently. It is a well planed system to cover the whole globe but the bandwidth available is less to meet today's communication needs.

Globalstar deployed with a constellation of LEO satellites has over 250,000 subscribers in 120 countries. Due to problems with the Globalstar satellite network announced early in 2007, Globalstar is at present suited only for land-based users in the lower 48 US states and southern Canada. Coverage exists in most of the Americas and their coastal waters. One can dial a convenient US mobile number without expensive international long-distance. In addition to voice services, 9600 bps data service is available for email and internet access. With required special hardware and software faxes can even be sent and received. In October 2010 Globalstar began the deployment of its new second generation satellites constellation and customers are reaping the benefits of the new satellites.

Thuraya system uses geosynchronous satellites and handheld satellite telephones to provide Voice, Internet/Data, Fax, short messaging (SMS), and GPRS communications. Remote location determination services via (GPS) are also available. Satellite coverage is now available in 140 countries spanning a large region covering Asia, including the Indian Sub-continent, Africa, Australia, the Middle East and Europe. Certain models of the Thuraya handheld phones also have terrestrial GSM Cellular capability.

It may be noted that satellite mobile systems are not popular where terrestrial mobile systems have good coverage.

3. MULTIMEDIA SATELLITE SERVICES

The multimedia services are video on demand, broadcast video, video conferencing, high speed internet, video telephony, remote database access, voice, e-mail/messaging, etc. requiring data rates from few kbps to upto 100 MBPS. The multimedia services require considerably greater bandwidth and here operators are forced to look at higher frequency bands, Ka or reuse spectrum at Ku band by using new technology/techniques. In the year 2000, it was felt that there would be a steady growth in demand for this service and several systems were proposed in the categories of GEO, LEO and GEO+MEO. The GEO satellites were proposed with multiple beams and onboard processing to work with corporate antennas ranging from 0.5 to 2 m diameter and power levels less than 10 W to receive upto 100 MBPS.

LEO systems such as Teledesic with 840 satellites, Skybridge with 64 satellites etc., were proposed with inter-satellite links. However the commercial failure of Iridium, Globalstar, and ICO were primary factor in halting these programmes. GEO-MEO combination was thought of with MEO meeting the needs of high quality delay sensitive (teleworking, telemedicine, video conferencing etc.) services. Some GEO systems have come up for high speed internet/video and the demand is expected to grow. The examples are Two-way system of Eutelsat, WildBlue system for North America, DirecTV and Space-way systems of Hughes Network. At present ICO Global Communication is having capability to provide ICO-Mobile Interactive Media service, through their GEO satellite, in the American continents, which includes TV in car on road, car navigation and satellite-connected emergency voice and text messaging assistance on road.

4. ADVANCED APPLICATIONS BASED ON SATELLITE PLATFORMS

Advanced applications based on satellite platform include remote-sensing through synthetic aperture radar, disaster management employing multi-spectral remote sensing satellites together with communication satellites, village resource centre receiving necessary inputs benefiting the rural masses, tele-education and telemedicine.

4.1 Radar Imaging

The Canadian Radarsat remote sensing Programme for resource management, maritime safety, ensuring SAR (Synthetic Aperture Radar) data available for research, mapping Antarctica and the whole world with stereo images etc., is targeting the following applications. With Radarsat -1 and 2 in orbit the proposed applications are iceberg detection, ice coverage monitoring, oil pollution monitoring, forest management, crop monitoring, shipping and fisheries.

On April 26, 2012 ISRO launched the Radar Imaging Satellite (RISAT) that carries a C-band SAR payload, operating in a multi-polarization and multi-resolution mode. SAR, being an active sensor, operating in the microwave range of electromagnetic spectrum, provides the target parameters such as dielectric constant, roughness, and geometry, and has the unique capability for day-night imaging, and imaging in all weather conditions including fog and haze, and also provides information on soil moisture. SAR payload is based on an active phased array technology using Transmit/Receive (T/R) modules, which provides necessary electronic agility for achieving the multi-mode capability, spatial resolutions of 3 m to 50 m and swath modes of 10 to 240 km to cater to different applications, including some of that of Radarsat-1 and 2 above.

4.2 Tele-Education

Tele-Education is an important application based on satellite platform especially when remote areas are targeted. Satellite instructional television experiment (SITE) was conducted in India during 1975-76 covering 2,500 villages, as a forerunner for all tele education programmes of later years. Programmes for school children, school teachers and rural audience on agriculture, health, hygiene, nutrition, etc., were transmitted. 40,000 teachers were trained during SITE and substantial knowledge gains accrued on health and hygiene among the rural population. This programme triggered off many initiatives in distance education, including establishment of IGNOU.

Training and development communication channel (TDCC) programme was implemented in various States of India with one-way video and two-way audio technology. The teaching-end includes a studio and an uplink facility. The participants at the classroom-end located nationwide receive lectures through simple dish antennas and have facility to interact with lecturers using telephone line. This network consists of more than 2000 classrooms spread over the country. Several Indian State Governments are using the TDCC system extensively for distance education, rural development, women and children development and industrial training. Under GRAMSAT programme the State capital is connected to districts and blocks. Gujarat, Karnataka, Madhya Pradesh, Orissa, Rajasthan and Andaman and Nicobar islands use this system extensively.

The efforts by the Government, various agencies and ISRO have succeeded in improving the quality of education to a great extent over the years in India. However the problem continues to be formidable given the size of the country.

India launched, in 2004, EDUSAT, a satellite dedicated exclusively for education. A typical EDUSAT system consists of a teaching end and several classrooms with receive only or interactive terminals. Live or recorded programmes are transmitted from the teaching end. The objective of education satellite system is to meet the challenge of number and quality in Education.

The EDUSAT primary school network implemented for Chamarajanagar District of Karnataka State has the teaching end in Bangalore and about 1000 schools with receive only terminal are connected via EDUSAT. This network facilitates distance learning for about 55,000 primary school students simultaneously and the content, in local language, is of the same quality as that imparted in leading schools in Bangalore. At present 51,100 receive only terminals are operating on EDUSAT all over the country. In addition there are 4,200 satellite interactive terminals operating on EDUSAT, mostly meeting the requirements of higher education.

4.3 Telemedicine

The next important application is telemedicine. There is a wide disparity in health care in India between urban and rural areas. Telemedicine consists of a specialist end in an urban location and a patient end in a remote location. The specialist gives consultancy based on the information received through the communication link, without having the need to touch the patient. ISRO has so far set up telemedicine facility in several hospitals in the country. At present 60 super speciality hospitals are connected to 306 remote/rural/district hospitals/health centres and 16 Mobile Telemedicine units through ISRO telemedicine networks. Through telemedicine networks regular consultations are held benefiting the population in Andaman & Nicobar, Lakshadweep, North East and J&K and backward and remote areas in the mainland.

4.4 Village Resource Centre

Another important application of satellite communications is the village resource centre (VRC). VRCs facilitate access to special information like land use, ground water potentials besides providing online interaction between local farmer and agricultural scientists. Applications also include telemedicine, tele education and training. At present there are more than 450 village resource centres operating across the country benefiting the rural population and the number of VRCs in the country is steadily increasing.

4.5 Disaster Management

For disaster management the space systems of ISRO consisting of Indian remote-sensing satellites and INSAT satellites, provide observation and communication capabilities to predict and forewarn disaster. The cyclone warning system based on INSAT system provides advance information on impending disaster from approaching cyclones. Specially designed satellite receivers have been installed in the vulnerable coastal areas of Tamil Nadu, Andhra Pradesh, Orissa, West Bengal and Gujarat. Special warning bulletins are transmitted in local languages to the affected areas. Remote sensing satellites provide tools to estimate drought and monitor floods in the river basins. Potential exists to mitigate and manage disaster when it occurs.

4.6 Satellite Aided Search and Rescue

Search and rescue aided by satellite is an important application of international significance. INSAT system in GEO complements the international GEO-LEO COSPAS SARSAT system, for providing service in the Indian Ocean region. Signals picked up from distress beacons from sea, air or land are transmitted through the satellite to the Mission Control Centre and from there to the Rescue Coordination Centre for search and rescue. This is an important service resulting in the saving of human lives and goods. Any one lost after a disaster in sea or air crash or in a land expedition and in possession of a registered 406 MHz beacon, will be rescued by this system.

5. VSAT

VSAT stands for very small aperture terminal system. This is the distinguishing feature of a VSAT system, the earth station antenna is typically less than 2.4 m in diameter. The small receive only terminal of direct broadcast satellite or direct to home system could be termed VSAT, but the appellation is usually reserved for private networks, mostly providing two way communications facility. Typical user groups include banking and financial institutions, ATMs, airline, hotel booking agencies and large retail stores with geographically dispersed outlets.

The basic structure of VSAT network consists of a hub station which provides broadcast facility to all the VSATs in the network. The VSATs themselves access the satellite in some form of multiple-access mode. The hub station may be operated by a service provider and shared by a number of users. Each user organization has exclusive access to its own VSAT network. Time division multiplex is the normal mode of transmission from hub to the VSATs. The access from VSATs to hub is more complex and various methods are used which are proprietary. The most popular access method is FDMA. TDMA can also be used; since the date transfer from VSATs is of busty nature a form of demand assigned multiple access (DAMA) is employed in some systems. VSAT systems operate in star configuration, which means the connection of one VSAT with another VSAT is through the hub involving two satellite hops and consequent delay. However today mesh connections are available where VSATs connect with one another through satellite in a single hop. VSATs operate in Ku band although there are some C band systems in existence.

6. GLOBAL POSITIONING SYSTEM

The Global Positioning System (GPS) is a global navigation satellite system (GNSS) developed by the US DOD and managed by the US Air Force. It is the only fully functional GNSS in the world, can be used freely, and is often used by civilians for navigation purposes. It uses a constellation of between 24 and 32 Medium Earth Orbit Satellites that transmit precise Microwave signals, which allow GPS receiver to determine their current location and the time.

Since it became fully operational in 1993, GPS has become a widely used aid to navigation worldwide, and a useful tool for map making, land surveying, commerce and scientific uses. Also, the precise time reference is used in many applications including the scientific study of earthquakes. GPS is also a required key synchronization resource of cellular networks, such as the Qualcomm CDMA air interface used by many wireless carriers in a multitude of countries.

The military sponsored GPS at the time of inception envisaged that major applications would be mainly military. Some twenty years after the initial plans were laid, GPS found even wider applications in the range of military as well as civil.

GPS is based on passive time-ranging in which the time taken for a signal to travel between the satellite and the receiver is measured. This transit time is then easily related to the distance between the satellite and the receiver by the velocity of light. The three dimensional position of the receiver (x, y, z) can be calculated if the absolute transit time, and hence the distance from three satellites, at known position is measured.

In practice, the transit time relative to a local time reference at the receiver is measured. This local time reference will be offset from GPS time by an unknown amount and is known as the receiver clock offset. The product of velocity of light and the transit time relative to the receiver clock is known as the pseudorange. As the receiver clock offset is common to all transit-time measurements, by taking a total of four pseudorange measurements between four GPS satellites and the receiver it becomes possible to solve for the position (x, y, z) and the receiver clock offset. However, this becomes possible provided the receive has an accurate knowledge of the position of the four satellites and the time offsets between each satellite and GPS time. The GPS control segment consisting of the master control station and a number of monitor stations, estimates these parameters and send them to the satellites. These parameters are then broadcast to the users in the navigation message received by the GPS receiver and used in the calculation of the position (x, y, z).

The pseudorange between the ith satellite and the j^{th} receiver (p_j^i) can be written as:

$$p_j^i = \rho_j^i + (t - t_j)\, c$$

Where ρ_j^i is the true range between the ith satellite and the jth receiver, t is the GPS time, t_j is the receiver time and c is the velocity of light. The true range is given by:

$$\rho_j^i = \sqrt{(x^i - x_j)^2 + (y^i - y_i)^2 \; + (z^i - z_j)^2}$$

Where x^i, y^i and z^i are the Cartesian coordinates of the i^{th} satellite and x_j, y_j and z_j are the Cartesian coordinates of the j^{th} receiver in an earth-centered earth-fixed (ECEF) coordinate reference system.

The ionosphere and the troposphere cause additional delays and to make suitable corrections, the relevant parameters are also broadcast to the users in the navigation message.

Pseudorandom sequence (PN ranging) is used for the pseudorange measurements in the GPS. The properties of autocorrelation function of a pseudorandom sequence facilitate perfect alignment of the received code with the locally generated replica. When the offset time $\tau = 0$ chips period, i.e., when codes are perfectly aligned, the value of the autocorrelation function is one. The term chip period refers to duration of a single bit in the pseudorandom sequence. The magnitude of the auto correlation function linearly decreases to zero as the offset time approaches $\tau = \pm$ 1chip period. At all other values of τ the autocorrelation is approximately zero. Thus it is possible to determine when a received pseudorandom sequence is synchronized with a locally generated replica to with in a small fraction of chip duration. Having performed the synchronization of a local code with the received code, it is a simple to calculate the pseudorange by measuring the time at which the replica code stared relative to the receiver clock. The precision of the pseudorange measurement is dependant on the signal-to-noise ratio in the code tracking loop. The number of chips in the sequence determines the largest time difference which can be unambiguously measured. Therefore, long codes are desirable in a navigation system.

The heart of the navigation payload is a group of two caesium and two rubidium clocks running at 10.23 MHz. All frequencies are derived from this clock onboard the GPS satellite. GPS satellites transmit signals in L-Band. These signals are modulated by 50 bps navigation messages, C/A code with code length of 1023 chips at 1.023 MchipPS and P-code with code length of 2.35×10^{14} chips at a chip rate of 10.23 MchipPS. P-code receiver on ground estimates ionospheric delay with greater accuracy than that provided by the ionospheric model. There is provision to control the accuracy of the C/A code derived standard positioning service (SPS) by phase modulating the clocks with noise like jitter. This degradation process is known as selective availability (SA). The P-code signal is used to provide the precise positioning service (PPS). P-code reception is reserved for military applications. Through the optional use of the encrypted Y-code, the use of the PPS can be restricted to allied military agencies. These agencies have the means to counter the effects of SA. Over the years civilian markets are beginning to take precedence.

7. SATELLITE NAVIGATION

Certain civilian applications require better accuracy, integrity, continuity and availability than that achieved with the stand alone GPS system. An example is the civil aviation requirement. Without augmenting the GPS ground infrastructure and applying differential techniques, the most demanding integrity and accuracy requirements for category III precision-approach landing cannot be met.

Satellite navigation of ISRO is at its infancy. The Ministry of Civil Aviation has decided to implement an indigenous Satellite-Based Regional GPS Augmentation System also known as Space-Based Augmentation System (SBAS) as part of the Satellite-Based Communications, Navigation and Surveillance (CNS)/Air Traffic Management (ATM) plan for civil aviation. The Indian SBAS is expected to bridge the gap between the European EGNOS (European Geo Stationary Navigation Overlay System) and the Japanese MSAS (MTSAT Space Augmentation System) to provide seamless navigation of aircraft from west to east and vice-versa. When implemented, the Indian SBAS system will play an important role in the introduction of satellite based navigation services in the Asia Pacific region. The Indian SBAS system has been given an acronym - GPS Aided GEO Augmented Navigation (GAGAN).

The first navigation payload was flown on GSAT-8 which was launched on May 21, 2011. Two more payloads will be subsequently flown, one each on two geostationary satellites.

8. DIRECT TO HOME SERVICE (DTH)

Direct to Home Service mostly operates in Ku band with less than 1 m diameter antenna at the user end. With digital TV transmission and the advancement in compression technology (MPEG), DTH has gained cost advantage and become very popular in recent time. One important consideration is rain attenuation suffered by the satellite signal in the Ku band especially in tropical region like the Indian region. Based on the rain fall statistics an attenuation margin is built in to the satellite RF link to mitigate the rain effect on Ku band transmission. It has been calculated that a satellite EIRP of 52 dBW in Ku band with a rain attenuation figure of 6dB provides good reception throughout the Indian subcontinent. However for Andaman and Nicobar islands where the rain fall is much higher, more link margin is required and this is uneconomical therefore not considered. The system is designed in C band for this region since C band is not affected by rain. The disadvantage however is larger antenna.

9. SPECIAL SATELLITE SERVICES

Video conferencing, Internet connectivity and E-mail are very useful satellite services. Even with increasing fiber penetration, in order to reach remote areas and hilly terrains, satellites are the only means providing connectivity for these services. These services are implemented by highly reliable VSATs.

9.1 Video Conferencing

Video conferencing is a teleconference enabled by a set of telecommunication technologies that allow two or more locations to interact via two-way video and audio transmissions simultaneously. There are basically two types of video conferencing; dedicated VTC (video teleconferencing) systems have all required components packaged into a single piece of equipment while desktop VTC systems are add-ons to normal PC's, transforming them into VTC devices. Simultaneous video conferencing among three or more remote points is possible by means of a Multipoint Control Unit (MCU). There are MCU bridges for IP and ISDN-based video conferencing. MCUs can be stand-alone hardware devices, or they can be embedded into dedicated VTC units. Video conferencing is employed in various situations, for example; distance education, telemedicine and business. VSAT based video conferencing system is employed to inter-connect locations spread over a large area with in the satellite coverage. With advances in data compression and coding, H.264/MPEG-4 compression standard provides good quality video conferencing. Video data rate of 256 KBPS works well, thus conserving the satellite bandwidth.

9.2 Satellite Internet Services

Satellite Internet services are used in locations where terrestrial Internet access is not available and in locations which move frequently. Internet access via satellite is available worldwide, including vessels at sea and mobile land vehicles.

Two-way satellite Internet service involves both sending and receiving data from the remote VSAT site via satellite to a hub teleport, which then relays data via the terrestrial Internet. The satellite dish at each location must be precisely pointed to avoid interference with other satellites. At each VSAT site the uplink frequency, bit rate and power must be accurately set, under control of the service provider hub.

There are several types of two way satellite Internet services, including TDMA and SCPC. Two-way systems can be simple VSAT terminals with a 60–100 cm dish and output power of only a few watts intended for consumers and small business or larger systems which provide more bandwidth. Such systems are frequently marketed as "satellite broadband" and can cost two to three times as much per month as land-based systems such as ADSL. The modems required for this service are often proprietary, but some are compatible with several different service providers. They are also expensive, costing in the range of Rs 30,000/- to 1,00,000/-.

Home users tend to make use of shared satellite capacity, to reduce the cost, while still allowing high peak bit rates when congestion is absent. There are usually restrictive time based bandwidth allowances so that each user gets their fair share, according to their payment. When a user exceeds their Mbytes allowances, the company may slow down their access or charge for the excess bandwidth used. For consumer satellite internet, the allowance can range from 200 MB to 17 GB per month. A shared download carrier may have a bit rate of 1 to 40 MBPS and be shared by up to 100 to 4000 end users. Note the average bit rate per end user PC is only about 10 to 20 KBPS. This is adequate for most people but will definitely not be suitable for people wanting to do large scale file transfers, video or music, or talk for long periods using VoIP phones.

The uplink direction for shared-user customers is normally TDMA, which involves transmitting occasional short packet bursts, for example when the mouse is clicked. Business users tend to opt for dedicated bandwidth services where any congestion is under their local control.

For portable satellite internet, the equipment usually come in the shape of a self-contained flat rectangular box that needs to be pointed in the general direction of the satellite—unlike VSAT the alignment need not be very precise and the modems have built in signal strength meters to help the user align the device properly. The most common such system is BGAN of INMARSAT; these terminals are about the size of a briefcase and have near-symmetric connection speeds of around 350–500 KBPS. Today INMARSAT offers BGAN Link broadband data services for users who have a requirement for high volumes of standard IP data in fixed locations. FleetBroadband of INMARSAT is the maritime communications service that provides broadband data and voice simultaneously through a compact antenna on global basis. SwiftBroadband is the aeronautical communications service of INMARSAT that offers voice and data communications through a single antenna to the whole aircraft, servicing cockpit, cabin and operational needs. Smaller modems exist like those offered by Thuraya but only connect at 144 KBPS in a limited coverage area.

10. CONCLUSION

Over the last 44 years since the launch of Early Bird the first Intelsat, communication satellites have changed phenomenally, the way the world communicates. Services have moved away from speech only to multimedia and there has been a remarkable growth in asymmetrical interactive services and small low cost terminals. Television and entertainment scenarios have changed considerably and global village has become a reality. In India, INSAT applications have grown over the last 25 years, since the launch of the first INSAT and these applications are indeed benefiting “man and society” redeeming the pledge by the founding fathers of ISRO to the country.

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SCIENCE, TECHNOLOGY AND APPLICATIONS OF SUPERALLOYS

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1. INTRODUCTION

SUPERALLOYS are heat-resisting alloys based on nickel, nickel-iron, iron or cobalt that exhibit a combination of mechanical strength and resistance to surface degradation. Superalloys are primarily used in gas turbines, coal conversion plants, and chemical process industries, and for other specialized applications requiring heat and/or corrosion resistance. The modern high-performance aircraft (jet) engine could not operate without the major advances made in superalloy development over the past 50 years. Based on the matrix element(s), superalloys can be broadly be classified into four families:

(i) Iron-base
(ii) Nickel-iron base
(iii) Nickel-base
(iv) Cobalt-base

Nickel-base superalloys are the most complex, the most widely used for the hottest parts. They have the highest creep strength among the above families. They currently constitute over 50% of the weight of advanced aircraft engines. A noteworthy feature of nickel-base alloys is their use in load-bearing applications at temperatures in excess of 80% of their incipient melting temperatures, a fraction that is higher than for any other class of engineering alloys. However, they are costlier than nickel-iron base and iron-base superalloys.

2. WROUGHT SUPERALLOYS

2.1 Solid Solution Vs. Precipitation strengthened Superalloys

Wrought superalloys in commercial service range from solid solution strengthened single-phase alloys to precipitation-hardened alloys. Inconel 600 and Hastelloy C are examples of solid solution strengthened (nickel-base) superalloys. Inconel 706 (nickel-base) and Inconel 718 (nickel-iron base) are examples of precipitation hardened superalloys. The 718 grade accounts for major part of the total superalloy tonnage produced/consumed. The precipitation hardening alloys have

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considerably higher strength values, when compared to solid solution strengthened alloys. The latter group of alloys is preferred when service conditions allow their use, because of their ease of fabrication, especially weldability. For the most demanding of elevated temperature applications, precipitation strengthened alloys are preferred. Table 1 gives the details of chemical composition for representative wrought nickel-base superalloy grades.

Table 1. *Chemical composition of representative wrought nickel base superalloy grades*

Alloy	*Ni*	*Cr*	*Co*	*Mo*	*Al*	*Ti*	*Nb*	*C*	*B*	*Zr*	*Others*
Inconel X750	73	15	–	–	0.8	2.5	0.9	0.04	–	–	6.8 Fe
Udimet 500	53.6	18	18.5	4.0	2.9	2.9	–	0.08	0.006	0.05	–
Udimet 700	53.4	15	18.5	5.2	4.3	3.5	–	0.08	0.03	–	–
Waspaloy	58.3	19.5	13.5	4.3	1.3	3.0	–	0.08	0.006	0.06	–
Astraloy	55.1	15.0	17.0	5.2	4.0	3.5	–	0.06	0.03	–	–
Rene 41	55.3	19.0	11.0	10.0	1.5	3.1	–	0.09	0.005	–	–
Nimonic 80A	74.7	19.5	1.1	–	1.3	2.5	–	0.06	–	–	–
Nimonic 90	57.4	19.5	18.0	–	1.4	2.4	–	0.07	–	–	–
Nimonic 105	53.3	14.5	20.0	5.0	1.2	4.5	–	0.20	–	–	–
Nimonic 115	57.3	15.0	15.0	3.5	5.0	4.0	–	0.15	–	–	–

2.1.1 Precipitation strengthening phases

2.1.1.1 Gamma prime

Gamma prime, γ', is the principal strengthening precipitate. Aluminum and titanium are added in amounts required to precipitate the fcc γ' (Ni_3Al,Ti), which precipitates coherently with the austenitic gamma matrix. Other elements, notably niobium, tantalum, and chromium, also enter γ'. This phase is required for high-temperature strength and creep resistance. The volume fraction of gamma prime clearly influences alloy strength. Early superalloys contained less than 25 vol% of gamma prime. Most wrought nickel base superalloys contain between 20 and 45 vol% of gamma prime. Gamma prime contents above approximately 45% render the alloy difficult to deform by hot or cold rolling. Beyond about 45% of γ', (60% in powder materials) hot working is no longer practical and components must be manufactured by casting. Nickel base cast superalloys contain approximately 60 vol% of gamma prime. This increased level of γ' results in greater alloy creep strength. Practically creep strength is proportional to volume percent over this range at temperatures of 700°C to 980°C. Detailed coverage of nickel-base cast superalloys is done in Section 5.

2.1.1.2 Gamma double prime

Gamma double prime, γ'', is another important hardening phase occurring in niobium-containing nickel-iron based superalloys. Here nickel and niobium combine in the presence of iron to form body-centered tetragonal (bct) Ni_3Nb which is coherent with the gamma matrix, while including large mismatch strains of the order of 2.9%. This phase provides very high strength at low to intermediate temperatures, but is unstable at temperatures above about 650°C.

2.2 Iron-Base Superalloys

Iron-base superalloys evolved from austenitic stainless steels and are based on the principle of combining a closed-packed fcc matrix with (in most cases) both solid-solution hardening and precipitate-forming elements. The austenitic matrix is based on nickel and iron, with at least 25% Ni needed to stabilize the fcc phase. Other alloying elements, such as chromium, partition primarily to the austenite for solid-solution hardening. The strengthening precipitates are primarily ordered intermetallics, such as γ' Ni_3Al, η Ni_3Ti, and γ'' Ni_3Nb.

2.3 Cobalt-Base Superalloys

Wrought cobalt-base alloys, unlike other superalloys, are not strengthened by a coherent, ordered precipitate. Rather, they are characterized by a solid solution strengthened austenitic (fcc) matrix in which a small quantity of carbides is distributed. (Cast cobalt alloys rely upon carbide strengthening to a much greater extent.) Cobalt crystallizes in the hcp structure below 417°C. At higher temperatures, it transforms to fcc. To avoid this transformation during service, virtually all cobalt-base alloys are alloyed with nickel in order to stabilize the fcc structure between room temperature and the melting point.

Nickel forms low melting point eutectics with nickel sulfide; in sulfur-bearing gases, the attack on nickel alloys may be devastating. Cobalt-base superalloys have superior hot corrosion resistance in atmospheres containing sulfur, e.g., in fuel-burning systems. whereas those based on cobalt have not.

2.4 Melting and Consolidation of Wrought Alloys

Among the traditional processes used to produce superalloys, vacuum induction melting (VIM), vacuum arc remelting (VAR), and electroslag remelting (ESR) are important.

2.4.1 Vacuum induction melting

Vacuum induction melting is carried out as the primary consolidation method to realize:

Achievement of very close control on composition.

Removal of undesired elements with high vapor pressure.

Low losses of alloying elements by oxidation.

Removal of dissolved gases, e.g., hydrogen and nitrogen.

2.4.2 Remelting

The primary VIM alloy is cast in the form of a consumable electrode and remelted to obtain a more homogenous ingot. This can be performed by either the VAR or ESR or electron beam cold hearth refining process (EBCHR). The last two techniques lead to improved refining. The maximum inclusion size (mainly oxides) can be reduced by up to an order of magnitude (300 to 30 μm), with a similar effect on the number of large inclusions (>25 μm). The EBCHR is however a costly route and the production rates are smaller than for ESR or VAR.

2.4.2.1 Electroslag remelting

Electroslag remelting (ESR) is carried out as the secondary melting step to realize:

Homogenous ingots free from macro-segregation, central unsoundness, that can occur in conventionally cast ingots where solidification occurs from outside inwards

Good ingot surface quality

High degree of purity/cleanliness

2.4.2.2 Vacuum arc remelting

Vacuum arc remelting (VAR) is carried out as an alternate method of secondary melting. The benefits accruing from VAR are:

Removal of dissolved gases – hydrogen, nitrogen, CO

Reduction of undesired trace elements with high vapour pressure

Improvement of oxide cleanliness

Avoiding macro-segregation and reducing micro-segregation

2.4.2.3 Triple melting

Several producers of critical rotating components in the gas turbine industry have adopted the use of a hybrid secondary melt process: VIM to ensure an initial electrode with low oxygen and precise chemistry, followed by ESR. The ESR electrode will be clean and sound but may contain freckles. The final segregation free structure is obtained through the application of a third melting process (VAR) to the ESR ingot. Alloy 718 is fabricated in this manner when used for the production of rotating blades and discs.

2.4.3 Maximum ingot size

The maximum ingot cross section that can be produced without unacceptable segregation depends on alloy composition. Some superalloys not prone to segregation can be produced in diameters 1000 mm or larger, e.g., Alloy 706 (41.5 Ni 16 Cr 2.9 Nb 0.2 Al 1.8 Ti 40 Fe), Waspaloy (Ni 58 Cr 19.5 Co 13.5 Mo 4.3 Al1.3 Ti 3.0 C 0.08 B 0.06). On the other hand, superalloys highly prone to segregation can be produced to a maximum diameter of ~ 500 mm and approximately 4.5 tonnes in weight, e.g., Alloy 718 (Ni-18.5 Fe-18 Cr-5.3 Nb-3 Mo-0.9 Ti-0.5 Al-0.03C) and Alloy 720 (Ni-18 Cr-14.8 Co-5 Ti-3 Mo-2.5 Al-1.2 W-0.04 Zr-0.02 B-0.02C).

2.4.4 Micro-segregation in ingots

As cast ingots can exhibit extensive micro-segregation. For example, interdendritic regions in alloy 718 ingot which represent the last metal to solidify are enriched in Nb, Mo and Ti; Nb levels up to 10% have been noticed. The type and extent of segregation is very alloy-dependent. The degree of Nb segregation has been related to difference in temperature between liquidus and solidus. Macro-segregation occurs in the form of positive segregation (freckles) and negative segregation (white spots) at large ingot diameters/unfavorable remelting conditions.

2.4.5 Homogenisation of ingots

Homogenisation of the as-cast ingot is done to reduce micro segregation. It is a heat treatment carried out at high temperatures and long times. Since homogenisation is a diffusion-controlled process, the temperature for the treatment is selected to be as high as possible without reaching the incipient melting temperature. Higher local solidification rates during secondary melting lead to finer secondary arm spacing, necessitating shorter time of homogenization. Control of local solidification rate during remelting is thus commercially important. In alloy 718, a good homogenization cycle distributes Nb and other elements fairly uniformly in the matrix and dissolves the unwanted Laves phase. Macro-segregation as well as nitrides and many carbides & carbonitrides persist in the microstructure and cannot be influenced by the homogenization treatment.

2.4.6 Hot working range

The temperature range over which superalloys can be successfully hot worked is relatively narrow and varies with chemical composition. For example, the hot working range is less for alloy 720 (100°C) than for Waspalloy (200°C). This is due to higher Ti + Al content in 720 (7.5 wt%) compared to 4.4 wt% in Waspalloy, which leads to (1) more segregation during solidification in 720, reducing the temperature for incipient melting (2) higher volume fraction and solvus temperature of gamma prime in 720, increasing the minimum forging temperature. The greater volume fraction of gamma prime in 720 also reduces ductility. Rotary forging using long forging machine can give large amount of reduction uniformly over a long length without reheating the product and is adopted for hot deformation of superalloys with narrow temperature windows for forging.

2.5 Heat Treatment of Wrought Alloys

Wrought alloys are, first, solution treated to dissolve nearly all γ' and carbides other than the very stable MC carbides. The solution treatment temperature has to be chosen based on the properties required in the end product. Some instances may call for solution treatment at a higher temperature followed by at a lower temperature Aging is then carried out to precipitate out γ' or γ' and γ'' depending on the alloy system. In some instances aging is carried out at more than one temperature to precipitate out different phases or realize different precipitate size distributions.

2.6 Metallurgical Stability of Superalloys

In some superalloys, if composition has not been carefully controlled, undesirable phases can form either during heat treatment or, more commonly, during service. These precipitates, known as TCP phases, are composed of close-packed layers of atoms parallel to {111} planes of the γ matrix. Usually harmful, they may appear as long plates or needles, often nucleating on grain-boundary carbides. Nickel alloys are especially prone to the formation of σ and μ. The formula for σ is $(Fe,Mo)_x\ (Ni,Co)_y$, where x and y can vary from 1 to 7. Alloys containing a high level of body-centered cubic (bcc) transition metals (tantalum, niobium, chromium, tungsten, and molybdenum) are most susceptible to TCP formation. The σ hardness and its platelike morphology cause premature cracking, leading to low-temperature brittle failure, although yield strength is unaffected. However, the major effect is on elevated-temperature rupture strength. Sigma formation must deplete refractory metals in the γ matrix, causing loss of strength of the matrix. Also, high-temperature fracture can occur along σ plates rather than along the normal intergranular path, resulting in sharply reduced rupture life. Platelike μ can form also, but little is known about its detrimental effects. Accordingly, in spite of their beneficial effect on oxidation resistance or creep strength, the overall contents of chromium, molybdenum and tungsten must be limited, the more so the larger the γ' volume fraction, since these elements partition preferentially to the matrix. Various semi empirical models are available for balancing alloy composition so as to avoid TCP phases.

2.7 Role of Carbon, Boron and Zirconium

High temperature creep properties of the superalloys are improved in many circumstances if carbon and boron are present. Carbon, boron, carbides and borides are preferentially located at the γ grain boundaries and this has a potent effect on the rupture strength via. the inhibition of grain boundary sliding. Thus carbon and boron are often referred as grain boundary strengtheners. This explains why carbon and boron levels are generally higher in polycrystalline or columnar grained superalloys used in cast form, and the absence of these elements in the single crystal superalloys for which grain boundary strengthening is unnecessary.

The improvement of creep properties by very small additions of boron and zirconium is a notable feature of nickel-base superalloys. Improved forgeability and better properties have also resulted from magnesium additions of 0.01 to 0.05%. It is believed that this is due primarily to the locking up of sulfur, a grain-boundary embrittler, by the magnesium. Mechanisms for these property effects are nuclear. However, it is believed that boron and zirconium segregate to grain boundaries because of their large size misfit with nickel. Because, at higher temperatures, cracks in superalloys usually propagate along grain boundaries, the importance of grain-boundary chemistry is apparent. Table 2 brings out how boron and zirconium additions improve the creep strength of Udimet 500 at 870°C.

Table 2. *Effect of boron and zirconium on creep of Udimet 500 at 870C*

Alloy	*Life (h)*	*% Elongation*	*σ for minimum second stage creep rate of 0.004%/h, MPa*
Base	50	2	117.2
Base+0.19%Zr	140	6	158.6
Base+0.009%B	400	8	193.1
Base+0.009%B +0.01%Zr	647	14	220.6

3. POWDER METALLURGY SUPERALLOYS

3.1 P/M Processing Replaced Forging for Several Superalloy Grades

Aircraft gas turbine disks, designed to operate at temperatures of about 650°C in current high-performance engines, require forgeable alloys with high yield strength (to tolerate overspeed without burst), high creep resistance. Such alloys are produced by resorting to a high homogeneous concentration of both solid-solution strengthening elements and the γ'-forming elements aluminum and titanium. These factors would limit forgeability of conventionally cast and wrought alloys. Hence they have to be produced through powder metallurgy route. Powder metallurgy (P/M) route is being extensively used in production of nickel-base superalloys. Several P/M superalloys have replaced forged alloys as turbine disks, including MERL 76, LC Astroloy, IN-100, René 95 and Rene 88 DT. Their compositions are such that it is difficult or impracticable to produce them through ingot metallurgy route. Details of chemical composition are given in Table 3.

Table 3. *Chemical composition of important disc alloys processed through powder processing*

Alloy	*C*	*Ni*	*Cr*	*Co*	*Mo*	*W*	*Nb*	*Hf*	*Al*	*Ti*	*V*	*B*	*Zr*
MERL 76	0.025	Bal	12.2	18.2	3.2		1.3	0.3	5.0	4.3		0.02	0.06
LC Astroloy	0.023	Bal	15.1	17.0	5.2				4.0	3.5		0.024	<0.01
IN-100	0.07	Bal	12.4	18.5	3.2				5.0	4.3	0.8	0.02	0.06
Rene 95	0.08	Bal	12.8	8.1	3.6	3.6	3.6		3.6	2.6		0.01	0.053
Rene 88DT	0.03	Bal	16	13	4	4	0.7		2.1	3.7		0.015	

3.2 Superior Features of P/M Processing

P/M processing is in several respects superior to conventional processing:

- Superalloys such as IN-100 or Rene 95 difficult or impractical to forge by conventional methods. P/M processing provides a solution
- It improves homogeneity/minimizes segregation, particularly in complex Ni-base alloy systems
- It allows closer control of microstructure and better property uniformity within a part than what is possible in cast and ingot metallurgy wrought products. Finer grain size can be realized.
- Alloy development flexibility due to elimination of macro-segregation.
- Due to the finer grain size, the consolidated powder products are often super-plastic and amenable to isothermal forging, reducing force requirements for forging.
- It is a near net shape process; hence significantly less raw material input required and also reduced machining cost, than in case of conventional ingot metallurgy.

3.3 Manufacture of Engine Discs through P/M Route

The gas turbine engine disc is the most important component produced through P/M route. The currently favored technology for production consists of the following steps:

1. Powder production by gas atomization (in vacuum or inert gas)
2. Powder consolidation by HIP or extrusion to form billet (extrusion more common)
3. Component production by isothermal or super-plastic forging to shape/dimensions.

3.4 Oxide Dispersion Strengthened Superalloys

An important application of P/M techniques is the production of oxide dispersion strengthened (ODS) superalloys. Commercial alloy compositions are based on nickel, iron or iron-chromium-aluminum matrices. The nominal compositions of the commercially important ODS grades are listed in Table 4. Mechanical alloying is employed to incorporate about 1 vol% oxide (typically Y_2O_3) particles into the alloy powder a ductile matrix, the only commercial technique currently being employed is mechanical alloying. The metal particle size initially is in the 2 to 200 µm range, while the oxide particles are less than 10 µm in size. The alloy powder and oxide particles are mixed and charged into a high-energy ball mill. The milling operation carried out dry, causes the superalloy particles to weld repeatedly to the oxide particles and then break apart. The resultant, acicular or platelike powders are composites with extremely fine, homogeneous microstructures. Consolidation is carried out by placing the powders in steel cylinders, aligning the ends closed, and either extruding to bar or rolling to plate or sheet.

Table 4. *Nominal chemical composition (wt%) of the most common ODS superalloy grades*

Grade	*Ni*	*Fe*	*Cr*	*Al*	*Ti*	*W*	*Mo*	*Ta*	*Y2O3*	*C*	*B*	*Zr*
MA754	bal	–	20	0.3	0.5	–	–	–	0.6	0.05	–	–
MA758	bal	–	30	0.3	0.5	–	–	–	0.6	0.05	–	–
MA760	bal	–	20	6.0	–	3.5	2.0	–	0.95	0.05	0.01	0.15
MA6000	bal	–	15	4.5	2.5	4.0	2.0	2.0	1.1	0.05	0.01	0.15
MA956	–	bal	20	4.5	0.5	–	–	–	0.5	0.05	–	–

This family of alloys possess strengths higher than most of the wrought and cast superalloys at temperatures >1000°C, as can be seen. The alloys have applications in hot sections of aircraft gas turbines, in powder generation equipment, in furnaces, and in the chemical process industries.

4. CAST SUPERALLOYS

4.1 Conventionally Cast Superalloys

Recognition of the material creep strength as an important consideration for the gas turbine engines, understanding generated between age hardening, creep and γ' volume fraction and the steadily increasing operating-temperature requirements for the aircraft engines resulted in development of wrought alloys with increasing levels of aluminum plus titanium. Component forgeability problems led to this direction of development not going beyond a certain extent. The composition of the wrought alloys became restricted by the hot workability requirements. This situation led to the development of cast nickel-base alloys. Casting compositions can be tailored for good high temperature strength as there was no forgeability requirement. Further the cast components are intrinsically stronger than forgings at high temperatures, due to the coarse grain size of castings. Table 5 gives chemical composition of representative grades of cast superalloys. Table 6 shows the superior stress rupture strengths of typical cast superalloy grades at three temperatures compared to those of typical wrought superalloy grades.

Table 5. *Chemical composition of conventionally cast superalloys*

Alloy	*Ni*	*Cr*	*Co*	*Mo*	*W*	*Re*	*Ta*	*Hf*	*Nb*	*Ti*	*Al*	*Zr*	*C*	*B*	*Others*	*Comments*
IN713LC	74.8	12	–	4.5	–	–	–	–	2	0.6	5.9	0.1	0.05	0.01		
Rene100	62.6	9.5	15	3	–	–	–	–	–	4.2	5.5	0.06	0.15	0.015	1.0 V	
IN731	67.7	9.5	10	2.5	–	–	–	–	–	4.6	5.5	0.06	0.18	0.015	1.0 V	
B1900	64.5	8	10	6	–	–	4.3	–	–	1	6	0.08	0.1	0.015		
Mar-M009	58.4	9	10	–	12.5	–	–	2	1	2	5	–	0.14	0.015		
Mar-M001	59	10	15	3	–	–	–	1.5	–	4.7	5.5	0.06	0.18	0.014	1.0 V	
Mar-M004	73.6	12	–	4.5	–	–	–	1.3	2	0.6	5.9	0.1	0.05	0.01		
Mar-M007	63	8	10	6	–	–	4.3	1.5	–	1	6	0.08	0.1	0.015		
Mar-M006	58.4	9	10	2.5	10	–	1.5	1.4	–	1.5	5.5	0.05	0.15	0.015		
Mar-M005	59	9	10	2	7	–	3.8	1.6	–	2.6	4.8	0.05	0.1	0.015		
Rene41	56	19	10.5	9.5	–	–	–	–	–	3.2	1.7	0.01	0.08	0.005		
Rene77	53.5	15	18.5	5.2	–	–	–	–	–	3.5	4.25	–	0.08	0.015		
Rene80	60.3	14	9.5	4	4	–	–	–	–	5	3	0.03	0.17	0.015		
Rene80Hf	59.8	14	9.5	4	4	–	–	0.8	–	4.7	3	0.01	0.15	0.015		
C1023	58.5	15.5	10	8	–	–	–	–	–	3.6	4.2	–	0.15	0.006		
IN738C	61.4	16	8.5	1.75	2.6	–	1.75	–	0.9	3.4	3.4	0.1	0.17	0.01		
IN738LC	61.5	16	8.5	1.75	2.6	–	1.75	–	0.9	3.4	3.4	0.04	0.11	0.01		
Nimocast95	57.5	19.5	18	–	–	–	–	–	–	2.9	2	0.02	0.07	0.015		
Udimet700	59	14.3	14.5	4.3	–	–	–	–	–	3.5	4.3	0.02	0.08	0.015		
Udimet710	54.8	18	15	3	1.5	–	–	–	–	2.5	5	0.08	0.13	–		
MarM432	50.2	15.5	20	–	3	–	2	–	2	4.3	2.8	0.05	0.15	0.015		

Table 6. *Rupture strengths of wrought and cast Ni-base superalloys at three temperatures*

Characteristic rupture strength (MPa)						
Alloy	*650C*		*815C*		*982C*	
	100h	*1000h*	*100h*	*1000h*	*100h*	*1000h*
Wrought Alloys						
Inconel X-750	552	469	179	110	24	
Udimet 700		703	400	296	117	55
Astroloy		772	407	290	103	55
Cast Alloys						
IN 100			503	379	172	103
MAR-M246			565	448	186	124

4.2 Directionally Solidified Superalloy Castings

The development of cast polycrystalline alloys was followed by process development, with specific interest directed toward grain orientation and directional-solidification (DS) turbine blade and vane casting technology. Applied to turbine blades and vanes, the DS casting process results in alignment of all component grain boundaries in such a way that essentially all transverse grain boundaries are eliminated. The major operating stresses in turbine blades/vanes are so aligned that the transverse grain boundaries provide relatively easy fracture paths. The elimination of these paths provides increased opportunity for further exploitation of the nickel-base alloy potential. The compositions of representative grades of DS alloys are given in Table 7. Development of the DS casting process to produce blades and vanes resulted in significant improvements in creep strength and ductility as well as in thermal fatigue resistance (5 × improvement).

4.3 Single Crystal Superalloys

The logical progression to grain-boundary reduction is the total elimination thereof. Thus, single-crystal turbine blade/vane casting technology soon developed, providing further opportunity for nickel-base alloy design innovation. The greatest advance in the metal temperature capability of turbine blades has been the single-crystal superalloy and process technology. Table 8 gives the chemical compositions of representative single crystal superalloys. Tantalum replaces titanium to a significant extent in single crystal superalloys, since it both strengthens γ' and raises the solidus temperature. Modern single crystal alloys can contain between 70 and 80% of γ'. This represents a useful maximum, since further increases towards 100% γ' lead to a significant drop in strength. Since no grain boundary strengthening is required in single crystal compositions, grain-boundary strengthening elements (boron, hafnium, zirconium, and carbon) could be eliminated from the composition, resulting in a substantial increase in the incipient melting temperature. Consequently higher solution treatment temperatures can be adopted to enable increased solutioning of the strengthening elements, without provoking incipient melting of the alloy. Some single crystal alloys introduced in late 1980's contain additions of the heavy element rhenium, which has been

Table 7. *Chemical composition of representative DS superalloys*

Alloy	*Ni*	*Cr*	*Co*	*Mo*	*W*	*Re*	*Ta*	*Hf*	*Nb*	*Ti*	*Al*	*Zr*	*C*	*B*	*Comments*
CM247LC	61.7	8.1	9.2	0.5	9.5	–	3.2	1.4	-	0.7	5.6	0.01	0.07	0.015	First generation
CM186LC	62.6	6	9	0.5	8	3	3	1.4	-	0.7	5.7	0.005	0.07	0.015	Second generation
DMD4	66.8	2.4	4	–	5.5	6.5	8	1.2	0.3	-	5.2	-	0.07	0.01	Third generation

Table 8. *Chemical composition of representative SC superalloys*

Alloy	*Ni*	*Cr*	*Co*	*Mo*	*W*	*Re*	*Ta*	*Hf*	*Nb*	*Ti*	*Al*	*Zr*	*C*	*B*	*Others*	*Comments*
CMSX2	66.2	8	4.6	0.6	8	–	6	–	–	1	5.6	–	–	–	–	First generation
CMSX4	61.7	6.5	9	0.6	6	3	6.5	0.1	–	1	5.6	–	–	–	–	Second generation
CMSX10	69.6	2	3	0.4	5	6	8	0.03	0.1	0.2	5.7	–	–	–	–	Third generation
DMS4	67	2.4	4	–	5.5	6.5	9	0.1	0.3	–	5.2	–	–	–	–	Third generation
TMS196	59.7	4.6	5.6	2.4	5.0	6.4	5.6	0.1	–	–	5.6	–	–	–	5.0 Ru	Third generation

found to retard particle coarsening. Improvements in creep strength were noticed particularly at very high temperatures (1000-1150°C).

5. OXIDATION, HOT CORROSION AND COATINGS

5.1 Low Temperature Corrosion

Some superalloy compositions show excellent resistance to corrosive media such as aqueous solutions and acids at low temperatures. The Ni-Cr-Mo compositions such as Alloys 625, C276, 59 and 686 have been developed for such applications. Chromium provides corrosion resistance in oxidizing media and molybdenum in reducing media. These alloys find extensive application in chemical processing industries.

5.2 Oxidation and Hot Corrosion

At elevated temperatures, oxidation resistance is provided by Al_2O_3 or Cr_2O_3 protective films. Accordingly, nickel-base alloys must contain one or both of these elements even where strength is not a principal factor. For example, Hastelloy X, one of the most oxidation and (hot) corrosion resistant of all nickel-base alloys, contains 22% Cr. Because chromium is known to degrade the high-temperature strength of γ', there has been a strong incentive to lower chromium content in modern superalloys. Thus, the level of chromium decreased from 20% in earlier wrought alloys to as little as 9% in modern cast alloys. Unfortunately, this compositional change degraded hot corrosion resistance to the point that superalloys used in gas turbines had to be coated.

Further, as turbine blade temperatures exceed 1000°C, Cr_2O_3 tends to decompose to CrO_3, which is more volatile and therefore less protective. To some extent, the loss of oxidation resistance has been compensated for by raising aluminum contents, although aluminum resides primarily in γ'. (Aluminum in small quantities promotes the formation of Cr_2O_3) However, Al_2O_3 is less protective than Cr_2O_3 under sulfidizing conditions, making coatings indispensable in aircraft turbines and, more recently, in industrial turbines

Other elements that contribute to oxidation and hot corrosion resistance are tantalum, yttrium, and lanthanum. The rare earths appear to improve oxidation resistance by preventing spalling of the oxide, while the mechanism for improvement with tantalum is not known. Yttrium is now widely used in overlay coatings of the NiCrAlY type.

Molybdenum and tungsten are considered to be the most deleterious solutes in terms of hot corrosion resistance. Nevertheless, one or both of these elements are required for strength, so that alloying for improved surface stability is often in conflict with alloying for strength. The two most prominent solutes that provide both strength and surface stability are aluminum and tantalum.

5.3 Coatings on Superalloys

Superalloys are often coated in order to improve their corrosion resistance. The coatings are of one of three types - Aluminide (diffusion) coatings, Overlay coatings and Thermal barrier coatings.

5.3.1 Aluminide coatings

The aluminide coatings constitute the most common type of coating for environmental protection of superalloys. An outer aluminide layer (CoAl or NiAl) with an enhanced oxidation resistance is developed by the reaction of Al with the Ni/Co in the base metal.

In recent years extremely thin layers of noble metals such as platinum have been used to enhance the oxidation resistance of aluminides. The high temperature performance of the superalloy is limited by oxidation behavior of the coatings.

5.3.2 Overlay coatings

The overlay coatings are generally referred to as MCrAl or MCrAlY (M = Fe, Co, Ni or Ni+Co). Vapor deposition process used to produce them; unlike the aluminide coatings, they do not require diffusion for their formation. A high temperature heat treatment performed (1040-1120°C) to homogenize the coating and ensure its adherence to the substrate. Incorporation of yttrium improves the corrosion resistance of the overlay coatings. Composition of the coating can be tailored, varying Cr, Al levels to optimize performance/improve mechanical properties of the coating.

5.3.3 Thermal Barrier Coatings

The thermal barrier coatings (TBC) provide enough insulation for superalloys to operate at temperatures as much as 150°C above their customary upper limit. The TBC's are ceramics, plasma sprayed partially stabilized zirconia is the most commonly used ceramic. The ceramic coatings use an underlay of a corrosion protective layer e.g., MCrAlY that provides the oxidation resistance and necessary roughness for top coat adherence. Important failure mechanisms for the TBC's are - the thermal expansion mismatch between the ceramic & metallic layers and environmental attack on the bondcoat.

6. APPLICATIONS

Although superalloys have a wide range of application and outstanding potential, the majority of today's superalloys are used in the aircraft gas turbine industry. Given in the Table 9 is an

Table 9. *Applications of superalloys in US*

AEROSPACE	
Gas Turbine	72%
Airframe	8%
POWER GENERATION	
Gas Turbine	10%
Nuclear	2%
Fossil	1%
CHEMICAL	6%
MISCELLANEOUS	1%

approximation of the distribution of superalloys in various applications in the US. Electric power industry and chemical process industry are expected to consume increasing quantities of superalloys in the coming times.

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WAYS OF SEEING STRUCTURES

ALPA SHETH[1]

1. INTRODUCTION

I enjoy teaching structures to first year students, introducing young minds to the romance of structures. You have clean, blank slates to work with; they do not carry baggage of useless mugged-up formulae and they have fire in their bellies. I like to teach architecture students in the dim hope that the next generation of structural engineers will not have to work with architects who are as seriously challenged in their understanding of how structures behave. Those of us in the practicing world, face much grief at the hands of some architects who have contempt for structure. As late Henry Degenkolb, a noted earthquake engineer in San Francisco once said, "*If we have a poor configuration to start with, all the engineer can do is to provide a band-aid – improve a basically poor solution as best as he can. Conversely, if we start-off with a good configuration and reasonable framing system, even a poor engineer cannot harm its ultimate performance too much.*"

I returned to teaching first year architecture students after a hiatus of five years. I had not been completely divorced from teaching in the interim period, taking earthquake engineering workshops at the fourth year level and chairing the college's academic council and yet nothing equipped me for the change. It seemed that the world had skipped a generation in that five year gap. In a developing country, there is an overarching sense of impatience of things not getting done fast enough, of never having enough good faculty or good enough students – It is like an adolescent kid who can't wait to grow up and sup with the adults. There is a culture of brashness in a country full of hope and youth which believes the best is yet to come. We know all of this, we live through it and yet you are not quite prepared.

2. NEW AGE STUDENTS

The first culture shock that hit me was when students young enough to be one's children addressed me in class by my first name. *'But we address the director by his first name too'*. The age-old

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sacred boundaries of a guru-shishya relationship had been breached while I was on the long sabbatical. There was more to come. In a college with attracted an affluent student class there was an all-pervading sense of entitlement, a smug expectation of life being laid out at their feet. There was almost a client-service provider connection at play, with us teachers being the service providers. If the students did not understand the subject matter, it was all your fault and you needed to do better. The client is never wrong. New university rules allow students who have no science background in the 11^{th} and 12^{th} to take up architecture. I found myself saddled with eighty students many of whom were from the commerce stream and had left behind physics, chemistry in their tenth grade.

I was dealing with a bunch of brazen kids who had no qualms in telling you that they did not understand what you were trying to tell them, that the concept of directional forces, bending moments and shear made no sense whatsoever to them. I persisted with dogged determination to teach the way I had done before—I felt that by being strict, giving frequent tests and tough grading I could straighten them out. It had worked for years, why should it not any longer. But a test I gave them after four weeks was a sobering reality check. Barely 30% of the students passed and it was quite clear that they were simply not oriented towards an abstract way of thinking or looking at issues. They seemed tortured by the equations popping out of the blackboard. The students seemed paralysed by math, they disliked arrows which showed vectors and force path. Not more than 70% were attending class. I wondered if that was the way of the future. How can teachers equip students with requisite knowledge when they had been fed by coaching classes on a diet of baby food—regurgitated resource material which simplifies every bit of information into bulleted points and bite-sized packets, stripping the student of any vestiges of independent and aggressive thinking capacity he may have possessed. The task at hand was to reclaim their rational minds before they became un-redeemably non-functional. My conventional notes for the first year had to be thrown out. I decided to let go of my comfort zone and we abandoned the classroom and chalk-blackboard for the college lawns to understand structural behavior hands-on.

I realized the need to turn my teaching method on its head. I had to start with very basic concepts, going right back to eighth grade Newtonian physics. I began to delve into very fundamental questions of structures, which one felt one knew so well and could communicate just as easily. It sent me asking myself a very philosophical question—What are the structures that stay with us and continue to occupy our mindspace long after we have seen them? How do we arouse the curiosity of young minds to understand structural behavior? Structures which usually engage us are those which inspire awe – A really tall building like the Burj Khalifa or the recent Japan's Tokyo Skytree make you wonder how these would have been designed. Likewise, longspan bridges such as the Golden Gate have continued to capture the image of romance and heartbreak in many Hollywood movies. Then there are the subtler kind, I told my students, which require us to understand some basic structural engineering to appreciate them. It is like music. You begin enjoying popular Bollywood numbers but then your interest deepens and you start to enjoy classical music. You want to know more about it. You realize that the enjoyment of classical Hindustani music is so much more enhanced if you understand ragas, lay, taal and you embark on the journey of learning classical music- thus also your relationship with structures. And the knowledge of lay, taal and ragas in structural engineering is understanding forces, equilibrium, moments, shear forces and so on. A child, I told them, understands equilibrium of forces. When he sits on the see-saw with his older brother, he knows intuitively that he needs to be farther away from the fulcrum than his bigger brother, for the see-saw to be balanced. *A basic class in structures is about reconnecting with your intuition and formalizing and honing what your instinct already knows.*

3. NEW EXPERIMENTAL WAYS OF UNDERSTANDING BEHAVIOUR

Structures, I assured the students, have always been built through time-long before engineering was formalized as an applied science. People built intuitively and empirically and even today more than 75% of our building stock in India is empirically built. Why then, the need for understanding structural behavior? Quite simply, because structures that inspire awe and shock (or wonder) cannot be designed and built empirically. As we evolve into more sophisticated and advanced societies, we hanker for what is not easily attainable and that which cannot be built without sophisticated structural engineering. Also, empirically built structures have not always been able to withstand the wrath of nature such as earthquakes, cyclones and such. One needs to develop a basic understanding of structural design to build sustainable structures. Understanding of different forces- Tension, Compression, Bending, Shear, Twisting is fundamental to becoming a good designer.

3.1 The Bridge Competition

The first exercise I gave the students was to build a 1m span bridge using spaghetti noodles, thread and glue. The exercise is not unique, except that it was given to students who had not yet taken a single course in engineering. They also needed to explain their design and why they used the material the way they did. We would load it at the centre with incremental loading. The winning project would be the one that had the highest weight carried to self weight ratio.

I was pleasantly surprised by the response. Suddenly the class blossomed into a cacophonic boom box of eighty kids who's competitive hackles had been raised. They grouped into teams and we had the most creative array of bridges—With access to the internet, they had a lot of reference material at hand but what was amazing to me was how they understood behaviour of members. Most of them had bundled spaghetti sticks tightly together for the axial members to avoid buckling and increase compressive force capacity. Some had even understood which members were in tension and provided lesser sticks for those. Optimization requirements of the competition had made them think hard about providing just enough sticks to a particular element based on its behavior, to get bang for their buck. Another interesting problem they told me that they worked hard to grapple with, were the connections. "We really had to make sure the connections did not come apart, because when they did, the entire mechanism unraveled and it was such a pain to get it all back together." They had learnt intuitively what we struggle to get across to even engineers-Connections must always be stronger than the members coming into it. Some students told me that in their efforts to optimize material use, the bridge had become so light, it kept swaying. Internet informed them about the problems in the Millennium bridge at London and the Tacoma bridge and they added stays to their bridge. Another problem that confounded them was the bridge deck. How were they to cater for the superimposed loads that would be placed on the deck? They did realize that the deck was "bending" and there was no way to resolved that force into an axial one. Most of them built a lattice of bundled spaghetti sticks to avoid compression buckling but a few smart ones provided a horizontal spaghetti truss as a diaphragm for the deck. Considering that it was their own journey of self learning of different types of forces and without support from faculty, it was a very commendable job. (See Fig. 1)

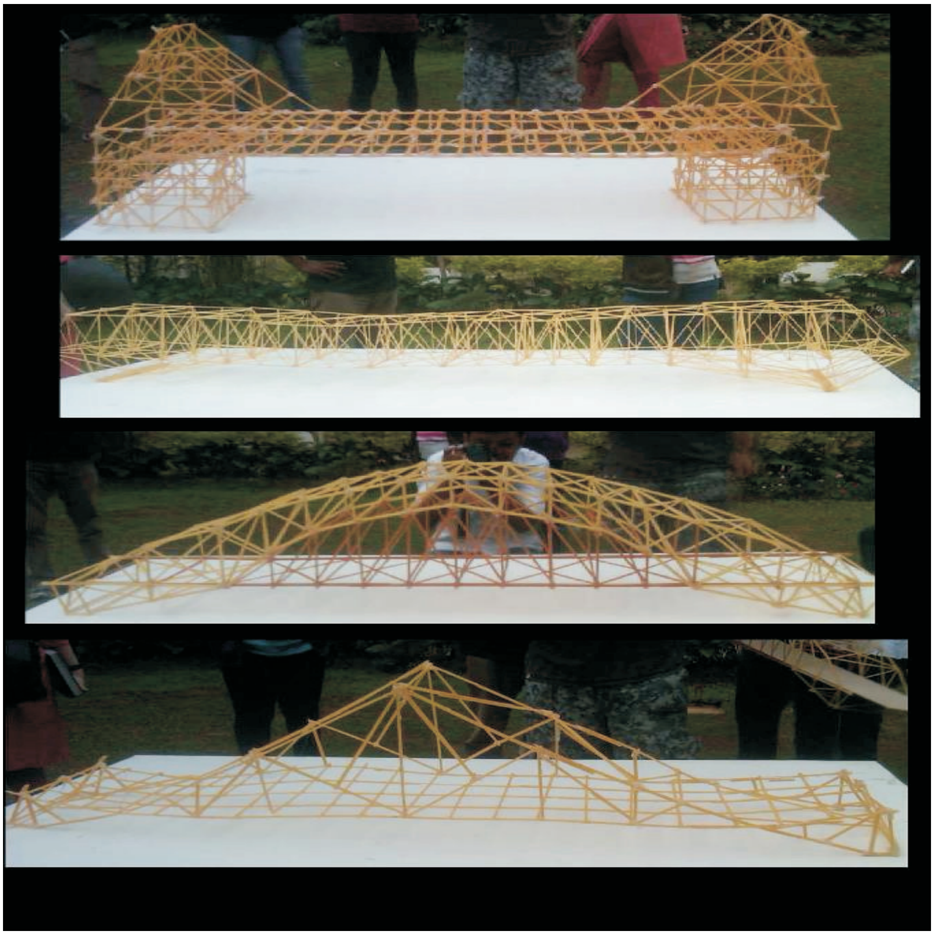

FIG. 1 SOME SPAGHETTI STICK BRIDGE MODELS

More importantly it fired their imagination. A few of them came up to me and said that they were not happy with the performance of their bridge and please would I see their new bridge next week even if it would not be considered in the competition. They knew where they had gone wrong, they said. It was another way of saying they now understood structural behavior better. Some of them came up to me and said they would have done better if they understood the spaghetti-stick material behavior better. That made it so much easier for me to expose them to Material behavior. I brought up the Stress-strain graphs for different materials. That, I said, was all that they needed to know to understand material behavior. They easily grasped the notion of ductility as the area under the curve, the slope of the elastic part of the graph as corresponding to stiffness quotient and the concept of ultimate yield stress. The graph which had earlier overwhelmed them suddenly was transformed into an easy pictorial fingerprint of the material.

3.2 The Bamboo Pavilion Project

We were thus able to make this transition to the next phase-that graphs and equations in structural engineering were not black boxes but an easy way of representing material properties and element behaviour. The good part of the experiment was that not just the students but other faculty were also charged up. Following up on the bridge project, as part of their basic design course, they built pavilions spanning twenty-four feet out of bamboo poles used in scaffolds- of about 4” diameter and approximately ten feet long. I was called in to review the pavilions and it was very satisfying to see how they had extended their understanding of material and structural behavior even further. Some had very creative cantilevered pavilions, others had made dome structures, some had made arched pavilions- the permutations and combinations were extensive and it was so joyous to see the students passionately work on the terrace at these installations.

3.3 Newspaper Chair Project

The students were next asked to design a chair made out of newsprint, glue and sticking tape. The innovative use of newspapers to carry compression and bending made a compelling case for their having developed an intuitive sense of structural behavior. They were asked to make the lightest chair which could bear their weight. Some of them made chairs which could bear the weight of 5 students on it. (shown in Fig. 2) And as they were architecture students it was gratifying to see the design and style element in the chairs.

4. NEW WAYS OF SEEING

The above experiments convinced me that the key to igniting a student’s passion to learn is engaging him in experiments and triggering him to ask the question “why so?” What one needs to develop in students is a way of seeing. If they develop that ability, they will, without any complex calculations, be able to see the how a structure has been resolved. To develop this ability, the students must be equipped with the tools of seeing. They must know the fundamental principles of mechanics of structures.

What followed thereafter was a more sustained interest in the subject matter and a desire to understand the dots, knowing well that at some point the dots would join up into a large picture. After their intuitive understanding of axial stress and bending stress, it was not so difficult to extend those concepts into formalized theory. They also understood why concrete was poor in tension and how it could be reinforced to improve its behaviour. Likewise, they began to understand why one could have incredibly light tension structures in steel. Connecting real life experiences to

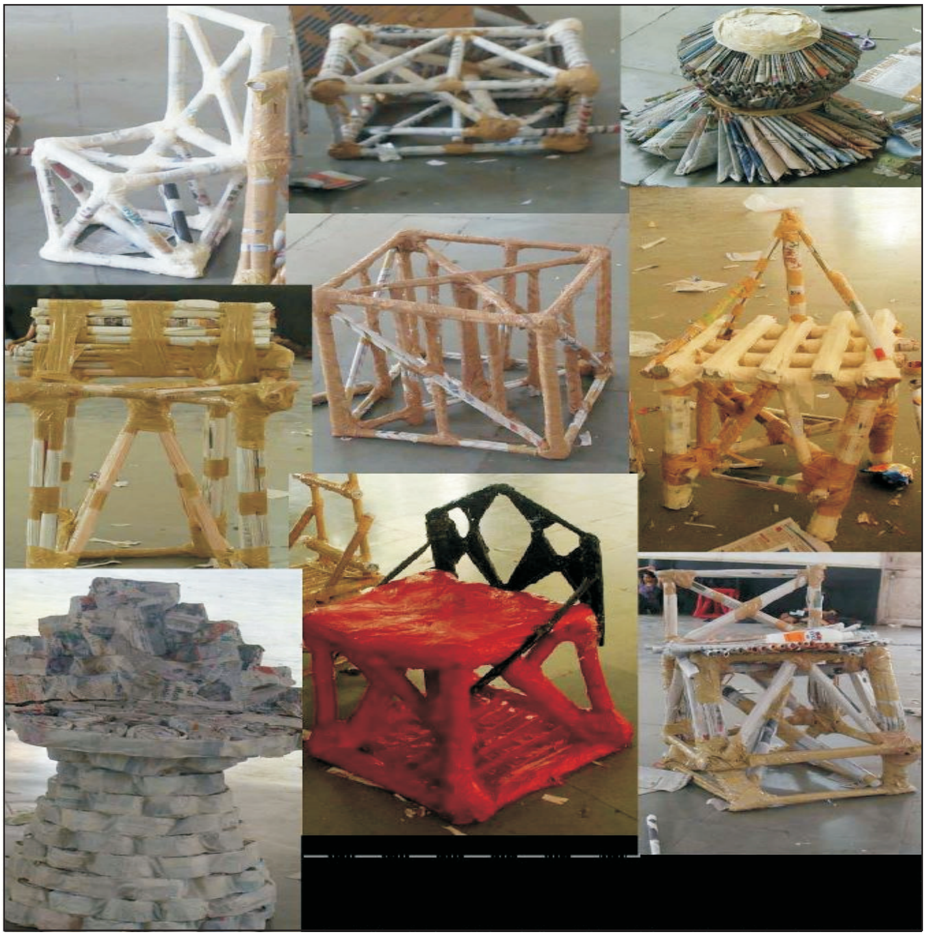

FIG. 2 COLLAGE OF CHAIRS MADE BY STUDENTS OUT OF NEWSPRINT AND TAPE

engineering concepts helps one get a foot in the door of a student's mind. But one cannot stop at that. For the student to rise above the ordinary, he must not shy from more aggressive cogitation of complex engineering problems.

It is my fervent belief that we need to have laboratories accessible to students from the first year. Students should be allowed to experiment with materials such as modeling clay, newspapers, noodles, candy-sticks to begin with and then concrete and steel, wood, brick. It is only when they test their creations to failure do they understand behavior of a material, a component and a system. Great architects/structural engineers such as Calatrava have worked as young boys in carpentry workshops understanding materials, form and anatomy to be better designers. Unfortunately in India, the laboratory classes and theory courses are divorced from each other. Our students rarely get a chance to work with their hands. If they must understand materials and their behaviour, they must be intimate with those materials. They must not be afraid of them.

The other problem which one faces is how to make the class accessible to the weakest student but by doing so not bore the brightest. This becomes increasingly difficult in classes as large as 80. There is a large variation in student capabilities thanks to different levels of intake for general and reserved categories or management seats. One of the ways that I have found to work is to have the same problem posed to students with different level of complexities—and the students are free to choose their preferred level of complexity. Thus, while base level of the spaghetti bridge competition was imposition of gravity superimposed live loads, the more advanced level could be to subject it to ground shaking. There is always the top ten percent for whom all you need to be is a facilitator/mentor as they progress on their path.

The task of a teacher is to fire-up young minds. While it is important to teach students the fundamentals of a subject—the building blocks as it were, it is equally important to guide students to the path of self-learning. In an ever-changing world, new knowledge grows by the hour and those that depend only on knowledge learnt at school and college will be left behind.

5. TEACHING TEACHES THE TEACHER

With the right attitude, a teacher probably learns more from teaching a class than a student does. It teaches you humility. Suddenly, you are dealing with a bunch of young minds who will speak out and will demand of you to be more articulate, to perform, to deliver. There is no concept of "I've consumed my budgeted man-hours on the project and you will need to pay more to get more". There is a sense of responsibility. Somewhere you remember your one professor at college who inspired you to be a better engineer and you wish you are that one professor to at least one of these students. And it is not just teaching the subject. You teach by example. Beneath the overt transfer of knowledge on the subject, there is the underlying thread of human values that are transferred. How you pay attention to the slowest student and also inspire the brightest. Students are sharp and they imbibe from you values that you are not even aware you espouse. It is not without reason that teaching is said to be the noblest profession. It is if you only allow it to be.

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SCIENCE, TECHNOLOGY AND APPLICATIONS OF TITANIUM AND ITS ALLOYS

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1. INTRODUCTION

The titanium minerals that are abundantly available for commercial exploitation are ilmenite ($FeOTiO_2$) and rutile (tetragonal TiO_2). Indian reserves of ilmenite are the world's largest and account for as much as 45% of the total world reserves. The metal and its value added products are therefore of high significance in the Country's context.

One distinguishes between commercially pure titanium and alloy grade titanium.

2. COMMERCIALLY-PURE (CP) TITANIUM

The chemical composition of the four most used grades of CP titanium is shown in the Table 1. Through small additions of ~0.2% palladium, the corrosion resistance in reducing media is improved.

Table 1. *Chemical Composition of unalloyed Titanium Grades*

Grade	*% oxygen*	*% iron max.*	*% hydrogen max.*	*% carbon max.*	*% nitrogen max.*
Grade 1	0.10	0.20	0.013	0.08	0.05
Grade 2	0.20	0.25	0.013	0.08	0.06
Grade 3	0.25	0.30	0.013	0.10	0.06
Grade 4	0.30	0.35	0.013	0.10	0.07

With unalloyed grades of titanium, by dissolving different levels of oxygen, UTS values between 290 and 740 N/mm^2 can be obtained, as shown in Table 2. With increasing temperature the strength decreases; the application of unalloyed titanium is therefore limited to ~300C.

3. ALLOY-GRADE TITANIUM

Depending on their influence on the β-transus temperature, the alloying elements of titanium are classified as neutral, α-stabilizers, or β-stabilizers. The α-stabilizing elements extend the α phase

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Table 2. *Mechanical properties of unalloyed titanium grades*

Grade	*0.2% Y.S. N/mm² min*	*UTS N/mm²*	*% Reduction in area min*	*Impact toughness (J), min.*
Grade 1	180	290-410	35	60
Grade 2	250	390-540	30	35
Grade 3	320	460-590	30	25
Grade 4	390	540-740	25	20

field to higher temperatures, while the β-stabilizing elements shift the β phase field to lower temperatures. Neutral elements have only minor influence on the β-transus temperature.

Among the α-stabilizers, aluminum is by far the most important alloying element of titanium. The interstitial elements oxygen, nitrogen, and carbon also belong to this category. β-stabilizing elements are subdivided into two groups. β-isomorphous elements - Mo, V and Ta are important elements belonging to this group due to their much higher solubility in titanium. β-eutectic elements - e.g., Fe, Mn, Cr, Co, Ni, Cu, and H – even very low volume fractions of these elements can lead to the formation of intermetallic compounds. Sn and Zr are considered neutral elements since they have (nearly) no influence on the α/β phase boundary. As far as strength is concerned, they are not neutral since they primarily strengthen the α phase. Table 3 gives typical grades of different families of titanium alloys.

Table 3. *Typical grades of different families of titanium alloys*

Alloy Type	*Alloy designation*	*Chemical composition*
	Grade 6	Ti5Al2.5Sn
Near α	TIMETAL 685	Ti6Al2.7Sn4Zr0.4Mo0.4Si
	TIMETAL 834	Ti5.8Al4Sn3.5Zr0.5Mo0.7Nb0.35Si0.06C
α + β	Ti-6-4	Ti-6Al-4V
	Ti-6-6-2	Ti6Al-6V-2Sn
	Ti-6-2-4-6	Ti6Al2Sn4Zr6Mo
β	Ti-10-2-3	Ti-10V-2Fe-3Al
	Ti-15-3	Ti-15V-3Cr-3Al-3Sn

4. PRODUCTION OF WROUGHT TITANIUM ALLOYS

4.1 Melting – Production of Ingot

Titanium sponge, fragmented master alloy, TiO_2 and conditioned scrap being recycled are mixed homogeneously, cold pressed into compacts with 65-70% density. Compacts are then plasma welded into a cylindrical electrode. Electrode is remelted in a vacuum arc furnace in a water cooled crucible. Cooling of the copper crucible is done by water. Melting is carried out at a vacuum level of 10^{-1} to 10^{-3} mbar.

FIG. 1 TITANIUM INGOTS OF VARIOUS SIZES

Due to heat caused by electric arc, titanium at electrode bottom melts and drops fall into underlying melting bath. Ingot formation progresses with electrode getting consumed progressively. Figure 1 shows titanium ingots of various sizes.

4.2 Forging

The deformation characteristics of all classes of titanium alloys are very sensitive to metal temperature during deformation processes such as forging. For each class of these alloys, forging pressure increases dramatically with relatively small changes in metal temperatures. For example, the forging pressure for the alloy Ti-8Al-1Mo-1V increases nearly three times as the metal temperature decreases by approximately 95°C. Therefore, it is important in forging titanium alloys to minimize metal temperature losses in the transfer of heated pieces from furnace to the forging equipment and to minimize contact with the much cooler dies during conventional forging processes.

Titanium alloys are highly strain rate sensitive in deformation processes such as forging-considerably more so than aluminum alloys or alloy steels. As the deformation rate is reduced from 10/s to 0.001/s, the flow stress gets reduced by up to ten times. For example, the flow stress for Ti-6Al-4V at 900°C, 50% strain and 10/s strain rate is 205 MPa; at 0.001/s strain rate, the flow stress is 50 MPa, a fourfold reduction. For the beta alloy Ti-10V-2 Fe-3AI as the deformation rate is reduced from 10/s to 0.001/s, the flow stress gets reduced by up to ten times.

For many materials the flow stress alone is not sufficient to design the processing route, since it provides no information on deformation capability and microstructural development. Processing maps are developed by analyzing the flow curve in combination with investigations on the microstructure of compressed specimens. The contour lines specify the efficiency of energy introduction into the material, which indirectly gives information about the tendency of the material to recrystallize or to form shear bands. In Ti 6-2-4-2, for instance, dynamic recrystallisation of α is observed at temperatures between 950 and 990°C and deformation rates between 1 and 10 s^{-1}. At lower temperatures (900-925°C) and high deformation rates (1-10 s^{-1}) shear bands form in areas with high deformation, which can lead to material separation. Therefore forging parameters have to be chosen so as not dwell in undesired regimes.

4.2.1 Closed die forging

Closed die forgings are made of titanium alloys with weight ranging from a few grams to over 1 Tonne.

Forge hammers as well as mechanical and hydraulic presses are used for their manufacture.

Challenge lies in obtaining uniform microstructure and mechanical properties all over the volume of forging, considering that large variations in cross section can occur. Critical parts like rotating compressor blades of aero-engine are manufactured using closed die forging. Figure 2 shows different components of titanium alloys produced by closed die forging.

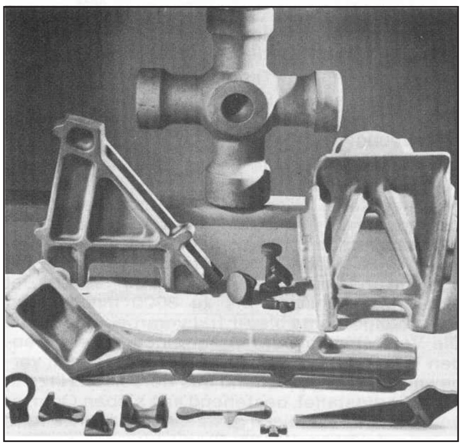

FIG. 2 COMPONENTS OF TITANIUM ALLOYS PRODUCED BY CLOSED DIE FORGING

4.3 Tube Manufacture

Tube manufacture is largely confined to commercially pure titanium. Seamless tubes are manufactured by hot extrusion followed by cold pilgering. Seam welded tubes are used extensively in heat exchangers in power plants, desalination of sea water, ship building etc. The starting material for production of seam welded tubes is cold rolled and slit-to-width strip, 0.4-0.9 mm in thickness depending on application. High demands are placed on dimensional and surface quality aspects of the strip. The tubes are manufactured in 15-30 mm Φ range.

For ~50% of non-aerospace applications, titanium is used in the form of tube and pipe. This is due to large use of titanium in heat exchanger applications and piping and tubing in seawater and chemical processing industries.

4.4 Heat Treatment

An oxidizing atmosphere is used to reduce hydrogen pick-up. If in spite of it, unacceptable hydrogen pick-up occurs, vacuum annealing is resorted to for removal of hydrogen. Unlike the case of steels, poor correlation exists between strength and hardness. Hence hardness can't be used to monitor heat treatment of titanium alloys.

There are essentially three types of heat treatments carried out for titanium alloys.

- Stress relieving treatment given to relieve residual stresses developed during hot working/ fabrication
- Annealing carried out to produce an optimum combination of mechanical properties, machinability, dimensional and structural stability
- Solution treatment and aging done to increase strength.

4.5 Pickling

Pickling has two functions to serve - removing the oxide scale and removing the α-case layer. Molten salt descaling is an effective method of removing oxide scale. Grit blasting is also effective in removing scale. HF-HNO_3 acid pickling used to remove underlying α-case, once oxide scale is removed. Bath conditions are to be closely controlled during acid pickling to prevent hydrogen pick-up.

4.6 Machining

Compared to high strength steels, titanium, due to its unique physical and chemical properties, poses the following problems:

- Lower thermal conductivity of titanium hinders quick dissipation of the heat caused by machining, leading to increased wear of cutting tools.
- Lower modulus of elasticity leads to high spring back, causing titanium parts to move away from the cutting tool.
- Lower hardness and high chemical reactivity of titanium lead to galling with the cutting tool.

4.7 Welding of Titanium

For fabrication of chemical engineering plant and equipment, commercially pure titanium is used. TIG & MIG welding methods are used. Welding of alloy titanium is difficult compared to welding pure titanium. Alpha alloys are weldable. Among $\alpha + \beta$ alloys Ti-6Al-4V has good weldability. β alloys are difficult to weld. Titanium being a reactive metal, entry of air to the weldzone is to be strictly prevented through protection with an inert gas cover to prevent access to air.

4.7.1 Electron beam welding

In aircraft industry alloy grade titanium is used. Electron Beam Welding (EBW) is extensively employed. TIG welding is also adopted, but to a limited extent.

Electron beam welding leads to very high quality welds and is frequently used where highest weld quality is desired, particularly in the aerospace industry. By welding in a vacuum chamber, gas absorption is prevented. EBW is superior to GTA and GMA welding and much better weld joints can be obtained. However, EBW is more expensive since all welding is done in a high vacuum chamber by mechanized equipment. This also restricts the size of the components to be welded as well as the freedom of movement in the weld chamber. Due the high power density of the electron beam, the heat penetration depth is low. The HAZ is very narrow. The resultant fusion and heat-affected zones yield a high depth to width ratio, which results in low distortion in EB-welded structures. Complicated work-pieces can be welded without distortion. Weld speeds are very high, and excellent reproducibility of the welds can be guaranteed. Even thick plates up to 100 mm can be welded without filler metals. If filler metal is required, the same alloy is used. Components with large wall thickness as well as thin walled components can also be successfully welded.

5. PHYSICAL METALLURGY AND PROPERTIES OF WROUGHT TITANIUM ALLOYS

5.1 Different Microstructures in $\alpha + \beta$ titanium alloys

Lmellar microstructures are produced by β annealing and β forging. Deformation avoids the pronounced and harmful decoration of grain boundaries with α phase. Bimodal microstructures, are equiaxed α in a transformed β structure. The solution heat treatment temperature and the cooling rate can modify the α volume fraction and the fineness of the transformed structure after solution heat treatment. Deformation at relatively low temperatures, or slow cooling rates after deformation, result in equiaxed microstructures with high α volume fraction. Depending on their processing history, the structures differ in fineness.

5.2 Fatigue Crack Growth-Dependence on Microstructure

The second stage of fatigue damage, after crack initiation and before final fracture is the growth of fatigue cracks. This is normally investigated on precracked compact tension specimens and the fatigue crack growth rate (da/dN) is plotted versus the amplitude of the stress intensity at the crack tip (ΔK). da/dN vs. ΔK curve is substantially influenced by the microstructure. For constant amplitude and R-ratio (minimum to maximum load) the lamellar microstructure of Ti-6Al-4V shows a more favorable fatigue crack growth behavior than the equiaxed structure. A look at the fracture surface points out substantial difference between the two microstructures with regard to roughness, fractured area per mm crack growth, and local crack plane orientation relative to the loading direction – observations that are able to explain the influence of microstructure on the fatigue crack growth behavior.

5.3 Creep and Fatigue Strength – Dependence on Microstructure

The microstructure has a strong influence on the mechanical behavior of near-α titanium alloys at elevated temperatures. The size and arrangement of the hexagonal α and the body-centered cubic β are of prime importance. Lamellar microstructures, originating from cooling from the β phase field and equiaxed microstructures, as a result of recrystallization process, can either individually have a fine or coarse distribution or can both be present in a bimodal microstructure. Compared with equiaxed microstructures, lamellar microstructures usually show superior creep behavior due to their coarser structure, meaning a lower volume fraction of phase boundaries. On the other hand, equiaxed and bimodal microstructures show superior fatigue properties due to their fine microstructures. Therefore for primarily creep limited titanium components used in the compressor of gas turbine engines lamellar microstructures (e.g., TIMETAL 685 or 829) are used, whereas bimodal structures (e.g., TIMETAL 834) are chosen for primarily low cycle fatigue limited parts. Selection depends on the area of application and on the design philosophy of the engine manufacturer.

5.4 Fracture Toughness – Dependence on Microstructure

Processing, i.e., microstructural modification has a large influence on fracture toughness. Lamellar microstructures demonstrate higher values than equiaxed structures.

5.5 Processing of Alloy 834 Discs

Alloy 834 is the most advanced conventional elevated temperature titanium alloy available today for gas turbine engine applications. Properties can be tailored by using various forging routes. As an example, two alternative α/β processing routes result in different α/β microstructures with the finer microstructure having higher LCF life. Forging in the β phase field leads to a lamellar microstructure and thus an improvement of creep strength and fracture toughness, at the expense of ductility, however. Depending on requirements, change of heat treatment parameters (solution heat-treatment temperature, quenching, and aging conditions) also can be adopted to realize a wide variation of properties.

6. MAXIMUM TEMPERATURE LIMIT FOR TITANIUM ALLOYS

Today, the maximum temperature limit for near-α alloys for elevated temperature applications is about 540°C. This temperature limitation for titanium alloys mean the hottest parts in the compressor, i.e., the discs and blades of the last compressor stages, have to be manufactured from Ni-based superalloys at nearly twice the weight. Additionally, problems arise associated with the different thermal expansion behavior and the bonding techniques of the two alloy systems. Therefore enormous efforts are underway to develop a compressor made completely of titanium. Titanium alloys are required that can be used at temperatures of 600°C or higher. This has been the impetus for extensive research and development work in the area of elevated temperature titanium alloys. As shown in Fig. 3, the maximum application temperature of titanium alloys has been raised from about 300°C to nearly 600°C over the last 40 years.

Within the last few years, the near-α class of elevated temperature titanium alloys has been the subject of particular development interest. An example of the state-of-the-art of this development is IMI834 (Ti-5.8Al-4Sn-3.5Zr-0.7Nb-0.5Mo-0.35Si), developed jointly in the UK by IMI titanium Ltd. and Rolls-Royce in the 1980's. With a potential use temperature of almost 600°C, the alloy was aimed at replacing the IMI 685 and IMI 829 alloys preferred in European jet

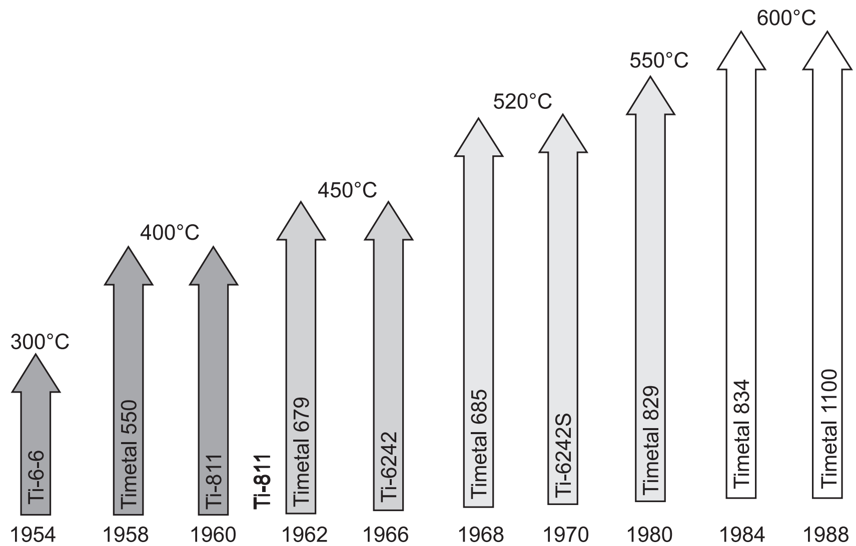

FIG. 3 INCRESE OF MAXIMUM APPLICATION TEMPERTURE OF TITANIUM ALLOYS

engines. After IMI was acquired by TIMET, this alloy was given the trade name TIMETAL 834 and has since found its way into European military jet engines. Presently it is also used as a compressor disc material in the last two stages of the medium-pressure compressor, and the first four stages of the high pressure compressor in variants of the Rolls-Royce Trent series commercial jet engine. A bimodal microstructure with a primary α volume fraction of 15% has proven to be an optimum microstructure for this particular application. IN US, Ti6-2-4-2 is still the preferred high temperature alloy for jet engine applications.

7. TITANIUM CASTINGS

Investment casting of titanium has several attractive features.

- Integral structural elements can be manufactured cost-effectively, with little or no machining effort
- Cast parts show excellent dimensional accuracy
- Castings have an excellent surface quality
- Satisfactory levels of mechanical properties can be guaranteed.

Molding materials should be non-reactive to liquid titanium or at least react in a delayed way - a challenging task, considering that titanium is a reactive metal. Conventional molding materials used in non-titanium casting, having a typical composition Al_2O_3-SiO_2, are not suitable; molten titanium will react and dissolve aluminum, silicon, as well as oxygen. Proprietary non-reactive shell systems have been developed and patented, incorporating facing of high melting metals (tungsten) or special ceramic oxide layers with greater thermodynamic stability than that of titanium oxide.

A number of technological improvements have been adopted to eliminate casting defects in titanium. To overcome the problem of limited fluidity, centrifuging has been employed to accelerate molten metal into mold cavity. Chemical milling has been employed to remove the contaminated surface layer, a few tenths of a millimeter in thickness. Hipping at ~1000 bar pressure of an inert gas atmosphere and ~900°C is adopted to eliminate shrinkage cavities, porosity etc.

While all titanium alloys are castable, customers would rather go for the "best known" alloy only, relying on proven compositions, rather than select the "best new" alloy, to design future parts.

8. TITANIUM-BASED INTERMETALLICS

The most important and by far the most intensively investigated titanium phase diagram is the system Ti-Al. Apart from the α and β phases, which are of central importance for the conventional titanium alloys, several intermetallic phases are present, such as α_2-Ti_3Al, γ-TiAl, $TiAl_2$ and $TiAl_3$. Of these only the α_2-Ti_3Al and γ-TiAl are of technical relevance today, since $TiAl_2$ and $TiAl_3$ are extremely brittle. Titanium aluminide alloys of technical interest are found in the range of the two phase field $\alpha + \alpha_2$ and γ-TiAl. With the exception of model alloys, the latter alloys are usually also two-phase $\alpha_2 + \gamma$ or multiphase alloys depending on the alloying elements. If these aluminides are alloyed with niobium, another intermetallic phase – Ti_2AlNb – appears, which is the basis for the class of orthorhombic titanium aluminides. Table 4 compares the properties of titanium aluminides with those of conventional titanium alloys.

Table 4. *Titanium aluminides compared with conventional titanium alloys*

Base	*Broad composition (At%)*	*Density (g/cm³)*	*Modulus (Gpa)*	*Ductility at Room Temp.*	*Creep Limit (C)*	*Oxdn. Limit (C)*
Ti_3Al	23-25% Al 11-18% Nb	4.1-4.7	100-145	2-10	760	650
TiAl	48-54% Al	3.7-3.9	160-176	1-4	1000	900
Ti_2AlNb	21-25 Al 25-30 Nb					
Conventional Ti alloys		4.5	96-100	20	600	600

9. APPLICATIONS OF TITANIUM

9.1 Non-Aerospace, Non-Biomedical Applications of Titanium

Corrosion resistance of CP titanium plays a major role, when the metal is used for manufacture of plate and tube heat exchangers for the chemical, power generation, or food industry. In addition, the good thermal conductivity of titanium, which is roughly 50% higher than for stainless steel, makes it a preferred material for heat exchangers. CP titanium has been found suitable in heat exchanger applications in which the cooling medium is sea water, brackish water, and also polluted water. CP Titanium has demonstrated its superior corrosion resistance to such media for decades. Figure 4 shows heat exchanger plates made of CP titanium. Both tubular and more compact plate-type heat exchangers are routinely applied in land based oil refineries and on off-shore oilrigs. Experience has shown that even water speeds of 10 ms^{-1} do not cause any erosion corrosion, cavitation, or impingement attack in the tubes. Therefore particularly thin walled condenser tubing can often be used with zero corrosion allowance. Worldwide millions of meters of welded and seamless titanium tubing in steam turbine power plants, refineries, chemical plants, air conditioning systems, multistage flash distillation, desalination and vapor compression plants, offshore platforms, surface ships and submarines, as well as for swimming pool heat pumps have documented titanium's life span and dependability compared to previously used copper-nickel alloys and stainless steel. In Japan, for example, condenser tubes consume about 20% of the domestic titanium use.

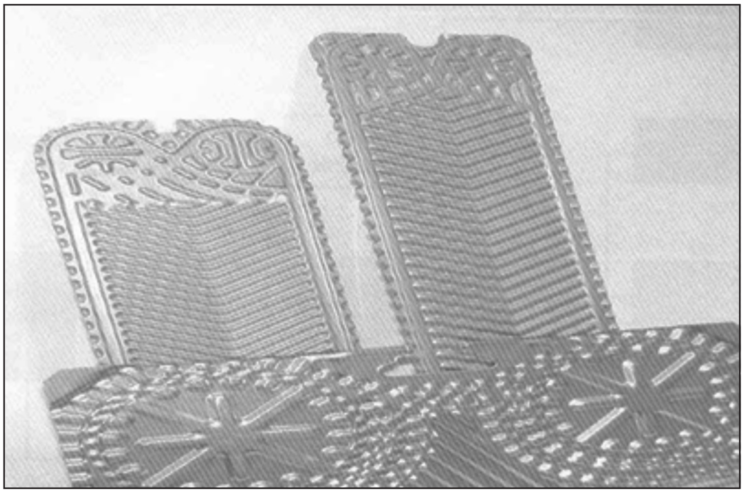

FIG. 4 TITANIUM HEAT EXCHANGER PLATES

9.1.1 Titanium Alloys for Steam Turbine Applications

A considerable portion of the down time of power plants for energy generation can directly be related to failures of steam turbine components. Of these failures, the majority occurs in low-pressure steam turbines, primarily at the steam-moisture transition zone in the last two rows of blades (L-1 and L). High operating stresses, poor corrosion resistant materials, and hostile operating environments are identified as prime failure causes. In the 1980's, the first trials on US steam turbines of replacing the standard 12 Cr steel with Ti-6Al-4V retrofit blades proved to be quite successful. Titanium test blades have performed in service for more than 20 years without failure. Therefore titanium alloys are today increasingly used for advanced steam turbine blades. The primary reasons are weight reduction of close to 60% compared to steel blades and high resistance to oxygenated acid chlorides, corrosion fatigue, and stress corrosion cracking.

Compared with steel blades, the lighter titanium alloys also permit longer blades for the same root stress, thus increasing the turbine efficiency. Presently ThyssenKrupp Turbinenkomponenten, Remscheid, Germany, the leading manufacturer of envelope and precision forged titanium low pressure steam turbine airfoils, is manufacturing the largest forged steam turbine blade in the world, measuring 1650 mm in length. For increased strength, new titanium alloys like Ti-6Al-6V-2Sn are proposed in Japan by Hitachi, as well as SP-700. Although the cost of titanium blades are estimated to be twice that for steel blades, avoiding a single forced outrage pays for more than the additional cost of a titanium blade row.

9.2 Titanium for Aerospace Applications

9.2.1 Growth of titanium alloy usage in airframe

Oftentimes, saving weight is the major reason for choosing titanium alloys in fuselage applications, thus making use of the high specific strength of the metal. Frequently, the substitution for high strength steels is worthwhile even if the steel's strength is higher, or for aluminum based alloys even if aluminum's density is lower. This has led to increased use of titanium alloys in fuselages over the past four decades. Today titanium accounts for approximately 9% of the structural weight of the Boeing 777. Similar numbers are found for airbus aircrafts.

9.2.2 Growth of titanium alloy usage in aeroengine

The main area of application for aerospace titanium alloys is in the gas turbine engine. Approximately one third the structural weight of modern turbine engines is made up of titanium. Besides nickel-based superalloys, titanium alloys are the standard engine material. Indeed the first jet engines introduced at the beginning of 1950,s by Pratt & Whitney in the USA and Rolls-Royce in England contained titanium alloys. Since then the titanium content has steadily increased, Furthermore, over the years an evolutionary trend in alloy design is observed from the $\alpha + \beta$ alloys to the elevated temperature near-α alloys.

9.2.3 Place of titanium in airframe and aero-engine materials

The percentage of structural weight for various material classes in modern large commercial aircraft is different for airframe and engine materials. The fuselage of the Airbus A330/340, for example, is manufactured of nearly two thirds aluminumis different for. At about 7%, titanium alloys have a similar share of the structural weight as steels. However, at over a third the structural weight, titanium is the second most common material in the jet engine following nickels-based superalloys; and by volume, titanium alloys are the most abundant material in the engine.

9.2.4 Wrought titanium alloys

9.2.4.1 Beta titanium alloy 10-2-3

Despite higher initial cost, primary components of aircraft landing gear are increasingly manufactured from forged titanium alloys. The higher up front cost pays off over the long term as high–strength steels typically need to be replaced at least once in an aircraft's lifetime due to their susceptibility to stress corrosion. Landing gear component replacement is avoided if made from titanium alloys; and the Boeing 777 has set the trend for their use. Here the main landing gear is almost completely manufactured from forged components of TIMETAL10-2-3, which nearly doubled the amount of titanium used on the 777. The weight-saving amounted to approximately 270 kg per aircraft.

9.2.4.2 Beta titanium alloy 15-3 for fuel tanks

In addition to superplastic forming, cold formable β alloys provide another cost effective route. MAN Technologie AG uses such an approach to produce the fuel tanks for the ESA on the Automated Transfer Vehicle (ATV) for the International space station (ISS). The Ti 15-3 tank half-shells are formed by a special, patented cold rolling process called counter-role spin forming.

Half shells for satellite tanks can also be manufactured by simple spin forming of the alloy 15-3. Compared to SPF processing, the required infrastructure and tooling are substantially cheaper.

9.2.4.3 Titanium alloy blisks

Evolutionary engine design stresses the need to further decrease the weight of the compressor blades and discs, while increasing component life or inspection intervals. This can be achieved by using an integrally bladed disc, or "blisk", design. The finished blisk is a single assembly where disc and blades are metallurgically bonded together. For small blade heights up to about 60 to 80 mm, it is more cost effective to machine a blisk from an oversized forged disc. Larger blades are generally attached to the disk by linear friction welding.

In addition to the weight reduction from a blisk design, the lack of a mechanical interface between the blades and the disks eliminates a common site for fatigue crack initiation. This can result in extended inspection intervals. Blisk technology is now a standard technology in small and medium size category compressors of commercial and military engines. In the Eurofighter's EJ200 engine, for example, all three stages of the fan section are a blisk design; the first two being manufactured using linear friction welding, the third by electrochemical machining.

9.2.5 Cast titanium alloys

Large intermediate casings (investment castings) for jet engines are produced by PCC-Wyman Gordon. The casings are located where the incoming air is ducted either into the engine by-pass or the core engine. Their primary function is to bear the rotating parts as well as to suspend the entire engine. Investment castings made of titanium are used in cold section of gas turbine engine and as condenser rotors.

9.2.6 Titanium-base intermetallics

Different sized γ TiAl investment castings are used turbocharger rotors. This application is in transition phase between laboratory and industrial application. γ TiAl turbine blades are also produced by investment casting. This application is in transition phase between laboratory and industrial application. The fifth stage of the low pressure turbine in the GE CF6-80C2 jet engine with turbine blades is manufactured from a cast Ti-47Al-2Cr-2Nb alloy. Each of the 98 blades has a length of 50 cm and at 217 g, the blades are only about 55% the weight of a conventional nickel-based superalloy blade. The reduced weight of the titanium aluminide blades would further enable an even lighter weight design of the entire turbine due to the lower centrifugal forces imposed on the disc. Use of these alloys in a large jet engine like the GE90 could save more than 150 kg. Due to cost, the casting route is favored for the production of TiAl low-pressure turbine blades. At present, the production of TiAl blades is delayed primarily due to cost considerations. In the mid-nineties, within the framework of a German hypersonic Technology Program, the feasibility of hot-structure γ(TiAl) components was investigated. At the end of 1995, a panel structure was fabricated from wrought γ(TiAl) sheet. Structural stability test was conducted on the panel and results published.

Titanium for biomedical applications

A number of metallic systems form the basis for biomaterials:

- Stainless steel, e.g., 316L
- Cast CoCr based alloys, e.g., CoCr30Mo6
- Wrought CoNiCr alloys, e.g., CoNi35Cr20
- cp-titanium and titanium alloys, e.g., Ti6Al4V
- cp-niobium
- cp-tantalum.

Of all the above, titanium is the preferred choice as biomaterial. In human body fluid titanium, tantalum and niobium show good corrosion resistance. Stainless steels, CoCr and CoNiCr alloys behave poorly. Repair of passive layer occurs fast in titanium, tantalum and niobium. It is slow in stainless steels, CoCr and CoNiCr alloys. Titanium, tantalum and niobium are reported to be biocompatible because they form protective surface layer. Titanium shows better bio-adhesion (integration of metallic implants by bone ingrowth) compared to 316L stainless steel. Titanium has young's modulus closest to that of bone. Biofunctionality (ratio of fatigue strength to young's modulus) is highest for titanium alloys. Titanium can be processed/fabricated to the required product shape, size and quality. Titanium is less expensive than Co-base alloys, niobium and tantalum.

Breakdown potential measurements of various implant materials in Hank's solution show a clear order of precedence. While CP-Ti and Ti-6Al-4V had high breakdown potentials of 2.4 and 2.0 V, respectively, the value for stainless steel and CoCr-alloys (cast and wrought) amounted to only 0.2 and 0.42 V, respectively. Titanium and its alloys, as well as niobium and tantalum, belong to that group of metals which, in the body fluid, cannot undergo a breakdown of passivity. Nevertheless, in all materials the passive layer can be mechanically damaged, for example by fretting of metal against metal (plate/screw system) or by the instruments used during surgery. Therefore the repassivation time of the passive oxide layer for these materials is very important. The repassivation behavior of various metals in saline solution was measured by means of a method described in the literature. As compared to other materials the oxide growth on CP-Ti and its alloys $t_{0.05}$ is accelerated.

If implants have to carry mechanical loads, titanium alloys are used. Their outstanding strength to weight ratio and excellent fatigue behavior are decisive for the choice of material for orthopedic devices. Favorable to other high strength metallic materials, titanium has a relatively low modulus of elasticity, which reduces the differences in stiffness between the human bone and the implant. This is important, for example, to the traditional application of titanium alloys as hip implants and knee joints, but also to bone fracture plates and screws, and intramedullary nails or plates for cranial surgery.

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SCIENCE, TECHNOLOGY AND APPLICATION OF 18% NICKEL MARAGING STEELS WITH PARTICULAR REFERENCE TO INDIAN SCENARIO

M. NAGESWARA RAO[1]

1. INTRODUCTION

Maraging steels based on iron–nickel–cobalt–molybdenum system have emerged as an outstanding family of materials with exceptional combination of characteristics, making them the designers' choice for specialized applications [1]. These grades generally contain 18 wt.% nickel and are commonly designated as 18Nixxxx, where xxxx is the nominal strength value in MPa attained after final heat treatment. Their outstanding attributes include ultra-high strength coupled with high fracture toughness, excellent formability under hot and cold working conditions, and ease with which heat treatment can be carried out to attain the high strength condition.

2. GRADES COMMERCIALLY AVAILABLE AND PROEPRTY LEVELS

Maraging steel is commercially available in different strength variants – starting from 1400 MPa and reaching up to 2400 MPa. The inverse relationship between strength and toughness, well established for high-strength steels, also holds good within the family of 18% Ni maraging steels, variants having higher strength showing lower fracture toughness. While the maraging steel variant 18Ni1700 is the most important grade in the series, the higher-strength variants 18Ni1900/2000 and 18Ni2400 are also used for specialized applications.

An important factor that has come in the way of extensive usage of maraging steels based on Fe–Ni –Co–Mo system is the high cost. Cobalt is an expensive alloying element and is present in the range 8–12 wt.% in these steels, depending on the strength level, contributing importantly to the cost. Accordingly efforts were made to develop cobalt-free variants of 18% Ni maraging steel with comparable fracture toughness–strength combination. The development and commercialization of cobalt-free maraging steels, comparable to the standard cobalt-bearing grades with 1400, 1700, and 2000 MPa strength levels, was reviewed by Floreen and Bayer [2].

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Table 1 gives the chemical composition of cobalt-bearing and cobalt-free grades [3, 4]. Tables 2 and 3 compare the typical mechanical properties of the cobalt-free and cobalt-containing grades at strength levels of 1700 MPa and 1900 MPa, respectively [3, 4].

Table 1. *Nominal chemical composition of cobalt-containing and cobalt-free maraging steel grades*

Element	*Cobalt-bearing 18Ni1400*	*Cobalt-bearing 18Ni1700*	*Cobalt-bearing 18Ni2000*	*Cobalt-free 18Ni1400*	*Cobalt-free 18Ni1700*	*Cobalt-free 18Ni2000*
Ni	18.5	18.5	18.5	18.5	18.5	18.5
Co	8.5	7.5	9.0	Nil	Nil	Nil
Mo	3.25	4.80	4.80	3.00	3.00	4.00
Ti	0.20	0.40	0.60	0.70	1.40	1.85
Al	0.10	0.10	0.10	0.10	0.10	0.10
Si	0.10 max	0.10 max	0.10 max	0.10 max	0.10 max	0.10 max
Mn	0.10 max	0.10 max	0.10 max	0.10 max	0.10 max	0.10 max
C	0.03 max	0.03 max	0.03 max	0.03 max	0.03 max	0.03 max
S	0.01 max	0.01 max	0.01 max	0.01 max	0.01 max	0.01 max
P	0.01 max	0.01 max	0.01 max	0.01 max	0.01 max	0.01 max
Zr	0.01	0.01	0.01	–	–	–
B	0.003	0.003	0.003	–	–	–
Fe	Bal.	Bal.	Bal.	Bal.	Bal.	Bal.

Table 2. *Nominal room temperature mechanical properties of cobalt-containing and cobalt-free 18Ni1700 maraging steels*

Property	*Cobalt-containing 18Ni1700*	*Cobalt-free 18Ni1700*
Ultimate tensile strength (MPa) (Long)	1730	1790
Ultimate tensile strength (MPa) (Trans)	1723	1790
0.2% Yield strength (MPa) (Long)	1695	1748
0.2% Yield strength (MPa) (Trans)	1690	1748
% Elongation in 4.5 $\sqrt{A}$ (Long)	10.0	10.5
% Elongation in 4.5 $\sqrt{A}$ (Trans)	8.1	8.9
% Reduction in Area (Long)	46.7	56.1
% Reduction in Area (Trans)	30.3	45.8
Charpy V notch impact (Nm) (measured on small diameter bars)	27	34
Plain strain fracture toughness (MPa $m^{1/2}$)	Not available	104.0

Table 3. *Nominal room temperature mechanical properties of cobalt-containing and cobalt-free 18Ni2000 maraging steels*

Property	*Cobalt-containing 18Ni2000*	*Cobalt- free 18Ni2000*
Ultimate tensile strength (MPa) (Long)	1962	2049
Ultimate tensile strength (MPa) (Trans)	1952	2046
0.2% Yield strength (MPa) (Long)	1915	1984
0.2% Yield strength (MPa) (Trans)	1910	1997
% Elongation in 4.5 √A (Long)	9.8	8.8
% Elongation in 4.5 √A (Trans)	6.6	7.5
% Reduction in Area (Long)	43.9	45.3
% Reduction in Area (Trans)	28.4	38.2
Charpy V notch impact (Nm) (measured on small diameter bars)	23	20
Plain strain fracture toughness (MPa $m^{1/2}$)	Not available	69.7 to 73.9 (data on two production heats)

3. PHYSICAL METALLURGY OF MARAGING STEELS

3.1 Phase Transformations in Fe-Ni Alloys

In Fe-18% Ni alloy austenite-to-martensite transformation takes place upon cooling and the martensite-to-austenite reversion occurs upon heating. The iron-rich end of the iron-nickel system, on which maraging steels are based, exhibits a thermal hysteresis in phase transformations that prevents or minimizes martensite-to-austenite reversion during aging heat treatment.

3.2 No Free Energy Barrier for Nucleation

It has generally been observed that no incubation period accompanies the precipitation reaction in maraging steels. For example, significant hardening occurs after very short aging times (less than one minute) in the 18Ni1700 grade. Similar behavior is seen with reference to 18Ni2000 and 18Ni2400 grades also. The lack of an incubation period implies the lack of a free-energy barrier to nucleation in these alloys. Peters and Cupp[5] attributed this lack of a free-energy barrier to two factors: the high degree of solute supersaturation and heterogeneous nucleation on dislocations. The lath martensite in the 18% nickel maraging steels has an extremely high dislocation density. Alloying atoms can diffuse quickly along dislocations, causing accelerated nucleation and growth of precipitates.

Floreen [6] has also theorized that the good structural fit between A_3B precipitates and the bcc martensitic matrix is also responsible for the lack of a free-energy barrier and the low activation energies associated with 18% Ni maraging steels. Metastable orthorhombic Ni_3(Ti, Mo) phase precipitates out during aging of cobalt-containing 18Ni1400, 18Ni1700, 18Ni2000 and 18Ni2400 grades. These precipitates are rod shaped, they typically measure 25 Å wide × 500 Å longin the peak aged condition, and their long axis has been observed to lie parallel to the <111> directions of the bcc lathmartensitic matrix. The strengthening that is imparted to the matrix is derived from the distorted matrix latticethat surrounds each Ni_3Mo precipitate. Metastable Ni_3(Ti, Mo) phase precipitates out in cobalt-containing and cobalt-free maraging steel grades distorting the bcc martensitic matrix in a manner similar to that achieved with the molybdenum-bearing, Ni_3Mo precipitate.

3.3 Overaging/Austenite Reversion

With prolonged aging, the structure tends to revert to the equilibrium phases - primarily ferrite and austenite. Fortunately, the kinetics of the precipitation reactions that cause hardening are such that considerable age hardening-that is, approximately 20 HRC points (1035 MPa) - occurs before the onset of the reversion reactions that produce austenite and ferrite. With long aging times or high temperatures, however, hardness will reach a maximum and then will start to drop. Softening in these steels usually results not only from overaging in the usual sense of the term - that is, coarsening of the precipitate particles - but also from austenite reversion. The two processes are interlinked; dissolution of metastable nickel-rich precipitate particles in favor of equilibrium iron-rich precipitates locally enriches the matrix in nickel, which favors austenite formation. Very substantial amounts of austenite (of the order of 50%) can eventually be formed by overaging.

3.4 Cobalt-Molybdenum Interaction

In cobalt-bearing grades Mo is present at a relatively high level. Cobalt does not directly enter into the aging reaction because it does not form a precipitate. However, this element does contribute to the aging reaction indirectly through a phenomenon referred to as the cobalt/molybdenum interaction. Numerous studies have confirmed that a synergistic effect exists between cobalt and molybdenum. This synergistic effect of cobalt on the strength of molybdenum-bearing maraging steels occurs because cobalt reduces the solubility of molybdenum in the bcc matrix and thus enhances the precipitation of Ni_3Mo. Consequently, a larger volume fraction of Ni_3Mo precipitates is obtained when cobalt additions are present, resulting in yield strength of the alloy system. Transmission electron microscopy work performed by Miller and Mitchell [7] and Floreen and Speich[8] has also shown that additions of cobalt promote a finer dispersion of Ni_3Mo precipitates. A finer distribution of precipitates will reduce the interparticle spacing, which, in turn, will increase the yield strength of the alloy system. In annealed martensite addition of 7% Co has a relatively small effect on the hardness, equivalent to the solid solution strengthening effect of Co. In aged martensite, on the other hand, addition of same amount of Co leads to a much larger increase in hardness.

3.5 Precipitating Phases

Based on the studies carried out by different workers on cobalt-containing grades, it can be concluded that $(Ni, Fe, Co)_3$(Ti, Mo) provides a comprehensive description of the strengthening precipitates that form during aging [9]. The relative proportion of Ti and Mo in the precipitates would depend on the chemical composition of the steel, with particular reference to the levels of Ti, Mo and Co. Thus, there will be more Mo substituting Ti in 18Ni1700 compared to what happens in 18Ni2400.

The Fe–Mo-based precipitates seem to contribute significantly to the strength of the cobalt containing grades in the peak-aged condition.

In the case of cobalt-free maraging steels,$(Ni, Fe,)_3$ (Ti, Mo) will be a comprehensive description of the strengthening particles [9]. However, there will be less Mo substituting Ti in cobalt-free grades, compared to the situation in cobalt-bearing grades with comparable strength. Ti makes a dominating presence in the strengthening phase.

4. THERMAL EMBRITTLEMENT

Maraging steels show marked degradation in toughness if they get exposed to temperatures in the range 780 to 950°C while cooling from high temperatures (e. g., 1200°C). This phenomenon has been termed thermal embrittlement (TE). It causes serious problems in processing components of thick sections of these steels [10]. TE has generally been characterized by a reduction in the Charpy impact energy [11-13]; Nes and Thomas [14] have shown that it also results in a decrease in ductility without impairing the strength. Ashida et al. [15] reported loss of ductility and toughness resulting from the precipitation of TiC on grain boundaries after a two-stage austenitising treatment (holding the austenite at 800 to 1000°C after solution treatment at 1200°C) of maraging steel. This treatment, as can be readily recognized, promotes TE. Sinha et al. [16] reported a decrease in plane strain fracture toughness (K_{Ic}) due to TE in rolled rings of C18Ni1700 grade maraging steel.

Various studies carried out on the subject have confirmed that TE is a direct consequence of TiC/Ti(C,N) formation by the chemical reaction of Ti and C(N) at the grain boundaries and that formation of Ti(C, N) film at grain boundaries is essential to the occurrence of TE. At temperatures in excess of 1175°C carbon is taken into solution. During slow cooling through or holding within the temperature range 750 to 1090°C carbon is reprecipitaed as a grain boundary film causing embrittlement.

5. THERMAL CYCLING FOR REFINEMENT OF GRAIN SIZE IN MARAGING STEEL

Saul et al. [17] were the first to demonstrate that reduction of the prior austenitic grain (PAG) size in cobalt-containing maraging steel grades can be realized by cycling the maraging steel between ambient temperature and a temperature in the austenitic phase field considerably in excess of solution treatment temperature. The optimum value of the upper temperature for effective grain refinement is very sensitive to the alloy composition and must be determined for each alloy. It was 927°C for 18Ni1700 and 1027°C for 18Ni2000 [15]. Saul et al were able to refine an ASTM grain size of −1/1 to an ASTM grain size of 6/7 in 18Ni1950 following three thermal cycles between room temperature and 1025°C. Figure 6 shows the micrographs illustrating the grain refinement obtained in 18Ni1700 by thermal cycling once between 875°C and room temperature. Nakazawa et al. [18] studied the effect of thermal cycling on 18Ni2400, among other compositions, and established that remarkable grain refinement can be achieved by choosing appropriate cycling conditions without degrading the strength and toughness.

The shear strains produced by the diffusionless shear transformations of martensite to austenite and of austenite to martensite provide the driving force for recrystallization during these thermal cycles. One should recall that grain sizes finer than ASTM 6/7 cannot be achieved by this process and that the process becomes less effective as the starting grain size becomes finer.

6. HEAT TREATMENT STEPS FOR MARAGING STEELS

Heat treatment of maraging steels to attain the high strength levels essentially consists of two stages

1. solution annealing
2. aging

6.1 Solution Annealing

6.1.1 Solution annealing – general

The maraging steels are prepared for age hardening through a heat-treating procedure commonly referred to as a solution anneal. Solution annealing entails heating the steel in the single phase austenite regime, holding for a sufficient time to place the alloying elements in solid solution, and then cooling to room temperature. It is essential to cool the steel completely to room temperature before aging in order to realize a microstructure comprising of essentially 100% martensite. If this is not done, the steel may contain untransformed austenite and does not satisfactorily respond to subsequent aging treatment resulting in the steel not attaining the expected strength level.

Maraging steel items are generally supplied in the solution annealed condition. The steels are best machined in the solution-annealed condition. Accordingly where machining is involved, it is carried out in the solution annealed condition; annealing again after machining is usually not necessary [19].

Solution annealing of finish-machined items and cold rolled sheet products has to be done in vacuum or controlled atmosphere furnaces to prevent surface damage.

6.1.2 Two stage/three stage solution annealing

Two-stage/three-stage solution annealing treatments were developed for cobalt-containing grades with strength levels upto 2400 MPa to undo the TE arising from cooling the maraging steel hardware from relatively high finishing temperatures. These treatments realize an excellent combination of strength, ductility, and toughness on a consistent basis [20, 21]. The first treatment comprises of soaking at 950°C followed by water quenching. The 950°C treatment causes a refinement of austenite grain size and delinking of grain boundaries and carbonitride precipitates. The fine grains formed after recrystallization at 950°C will have boundaries relatively free from carbonitrides. The second stage in a two-stage treatment involves soaking at 820°C followed by water quenching/air-cooling. Table 4 [21] illustrates the beneficial effect of the two-stage solution treatment over the single-stage treatment on the mechanical properties of C18Ni2400 in the aged condition. The remarkable improvement achieved with respect to ductility (% elongation and % reduction in area) and fracture toughness is obvious from Table 4.

Table 4. *Two stage heat treatment improves K_{Ic} and tensile properties – Data obtained on 4 heats of maraging 350*

Heat treatment	*Ultimate tensile strength (MPa)*	*0.2% Yield strength (MPa)*	*% Elongation (4D)*	*% Reduction in area*	*Fracture toughness K_{Ic} (MPa $m^{1/2}$)*
820 °C Solution treatment + aging	2345 to 2365	2307 to 2350	5.0 to 6.5	25 to 31	34 to 38
950 °C + 820 °C Solution treatment + aging	2360 to 2410	2307 to 2355	8.0 to 8.5	32 to 38	41 to 42

For products with a large cross-section, a three-stage heat treatment, consisting of soaking at 950°C followed by water quenching, a second soak at 950°C followed by water quenching and a third stage involving soak at 820°C followed by water quenching/air cooling was developed [20, 21]. With this treatment, it was demonstrated that an excellent combination of strength and toughness could be realized even in heavy forgings and components with complex shapes (large variation in cross section from one location to another) [9, 20, 21].

6.2 Aging

Age-hardening treatment after solution annealing usually consists of reheating the steel into the temperature range of 455 to 510°C, holding at this temperature for 3 to 12 h, and air cooling to room temperature. The most commonly practiced aging treatment for grades C18 Ni1400, C18 Ni1700 and C18 Ni 2000 grades comprises of holding the steel at 480°C for 3 to 8 h. For C18 Ni 2400 grade the aging treatment generally consists of holding the steel for 3 to 6 hours at 495 to 510°C.

7. ADVANTAGES OF WORKING WITH MARAGING STEELS

7.1 Little Dimensional Change During Aging

The low-carbon martensite formed after solution annealing is relatively soft - about 30 to 35 HRC. The precipitate particles that form during age hardening are of a lattice size comparable to that of the martensite matrix and cause little distortion of the matrix. The dimensional changes due to aging are thus very slight. This characteristic allows the steel to be age hardened to very high strength levels, while minimizing changes in the shape of the part being hardened. Therefore, fairly intricate shapes can be machined in the soft condition and then hardened with a minimum of distortion [22].

7.2 Ultra-High Yield and Tensile Strengths, High Fracture Toughness

One of the distinguishing features of maraging steels is superior toughness compared to conventional steels. The K_{Ic}values for maraging steels are much higher in comparison to those of quenched and tempered alloy steels for comparable tensile strength levels. The toughness of maraging steels is sensitive to purity level, and carbon and sulfur levels in particular should be kept low to obtain optimum fracture toughness.

7.3 Good Weldability

One of the main virtues of maraging steels is their excellent weldability. This is importantly due to the fact that the low carbon content in these steels produces a soft, ductile martensite on cooling. The weld heat-affected zone in maraging steels can be divided into three regions. The region closest to the fusion line contains coarse martensite produced by solution annealing. Next is a narrow region containing reverted austenite produced by heating into the 595 to 805°C range. Finally, there is a region where the maximum temperature reached during welding ranges from ambient temperature up to 595°C; this region contains martensite that has been age hardened to different extents. The heat-affected zone in an as-welded structure is relatively soft. Because the metal in the area immediately surrounding the weld is soft and ductile, residual stresses are low, and the susceptibility to weld cracking is considerably less than in steels hardened by quenching. Subsequent local aging brings the hardness of the weld zone up to that of the base metal; this effect is also shown in the figure. Resolution heat treating is advisableafter welding, if optimum properties are desired in the heat-affected weld zone.

Figure 1 is a listing of the different advantages of working with maraging steels. Table 5 gives the various applications for maraging steels. While for majority of applications the materials are used in peak aged condition (aging temperature of 480 to 510°C depending on the grade), applications such as die casting tooling requires the use of an aging temperature of approximately 530°C to provide an overaged structure that is more thermally stable.

- Ultra-high yield and tensile strengths, up to 2500 MPa
- High fracture toughness
- Simple heat treatment at low cost, little dimensional change
- No quench cracking
- No problem of decarburization
- Can be heat treated in large cross secdtions
- Good weldability
- Hot and cold working possible by most commercial methods
- Hot strength to ~500°C
- Good machinability in the solution treated condition

FIG. 1 ADVANTAGES OF WORKING WITH MARAGING STEEL

Table 5. *Applications of maraging steels*

Aerospace & Aircraft	*Military*	*Production Tooling*	*Nuclear sector*
Large-sized rocket motor casings	Rocket motor casings	Dies for hot forging	Nuclear enrichment rotors
Relatively small special purpose rocket motor casings	bridges	Extrusion press rams, dies and containers	
Landing gear		Dies for die-casting of Al and Zn	

8. DEVELOPMENT OF MARAGING STEEL FOR THE INDIAN SPACE PROGRAMME

India's Space Programme included launching of satellites weighing upto ~2000 kg in sun synchronous polar orbit using indigenously developed launch vehicle known as Polar satellite Launch Vehicle (PSLV). The first stage of this vehicle comprises of a motor case made of 5 segments, about 3 meters in diameter and 20 meters in length. Figure 2 shows schematically the first stage motor case of PSLV. Plates 8 mm in thickness and rings of sizes upto 3 meters in diameter made of maraging steel with yield strength of 1800 MPa are used in fabricating the motor case. In the following two important items of development work are described in detail – (i) Production of rings meeting the specification and (ii) Development of filler wire for TIG welding to realize 90% of the base metal strength and toughness in the weld joints.

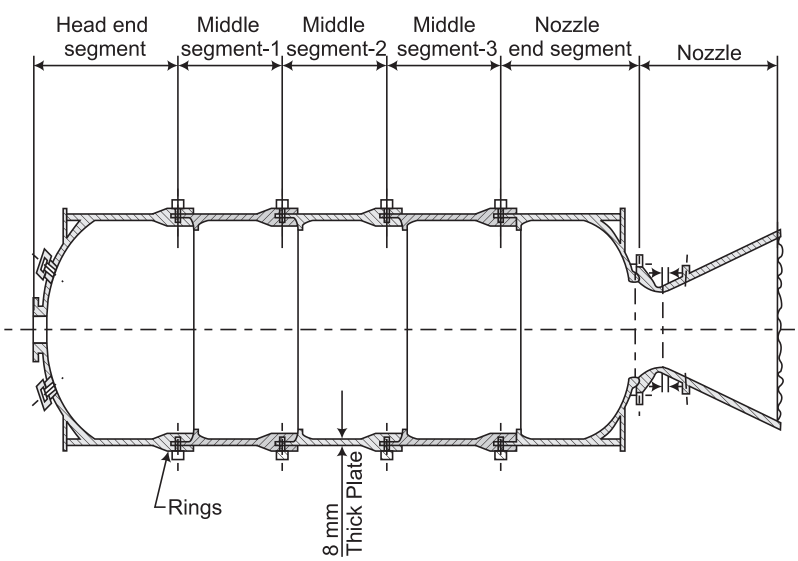

FIG. 2 SCHEMATIC DIAGRAM OF PSLV FIRST STAGE MOTOR CASE

8.1 Rolling of Rings of Maraging Steel

The initial batches of rings (campaign A) were produced by pre-heating the starting stock to 1200/1250°C, soaking at this temperature followed by ring rolling. Rings were air-cooled after rolling and subjected to a final heat-treatment comprising of solution treatment at 820°C followed by aging for 3 to 4 hours at 480°C. Evaluation of the mechanical properties of the rings was carried out in both tangential and radial directions. It was found that the K_{Ic} values were lower than the specified minimum of 90 MPa√m. K_{Ic} values in the tangential direction were particularly low, typically in the range 75 – 80 MPa√m. K_{Ic} values in the radial direction were generally in the range 80 – 85 MPa√m.

Microstructural examination of the rolled rings revealed a somewhat elongated grain structure elongation being in the tangential/circumferential direction. There was no evidence of recrystallization and prior austenitic grain (PAG) boundaries were found decorated with carbonitride particles. Scanning electron microscopy of the fracture surface showed that it is a predominantly intergranular failure. Secondary cracks running along grain boundaries can also be seen.

Efforts were made in campaign B to suppress the carbonitride precipitation by water quenching the rings immediately after ring rolling (in place of air cooling in campaign A). There was an improvement in the K_{Ic}, the minimum value now obtained being 80 MPa√m, but this was not enough to meet the customer's specification. Failures to realize the required K_{Ic}, in the campaigns A&B were related to grain boundary precipitation of carbonitrides. The grains were elongated in the circumferential/tangential direction and the 820°C treatment was not effective in causing recrystallisation of the elongated grain structure. The PAG boundaries aligned in the tangential direction and decorated with carbonitride particles thus provided easy crack propagation paths when K_{Ic} was tested in the tangential direction. The rings after hot-rolling were allowed to cool through the embrittlement range (980–820°C) and the well studied phenomenon of thermal embrittlement in maraging steel leads to preferential precipitation of carbonitride particles at the PAG boundaries. Poor K_{Ic} values in the tangential direction were the consequence.

An attempt was made in the subsequent campaign (campaign C) to carryout hot working through the temperature range for precipitation of carbonitrides. The aim was to prevent a microstructure of PAG boundaries decorated with carbonitride particles from evolving. Figure 3 shows schematically the proposed hot working schedule.

It was taken note that rings of low alloy steels of similar size were rolled by using pre-heating temperatures in the range 1100–1150°C. Zechmeister et al., [23] showed that K_{Ic} of maraging steel embrittled by grain boundary precipitation of titanium carbonitrides can be considerably improved by a sufficiently high amount of hot forming in the temperature range in which thermal embrittlement occurs. By destroying the grain boundary network of carbonitrides, the hot working contributes to improvement in $K_{Ic.}$ This study thus supported the usefulness of hot working through the carbonitride precipitation range to keep embrittlement at bay. It was also believed that a low finishing temperature was conducive to realizing a fine grain size/refined micro structure in the rings. To this end a relatively low pre-heating temperature was adopted (1100–1150°C as opposed to 1200 –1250°C adopted for campaigns A&B). However failures were encountered in realizing the desired final size and shape of the rings. The mill-tripped before ring rolling could be

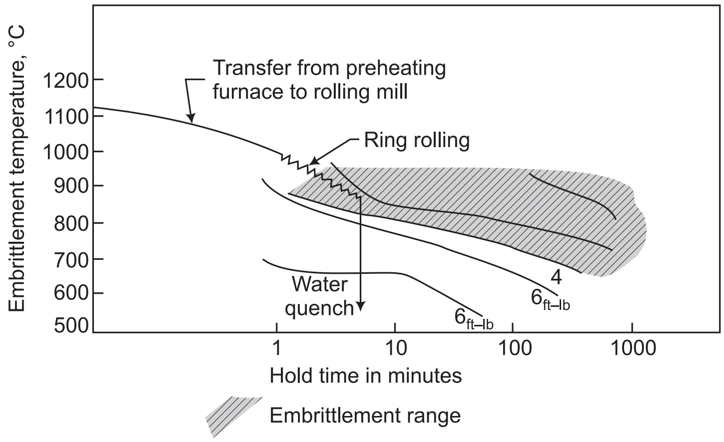

FIG. 3 SCHEMATIC OF THERMO-MECHANICAL WORKING ATTEMPTED

completed. The incompletely rolled rings had often non-uniform wall thickness, non-rectangular cross section and considerable distortion/ovality was noticed.

With failure in campaign C, the pre-heating temperatures for the stock were revised upward to 1200-250ºC for the next campaign (D). This lead to satisfactory completion of the ring rolling operation in that the aimed final dimensions of the rings were realized with acceptable levels of distortion/ovality.

The flow stress of maraging steels is highly sensitive to the processing parameters. Avadhani [24] and Suresh and Avadhani [25] carried out detailed studies, among others, on the functional dependence of flow stress of maraging steel grade X 2 NiCoMo 18 8 5 and 0.3C CrMoV steel on the temperature, strain rate and strain. Figures 4 and 5 show some of the results obtained by him for the two steel grades on a comparative basis. Figure 4 shows the variation of flow stress as a function of temperature at a strain level of 0.1 ata strain rate of 10.0/sec. The much faster increase in the flow stress of maraging steel with decreasing temperature in comparison to 0.3C CrMoV steel is obvious. Figure 5 shows the variation of flow stress with change in strain rate. The higher sensitivity of flow stress of maraging steel to strain rate compared to 0.3C CrMoV steel is seen from Fig. 5, flow stress of maraging steel increasing at a faster rate with increasing strain rate. During ring rolling strain rates increase with deformation and are generally high (1 – 20/sec). It follows that the reduced temperature adopted for hot working taken together with relatively high strain rates prevalent during ring rolling contributed to large increase in flow stress of maraging steels. Even when rolling was done with pre-heating in the range 1200 to 1250°C, mill had to exert forces at its maximum rated level in the radial direction; with preheating in the range 1100 to 1150°C, the large increase in the flow stress of the steel has pushed up the tonnage required for rolling beyond the capacity of the mill. Consequently the mill stalled and rolling got interrupted. It was possible to roll low alloy steel rings of similar size after pre-heating at 1100-1150°C, not only because of their relatively low flow stress at the rolling temperature but also because their flow stress is much less sensitive to variations in rolling temperature and strain rate.

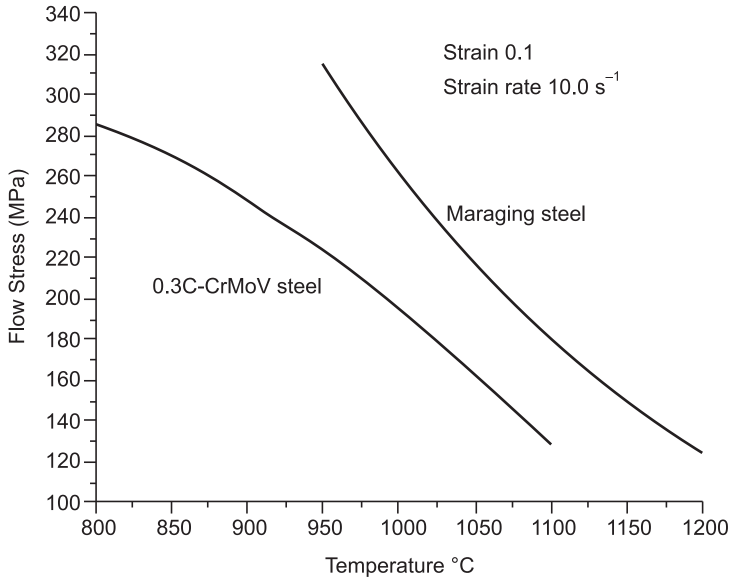

FIG. 4 VARIATION OF FLOW STRESS AS A FUNCTION OF TEMPERATURE AT A STRAIN LEVEL OF 0.1 AT A STRAIN RATE OF 10.0/SEC

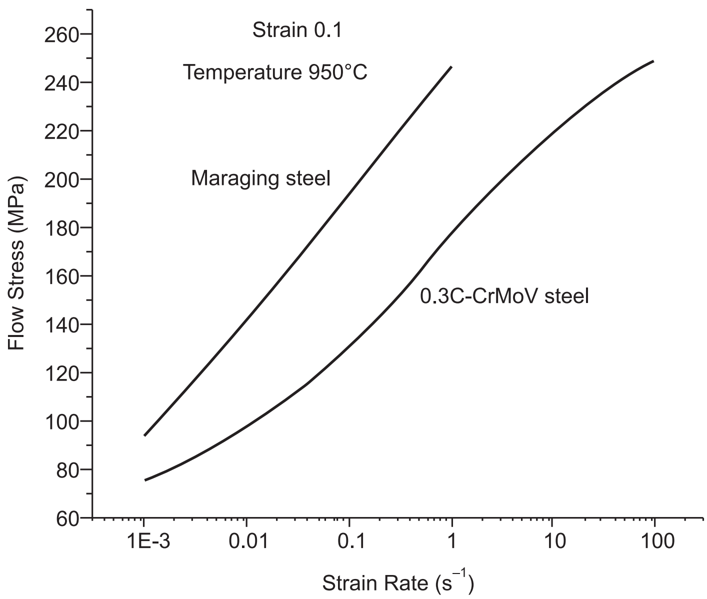

FIG. 5 VARIATION OF FLOW STRESS WITH CHANGE IN STRAIN RATE

While rolling could be satisfactorily completed by resorting to a preheating temperature of 1200 to 1250°C, consistently high fracture toughness values could be obtained only after resorting to a two or three-stage solution treatment following the hot working operation as described in Section 6.1.2. Scanning electron micrography of fracture surface of broken test specimen cut from rings subjected to two or three-stage solution treatment showed that the fracture is transcrystalline.

8.2 Development of Filler Wire for TIG Welding

Fabrication of the rocket motor casing involved TIG welding. The use of a filler wire (W1) similar in composition to the maraging steel base material resulted in segregation of alloying elements, particularly molybdenum and titanium, at the substructure boundaries in the weld fusion zone. During subsequent aging this led to accelerated austenite reversion. Austenite being a soft phase, this resulted in poor yield strength of the weld-joint. Some of the fracture toughness values obtained on the weld joint were also not satisfactory. Solution treatment at 820°C followed by aging at 480°C did not remove the segregation and consequently did not improve the mechanical properties of the weld joint. It is only at a high temperature of the order of 1250°C that the composition became homogenized. Use of a filler metal (W2) with reduced molybdenum and titanium contents and increased cobalt and aluminum levels brought down the segregation effect considerably and improved the mechanical properties. Table 6 gives the chemical composition of the two filler wires W1 and W2. Reduced Mo and Ti levels prevented austenite reversion by bringing down the segregation effect. Increased Co and Al levels made up for the loss in strength resulting from reduced Mo and Ti levels. Table 7 summarizes the effect of switching over from W1 to W2 on the microstructure and mechanical properties of the weld joint and Table 8 gives the relative yield strength values of the weld joint obtained with filler wires W1 and W2 after different heat treatments.

Table 6. *Chemical Composition of W1 (Parent Material) and W2 Filler Wires*

Filler Wire Material	*C*	*Mo*	*Ni*	*Al*	*Cu*	*Ti*	*Fe*
W1 (Base Material)	0.01	4.6	18.9	0.15	8.3	0.41	Bal.
W2	0.006	2.5	18.2	0.46	11.9	0.16	Bal.

Table 7. *Comparison of the results obtained with filler metals W1 and W2*

Filler wire	*Microstructure*	*Mechanical properties*
Base metal (W1)	Segregation of Mo & Ti, austenite reversion temperature decreases, resulting in austenite pooling when aged at ≥ 425°C	Reduced strength; K_{Ic} adversely affected under certain conditions
W2	No austenite reversion upto aging temperature of 520°C	Acceptable strength and K_{Ic} over a wide range of tempering temperatures

Table 8. *Tensile properties from transverse weldment specimens*

Condition	*YS with WI (MPa)*	*YS with W2 (MPa)*
Aged at 480°C	1310	1440
Aged at 520°C	1400	1460
Resolutionized and age at 480°C	1355	1550

Acknowledgement

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INDIGENOUS DEVELOPMENT OF TECHNOLOGIES FOR PRODUCTION OF CRITICAL TITANIUM HARDWARE FOR STRATEGIC SECTORS

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1. INTRODUCTION

Over the last three to four decades, there have been significant developments in India with reference to making, shaping, treating and application of titanium alloys. The Country's capabilities with respect to making a variety of titanium alloys in different millforms required for strategic sectors in the country have seen a quantum jump. Advanced technologies have also been established for conversion of these alloys into different components in the Country. The Country has thus made much progress in the direction of harnessing the rich titanium resources it can boast of. Requirements of the strategic sectors, particularly the Aeronautics and Space, have been instrumental in providing the driving force for indigenous development of different technologies for alloy making and down stream processing. This paper makes an attempt to provide an overview of these developments.

2. INDIGENISATION OF PRODUCTION OF VARIOUS TITANIUM ALLOY MILLFORMS

With the setting up of MIDHANI at Hyderabad, most of the important titanium alloys required for Indian aeronautics and aerospace programmes were indigenized in different forms like billets, rods, plates and sheets meeting international standards. At MIDHANI titanium alloy billets weighing up to 4 tons could be produced on a regular basis. The alloys developed include all the three classes – alpha, alpha + beta and beta. MIDHANI has established the technology for production of not only the Western titanium alloys but also the Russian alloys. Thus in the field of aeronautics, MIDHANI is able to supply titanium alloys required for Western aircraft engines but also those required for engines for Russian-built military aircraft. Table 1 shows details of Western titanium alloy grades production of which in different product forms has been established at MIDHANI. Table 2 gives similar information for Russian titanium alloys.

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Table 1. *Western Titanium alloy grades indigenous production of which is established*

Alloy type	*Alloy designation*	*Chemical composition*
α	Grade 6	Ti-5.5Al-2.5Sn
Near α	Ti685	Ti-6Al-2.7Sn-4Zr-0.4Mo-0.4Si
	Ti834	Ti-5.8Al-4Sn-3.5Zr-0.5Mo-0.7Nb-0.35Si-0.06C
β + α	Ti-6-4	Ti-6Al-4V
β	Ti-15-3	Ti-15V-3Cr-3Al-3Sn

Table 2. *Russian Titanium alloy grades indigenous production of which is established*

Alloy type	*Alloy designation*	*Chemical composition*
α	VT-5-1	Ti-5.5Al-2.5Sn
	VT-5	Ti-5Al
	PT7-M	Ti-2.2Al-2.5Zr
Near α	OT4-1	Ti-2Al-1.3Mn
	VT 18	Ti-7Al-11Zr-0.6Mo-1Nb
	VT 20	Ti-6.5Al-1.3Mo-1.3V-2Zr
α + β	VT 9	Ti-6.4Al-3.3Mo-1.5Zr-0.25Si
	VT-14	Ti-4.5Al-3Mo-1V
	OT4-1	Ti-2Al-1.3Mn

3. IMPROVEMENT OF MACRO QUALITY AND ULTRASONIC INSPECTABILITY OF FORGED BILLETS OF TITANIUM ALLOYS [1, 2]

The alloy Ti-6Al-4V is the so-called workhorse among all titanium alloys, in that it is the most used composition for aerospace applications and large amount of application engineering data has been generated on this grade over the years.

The material finds important use for aerospace applications in the country. A number of critical components are manufactured by carrying out hot working of the starting billet stock through operations such as forging and rolling. It has been the constant endeavor to produce the components with increasing levels of structural integrity. In order to produce the components with a high degree of soundness, the component manufacturer places corresponding demands on the supplier of the starting billet stock. The component manufacturer has been tightening his acceptance standards including prominently those for ultrasonic testing. However, in order to ensure a higher degree of freedom from defects, it becomes necessary to be able to inspect the billets to more stringent defect standards, i.e., there has to be a corresponding improvement with respect to the inspectability of the material by ultrasonics. One has thus to realize the billet material with as high a transparence as possible to the incident ultrasonic beam.

Depending on the size and shape of the component to be produced by hot working, the starting billet size has to be chosen. It turned out that Ti-6Al-4V billet as large as 350 mm ϕ had to be produced and inspected ultrasonically for manufacture of certain aerospace components. The increasing difficulty encountered in ultrasonic inspection with increasing size of the billet is well documented, with the larger billets being amenable to UST to only relatively loose defect standards.

The manufacture of the billets originally comprised of producing a double vacuum arc remelted ingot, ~ 850 mm in ϕ, and forging it down typically to 500 - 550 mm ϕ, by pre-heating/intermediate heating in β phase field. The reduction was carried out in a number of heats, with pre-heating temperature for the first heat and intermediate heating temperature for the subsequent heats lying in the single-phase β region. The forging in each heat continued through the two-phase ($\alpha + \beta$) field, so long as it was possible to give sizable reductions by hot working. Forging from 500 - 550 mm ϕ to the final forged billet stage was carried out in the $\alpha + \beta$ phase field. The material was then subjected to mill annealing at 700°C (973 K). Figure 1 shows the process flow sheet for the production of billets as per the original practice.

Production of 850 mm ϕ ingot by vacuum arc remelting
↓
Forging in the β phase field to ~400 mm ϕ
↓
Forging in the $\alpha + \beta$ phase field to the final billet dimension (150-300 mm ϕ)
↓
Mill annealing

FIG. 1 HOT PROCESSING SCHEDULE FOLLOWED INITIALLY

The ultrasonic inspectability of the material so produced was found to be poor; whereas typically a billet of ~200 mm ϕ was expected to be inspected and cleared to a 1.2 mm FBH standard, it was in reality not possible to carry out inspection to such defect standard due to high noise level and resulting poor signal to noise (S/N) ratios. It was possible to inspect the 200 mm ϕ billets to only a relatively loose defect standard of e.g., 3.2 mm FBH. The billets were not acceptable to customers from aerospace, as they were insisting on having the 200 mm ϕ billets inspected to 1.2 mm FBH standard. They were emphatic that it should be demonstrated by the supplier that the billets are free from defects equivalent to or more severe than 1.2 mm FBH.

The poor inspectability of the billet was also associated with an unacceptable macro-quality of the billet. Macrostructure of the transverse sections was coarse and nonuniform. It corresponds to Level 40 as per Publication ETTC-3 prepared by the Technical Committee of European Titanium Producers covering macrostructural standards for titanium alloy bars. As regards the microstructure, it was noticed that the material had essentially a hot-worked microstructure and colony structure was present (Fig. 2).

Much effort has gone into modification of the processing of billets with the objective of improving the clarity of the material to ultrasonic beams and enhancing the S/N ratio.

FIG. 2 MICROSTRUCTURE OBTAINED BY ORIGINAL PROCESSING ROUTE

A modified process was finally arrived at for production of the billets to the required quality. The salient steps of the process are presented in Fig. 3. As in the original process, the 850 mm ϕ ingot was forged down by preheating/intermediate heating the ingot/semi, respectively in the β phase field. Forging was continued until a semi size of 500 mm Φ was reached. The semi billet was forged to 450 mm Φ in $\alpha + \beta$ range. The 450 mm Φ material was then heated to a temperature just above the β transus, soaked for a time just sufficient to attain a uniform temperature all over the transverse section and brought down to room temperature by adopting water quenching. The material was then forged in the $\alpha + \beta$ phase field until the final dimension was reached. Finally the material was given an annealing treatment in the $\alpha + \beta$ phase field. Initial trails were carried out with annealing at 700°C (973 K). It was found that recrystallisation of the hot-worked material was not complete. Figure 4a shows the corresponding microstructure. Annealing of the subsequent batches was carried out at a higher temperature, typically 950°C (1223 K). The resulting microstructure is shown in Fig. 4b. It is a bimodal structure with recrystallised, equiaxed primary α grains and recrystallised, equiaxed β grains coexisting. A lamellar structure is seen within the β grains. Machining of the billet to the required supply size was then carried out.

Production of 850 mm ϕ ingot by vacuum arc remelting

↓

Forging in the β phase field to ~400 mm ϕ

↓

Homogenize slightly above the β transus and water quench

↓

Hot work in the $\alpha + \beta$ phase field to the final billet dimension(150-300 mm ϕ)

↓

Recrystallization anneal in the $\alpha + \beta$ phase field

FIG. 3 REVISED HOT PROCESSING SCHEDULE

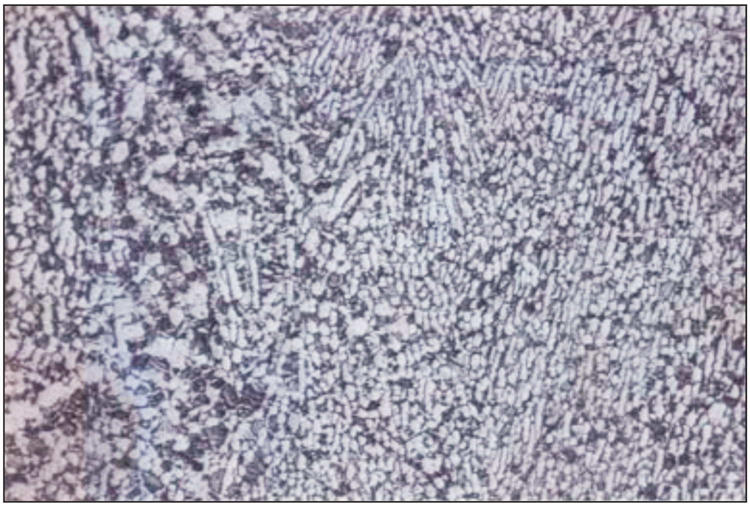

FIG. 4(a) MICROSTRUCTURE OBTAINED BY MODIFIED PROCESSING ROUTE WITH ANNEALING IN THE $\alpha + \beta$ PHASE FIELD AT 700°C

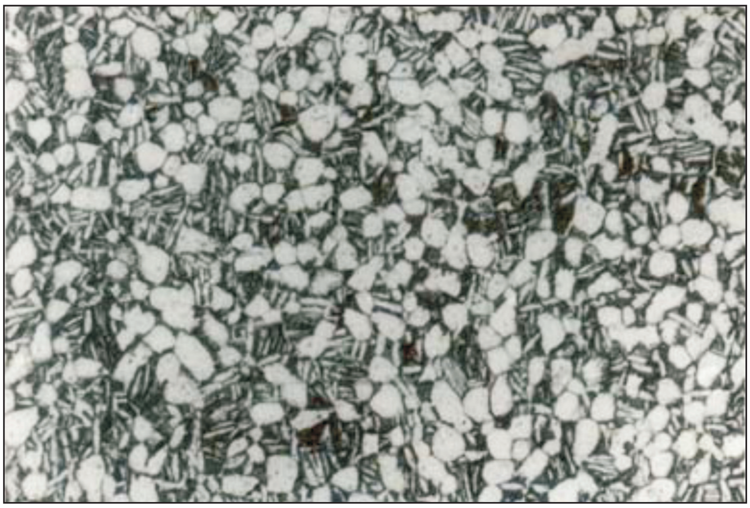

FIG. 4(b) MICROSTRUCTURE OBTAINED BY MODIFIED PROCESSING ROUTE WITH ANNEALING IN THE $\alpha + \beta$ PHASE FIELD AT 950°C

It was observed that the modified processing with the final annealing done at 700°C resulted in some improvement in the signal-to-noise ratio, the S/N ratio increasing to 0 to + 2dB. On the other hand the modified processing with the final annealing done at 950°C led to a dramatic improvement in the ultrasonic inspectability, with the S/N ratio reaching a level of 6 dB. It then became possible to inspect billets of 200 mm ϕ to a defect standard of 1.2 mm FBH and billets as large as 350 mm in ϕ could be inspected to 2.0 mm FBH standard. The microstructure and signal-to-noise ratios obtained after different methods of processing are summarized in Table 3.

Table 3. *Microstructure and signal-to-noise ratios obtained after different methods of processing*

Sl. No.	*Processing details*	*Microstructure*	*S/N ratio*
1	Original processing route	Recrystallisation not complete; colony structure persistent	– 2 to – 4 dB
2.	Modified processing route with final annealing done at 700°C	Recrystallisation not complete; colony structure prominently present.	0 to 2 dB
3	Modified processing route with final annealing done at 950°C	Recrystallised; bimodal type of microstructure	6 dB

The modified forging practice with final anneal at 950°C was also found to improve the macroquality of the billets. The macrostructure is relatively fine and largely uniform over the transverse section; it corresponds to Level 20 of ETTC3, signifying a much finer and uniform macrostructure.

The fine microstructure and absence of colony structure resulting from the modified processing with the final annealing treatment at 950°C (1223 K) is believed to be primarily responsible for the major improvement seen in the ultrasonic inspectability. The fine and uniform macrostructure seen after modified processing with 950°C (1223 K) final anneal is believed to be the result of a relatively fine microstructure evolving all over the cross section.

Summarising, the macro-quality, micro-quality and ultrasonic inspectability of Ti-6Al-4V billets could be greatly improved by appropriate modifications in processing schedule. The improved quality met all the stringent requirements stipulated by customers from aeronautics/aerospace.

4. PRODUCTION OF TITANIUM ALLOY DICS FOR AERO-ENGINE APPLICATIONS THROUGH ISOTHERMAL FORGING ROUTE [3, 4]

The deformation characteristics of all classes of titanium alloys are very sensitive to metal temperature during deformation processes such as forging. The forging pressure increases dramatically with relatively small changes in metal temperatures. For example, the forging pressure for the alloy Ti-8Al-1Mo-1V increases nearly three times as the metal temperature decreases by approximately 95°C. Therefore, it is important in forging titanium alloys to minimize metal temperature losses in the transfer of heated pieces from furnace to the forging equipment and to minimize contact with the much cooler dies during conventional forging processes.

Titanium alloys are highly strain rate sensitive in deformation processes such as forging - considerably more so than aluminum alloys or alloy steels. For example, as the deformation rate is reduced from 10/s to 0.001/s, the flow stress of representative alpha plus beta alloy Ti-6Al-4V gets reduced by up to ten times. The flow stress for Ti-6Al-4V at 900°C and 50% strain is 205 MPa at 10/s strain rate and 50 MPa at 0.001/s strain rate, a fourfold reduction. For the representative beta alloy Ti-10V-2Fe-3Al, as the deformation rate is reduced from 10/s to 0.001/s, the flow stress gets reduced by up to ten times.

In isothermal forging, the die and the work-piece are maintained at the same temperature throughout the forging cycle. This eliminates die chilling and leads to uniform deformation of the material at relatively low forging pressures. Further, forging is carried out at very low strain rates thereby reducing the load required to process strain rate sensitive materials such as titanium alloys. Near isothermal forging or hot die forging is a variation of isothermal forging where the dies are maintained at 100 to 200°C less than the work-piece temperature during forging. This process facilitates the use of low cost dies. While some amount of die chilling occurs, it is way better than the conventional forging.

MIDHANI developed the near alpha titanium alloy Ti6 Al5 Zr0.5 Mo0.25 Si in the form of forged and machined bars 160 mm in diameter. The alloy is used extensively as disc material in the high pressure compressor region of the Adour aeroengine. The alloy exhibits excellent thermal stability and creep properties upto 520°C. Table 4 shows the conformity of the material produced by MIDHANI with respect to various specification requirements.

Table 4. *Superior Properties obtained with Midhani–Manufactured 685 Alloy*

Attribute	*Specified*	*Obtained*
Creep Elongation 450MPa at 450°C for 100 Hours	0.1% Max	0.04 - 0.08
Macrostructure as per AMS 2380A	30	10 – 20
Microstructure (Grain Size)	< 3.0 mm	1.0-1.4 mm
Ultrasonic Testing as Per AMS2631 and AMS2380A	Class A1 (1.2 mmFBH)	Comfortably meets the Specification

Starting with the above billet material, discs were produced using near isothermal forging process. Material was thermo-mechanically processed to obtain fine equiaxed primary α in β matrix to render it amenable to Super Plastic Forming. After a ~1000°C soak in an electric furnace, billets were moved from the furnace to the heated dies. Die was maintained at 900-925°C using an induction heating facility. Forging was done on a 2000MT Capacity Hydraulic press. Die conforming to disc shape was made of nickel base superalloy ZhS6U. The strain rate imposed was $\sim 10^{-3}\ s^{-1}$. The parameters used for near isothermal forging of 434 mm outside diameter discs are shown in Table 5.

The discs were processed to near net shape in two stages and the Table shows the process parameters for each of these stages.

The discs produced met the required property levels, as shown in Table 6a and 6b.

FIG. 5 SHOWS A NEAR-ISOTHERMALLY FORGED DISC

Table 5. *Processing parameters for near-isothermal forging of discs*

Parameter	*Preforming*	*Disc forging*
Billet dimension (mm)	ϕ 180 × 345	ϕ 232 × 208
Billet temperature (°C)	950	1000
Die temperature (°C)	920	920
Ram speed (mm/sec)	0.2	0.2
Deformation (%)	40	Till 2 mm flash

Table 6a. *Tensile properties of isothermally forged discs*

Property		*Specification*	*Result obtained radial*	*Result obtained tangential*
Tensile (room temperature)	Proof strength (MPa)	≥ 850	922-967	971-987
	Ultimate tensile strength (MPa)	≥ 990	987-995	1017-1056
	Elongation %	≥ 6	7-13	8-13
	Reduction in area %	≥ 15	13-24	14-22
Tensile (520°C)	Proof strength (MPa)	≥ 480	486-550	497-555
	Ultimate tensile strength (MPa)	≥ 620	625-654	628-711
	Elongation %	≥ 9	9-14	11-17
	Reduction in area %	≥ 20	30-39	14-22
Notch tensile	N/P ratio	≥ 1.35	1.51-1.68	1.50-1.68

Table 6b. *Other mechanical properties of isothermally forged discs*

Property		*Specification*	*Result obtained radial*	*Result obtained tangential*
% Creep strain	450°C/450 MPa/100 hours	0.15 max	0.10-0.13	0.10-0.14
Post creep tensile	Proof strength (MPa)	≥ 850	971-1026	1009-1048
	Ultimate tensile strength (MPa)	≥ 990	995-1071	1026-1071
	% Elongation	≥ 6	6-9	7-9
	% Reduction in area	≥ 10	13-20	12-24
Low cycle fatigue	85 – 850 MPa Cycle 10-20-10-20 s	8000 cycles	8297-15001	8742-15522

All 5 stages of discs required for high pressure compressor of Adour engine were successfully manufactured out of near alpha titanium alloy. Subsequently, forging of discs out of triple melted Ti6Al4V alloy for the Kaveri Engine was successfully carried out.

5. FABRICATION OF TITANIUM ALLOY AIR BOTTLES FOR INDIAN MISSILE PROGRAMMES THROGUH THE SUPER PLASTIC FORMING (SPF) ROUTE

Titanium alloy air bottles for missile projects were in the past manufactured ELI grade of Ti6Al4V through a route comprising of hot forming of hemispheres and tungsten Inert gas (TIG) welding of two such hemispheres. An alternate manufacturing route comprising of Super Plastic Forming (SPF) of hemispheres and Electron Beam Welding (EBW) of two such hemispheres to form the bottle has now been developed. The bottles fabricated through (SPF+EBW) route cleared for flight trials.

In the superplastic forming technology, the exponent m which characterizes the intensity of flow stress dependence on flow rate has an important place [5]. If there is onset of necking during plastic deformation, the local strain rate increases since displacement per time unit imposed by the tensile test machine is concentrated on this neck. The ‘dynamic strain hardening’ characterised by the exponent ‘m’ then causes an increase in flow stress and thus stabilizes the potential necking area. Local necking is suppressed and the specimen is homogeneously strained further along its entire gauge length. This process is repeated multiple times until after several hundred percent straining a weak point finally leads to local necking and fracture of the specimen. A high degree of superplasticity, as manifested by high value of fracture strain, is favored at high ‘m’ values. Plastic deformation rates of >1000% can be achieved at high ‘m’ values [5]. The ‘m’ value is a function of the strain rate, showing a maximum in the strain rate range 10^{-3} to 10^{-4}/sec. The strain rate adopted for superplastic forming of Ti6Al4V ELI hemispheres has been in the range 1.3×10^{-4} to 10^{-3} s^{-1}. The temperature chosen for forming the hemispheres was typically 925°C. The dies are heated to the same temperature as the work piece. Due to the high temperatures and simultaneously relatively low flow stresses deformation by means of gas pressure has found widespread application. Because of high affinity of titanium to oxygen and hydrogen, inert gases are exclusively used as the pressure medium. The stresses applied were in the range of 2-20 MPa.

In order to realize good superplastic behavior, the grain size of the starting plate material was controlled through close control on the process parameters adopted during forging and rolling. The grain size was typically in the 5-15 μm range. The stability of the fine grained microstructure at the deformation temperature is of paramount importance to achieve a good SPF behavior. Fortunately because of the two phase $\alpha + \beta$ microstructure, the grain size remained fine throughout the forming process. Figure 6 shows a superplastically formed hemisphere made of ELI grade Ti6Al4V and a gas bottle which has been produced through electron beam welding of two such hemispheres.

FIG. 6 SUPERPLASTICALLY FORMED HEMISPHERE AND ELECTRON BEAM WELDED AIR BOTTLE MADE OF ELI GRADE Ti-6Al-4V

6. FABRICATION OF TITANIUM ALLOY AIR BOTTLES/DOMES FOR IINDIAN SPACE PROGRAMMES THROUGH FORGING/PLATE FORMING ROUTE [6]

Gas bottles for ASLV and initial PSLV flights of Indian Space flights were realized from closed die forging. Subsequently development of plate route for processing of hemispherical domes was taken up. Plate route gas bottles were successfully qualified for second stage of PSLV. This resulted in a cost saving of ₹ 8 lakhs per bottle. Presently these gas bottles are being mass produced for PSLV and GSLV programmes, leading to extensive savings in strategic material and manufacturing cost. Gas bottles with various nominal diameters – 200/400/600 mm were developed through plate forming route and qualified for Indian launch vehicles and satellites. One of the Indian spacecrafts uses large (1200 mm nominal diameter) spherical tank of Ti6Al4V alloy in STA condition for storing liquid propellant. Use of the alloy in STA condition reduces weight of the propellant tank, as the strength achieved for the alloy in STA condition is about 20% greater than in the annealed condition. VSSC developed the large (1200 mm diameter) hemispherical domes through plate forming technique., as the existing press/hammer capacity available in India was not sufficient to forge such large hemispherical domes. Figure 7(a) shows the STA hemispherical dome (1200 mm diameter) and Fig. 7(b) the spherical gas bottle (600 mm diameter). The 1200 mm diameter hemispherical domes in STA condition is the largest titanium alloy component developed in India. Other special components developed through plate forming route include seamless conical components of 850 mm larger diameter (Fig. 8). This component replaced the component realized in the past through petal forming and TIG welding.

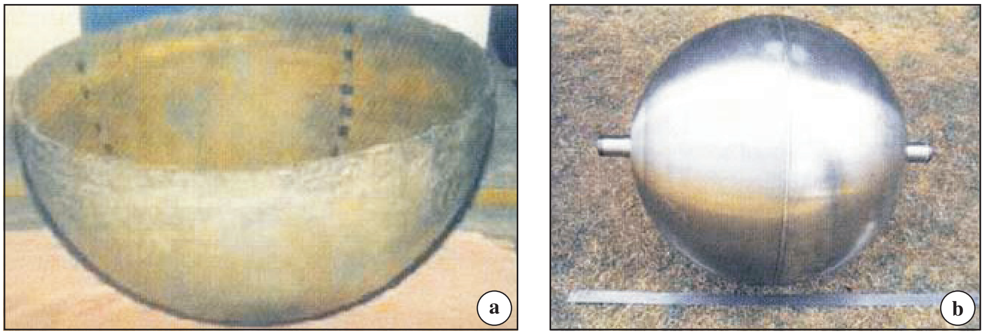

FIG. 7 (a) HEMISPHERICAL DOME IN STA CONDITION (1200 MM DIA).
(b) GAS BOTTLE DEVELOPED BY PLATE-ROUTE (600 MM DIA.)

FIG. 8 SEAMLESS CONICAL COMPONENT DEVELOPED THROUGH PLATE-FORMING ROUTE (850 MM MAX. DIA., 45 DEGREE CONE ANGLE)

Ti6Al4V, the workhorse titanium alloy, is used extensively for applications as gas bottles, propellant tanks and structural members in launch vehicles and spacecrafts. For sub-zero applications (up to 90 K), purer version of this grade called Ti6Al4V-ELI (Extra Low Interstitial), is used where oxygen level is controlled to retain sufficient toughness at cryogenic temperatures. For aerospace applications at cryogenic temperatures as low as 4 K, Ti5Al2.5Sn-ELI alpha type single phase alloy is more suited. For this alloy, ratio of tensile strength to yield strength at ambient and at cryogenic temperatures remains nearly the same. This characteristic along with excellent notch toughness makes the alloy attractive for cryogenic applications. Processing of hemispherical forgings of this alloy was developed through closed die forging route. Figure 9 shows the hemispherical forgings of this alloy for high pressure gas bottle application for liquid hydrogen environment and the corresponding single phase alpha microstructure.

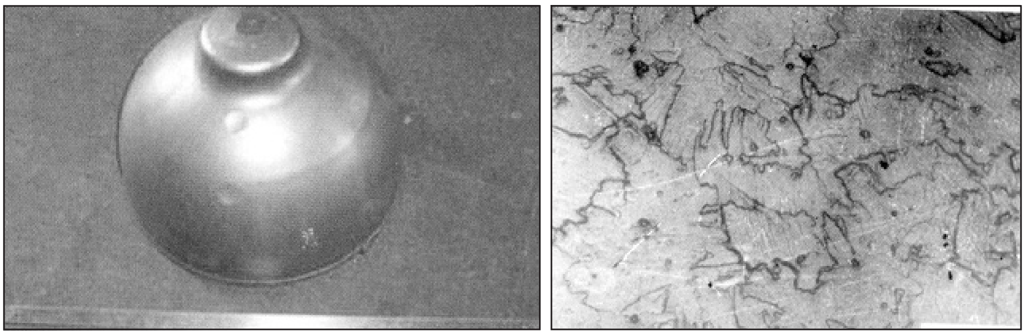

FIG. 9 Ti5Al2.5Sn ELI ALLOY HEMISPHERICAL FORGINGS FOR HIGH PRESSURE GAS BOTTLES FOR LIQUID HYDROGEN ENVIRONMENT WITH SINGLE PHASE α MICROSTRUCTURE

7. DEVELOPMENT OF ELECTRON BEAM WELDING TECHNOLOGY

In aircraft industry alloy grade Ti is used. Electron Beam Welding (EBW) is extensively employed. TIG welding is adopted only in a few cases. Much better joints can be obtained by EBW of alloy grade Ti. By welding in a vacuum chamber, gas absorption is prevented. The HAZ is very narrow and influence of welding on structure is minimal. Complicated work-pieces can be welded without distortion. Components with large wall thickness as well as thin walled components can also be successfully welded. As a natural corollary to this, EBW was the route chosen to weld the two hemispherical parts to build air/gas bottles and spherical propellant tanks. EBW technology was established both in ISRO and DRDO organizations for the fabrication of air/gas bottles, spherical propellant tanks. EBW technologies are being practiced by HAL units for the fabrication of compressor part of the aero-engine. Today facilities and technologies for EBW of titanium alloys are available in ISRO, laboratories of DRDO and aero-engine building units of HAL.

8. DEVELOPMENT OF SPECIFIC MATERIALS/PRODUCTS

8.1 Development of Ti-15V-3Cr-3Sn-3Al, a metastable beta alloy [6]

Ti-15V-3Cr-3Sn-3Al is a metastable beta alloy. It has a high strength and good weldability. The metastable beta phase is obtained on solution treatment and subsequently fine alpha phase precipitation takes place during aging, leading to very high strength. The beta phase is soft and hence the alloy is highly cold workable in solution treated condition. This characteristic of the alloy is used to realize the material in the form of thin sheets, strips and other shapes through cold forming in the solution treated condition. The alloy is used up to 300^{o}C for aerospace applications in the form of strip, sheet, ducting etc. The specific strength of this alloy is higher than corresponding values of other structural materials known for their high strength to weight ratio, including maraging steel, as brought out in Table 7.

Table 7. *Superior specific strength and fracture toughness of Ti15-3 alloy*

Property	*AA2219 Al alloy (T87)*	*Maraging steel (STA)*	*Ti-6Al-4V alloy (annealed)*	*Ti-15V-3Cr-3Sn-3Al (STA)*
YS, MPa	370	1750	880	1195
Tensile strength, MPa	440	1800	940	1315
Density, g/cc	2.82	8.0	4.5	4.8
Specific YS	13.4	22.3	19.9	25.4
Fracture toughness, MPa√m	36.23	110	57	110

ISRO has taken up the development of this alloy for application as separation system, which required strips of 3 × 30 × 6000 mm. Inherent property of excellent corrosion resistance has been an important consideration in selection of the alloy for the strip application, as the strips are stored near corrosive coastal environments.

There were different problems faced during the development of this alloy. Presence of high weight percent of alloying elements (24%) makes the alloy prone to segregation during melting. Further the beta alloy requires higher deformation loads during hot working. These problems were overcome by selection of high vanadium-containing master alloy with multiple vacuum arc melting and optimization of hot working/heat treatment schedules. The processing technology for 3 mm thick × 6000 mm long strips required for separation system had been successfully developed in association with MIDHANI.

8.2 Development of Half Alloy Tubes [6]

Chemical composition of the half alloy is Ti-3Al-2.5V. It is called so due to the presence of half the amount of alloying elements as compared to the work horse Ti-6Al-4V alloy. Lower amount of alloying elements makes it amenable to cold working. Accordingly it is feasible to realise tubes through a manufacturing route involving cold processing. The same is not possible with Ti-6Al-4V.

Upper stage of advanced Indian launch vehicles of the Indian Space programme required 118 mm OD × 1.6 mm wall thickness (WT) seamless tubes for use as truss members. Seamless tubes of such a large OD/WT were not available even through import. The processing technology for the tubes was developed through hot extrusion and cold pilgering route using the facilities at Nuclear Fuel Complex, Hyderabad. The pilgering is followed by stress relieving operation. Figure 10 shows the half alloy tubes so manufactured.

FIG. 10 COLD PILGERED HALF ALLOY SEAMLESS TUBE

8.3 Development of Ti Alloy Rings

Ti6Al4V rings of nominal outer diameter as large as 1400 mm could be successfully produced through ring rolling process, using the mill at HAL, Bangalore. The rings are required for various space programmes. Rings of the near alpha titanium alloy Ti6Al5Zr0.5Mo0.25Si have also been successfully rolled at HAL.

8.4 Development of Titanium Aluminides [7]

Extensive development work has been carried out at DMRL on Ti_3Al based and orthorhombic Ti_2AlNb based titanium aluminides. Table 8 lists the titanium aluminides developed by DMRL for application in aircraft turbine engines. The primary driving force is to replace the nickel-based alloys with a density of 8-8.5 gm/cc with lower density materials. Conventional technologies can be used for processing them. Compressor blades of Ti-24Al-15Nb could be successfully processed at HAL for the Indian aero-engine development program using the conventional closed die forging route. However, there are some serious issues which have come in the way of their being used as aero-engine materials. They exhibit poor resistance to fatigue crack growth. They have low fracture toughness. Under the circumstances, designers have clearly shown preference to use of nickel-base alloys or titanium alloys developed for very high temperature application like 834.

Table 8. *Titanium aluminides developed at DMRL*

Sl. No.	*Nominal chemical composition*
1	Ti-24Al-15Nb
2	Ti-27Al-16Nb
3	Ti-27Al-14Nb-1 Mo
4	Ti-24Al-20Nb
5	Ti-25Al-27Nb

8.5 Development of Precision Forgings

HAL has established technology to produce up to 250 mm long and 100 mm wide precision forged blades out of Ti alloys with tolerance of +0.3-0.0 mm and surface finish of < 1 μ weighing upto 1.2 kg. HAL has capabilities to produce upto 250 mm long 100 mm wide and 60 mm thick non-blade precision forgings out of Ti alloys with surface finish of 6-8μ weighing up to 2.5 kg. HAL's F&F plant has produced complex airfoil forgings for compressor blades and vanes in Ti64 and GTM900 alloys for the Kaveri Engine program. Similarly HAL, Koraput has technologies to produce blades of Russian titanium alloys such as VT-9 for the MiG engines through precision forging route.

Acknowledgement

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INDIGENOUS DEVELOPMENT AND PRODUCTION OF LARGE CROSS-SECTIONED NiCrMoV STEELS FOR CRITICAL APPLICATIONS

M. NAGESWARA RAO[1]

1. INTRODUCTION

Nickel-chromium-molybdenum-vanadium based low alloy steels are employed extensively all over the world for manufacture of large cross-sectioned forgings, e.g., long shafts sometimes with a number of steps over the length. The forgings find applications in power generation sector, defence and other critical areas where high strength, high hardness and good toughness constitute important requirements. Different variants of the NiCrMoV based low alloy steels have been produced in the country and there have been some important developments over the last three decades or so in their processing. Major improvements have been made with reference to quality and reliability of end product. The paper describes the development work carried out, the various failures encountered during development, the failure analyses carried out and the technological solutions adopted to prevent those failures. Much of the discussion centers on the steels produced in the form of long stepped shaft forgings.

2. CHEMICAL COMPOSITION OF NiCrMoV STEELS

Details of the chemical composition specified for important grades of NiCrMoV steel produced in the country for manufacture of large cross-sectioned products are given in Table 1. It can be seen that P and S are to be present at very low level. Refining by Electroslag Remelting (ESR) or Vacuum Arc Remelting (VAR) has been adopted to produce the steel with improved cleanliness, soundness of the ingot, better chemical homogeneity over the ingot volume, improved forgeability and higher manufacturing yields. If the steel is processed through ESR, much lower S levels are obtained than the maximum indicated in the Table. Steel grade at serial number 1 is an earlier variant and grades at serial numbers 2 to 4 manifest improvements made over the years in terms of attaining better strength-toughness combination.

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Table 1. *Chemical analysis of different NiCrMoV steels*

Sl. No.	C	Mn	Si	Cr	Ni	Mo	V	Al	S	P
1	0.25-0.40	0.25-0.40	0.25-0.40	0.5-1.0	2.7-3.3	0.40-0.70	0.25 max	–	0.015 max	0.015 max.
2	0.25-0.45	0.20-0.70	0.10-0.35	0.7-1.2	2.7-3.3	0.40-0.70	0.25 max	–	0.015 max	0.015 max
3	0.33-0.40	0.25-0.50	0.17-0.37	1.2-1.7	3.0-3.5	0.35-0.45	0.10-0.20	–	0.012 max	0.012 max
4	0.33-0.38	0.30-0.50	0.10-0.25	1.2-1.5	2.8-3.1	0.40-0.50		0.013-0.025	0.008 max	0.01 max

3. SPECIFIED MECHANICAL PROPERTIES OF NiCrMoV STEELS

Table 2 gives the mechanical properties specified for steels listed in Table 1. It can be seen that steels at serial numbers 2 to 4 have better strength-toughness combination than steel at serial number 1. Specification for steel 4 calls for guaranteed fracture toughness.

Table 2. *Mechanical properties specified for the NiCrMoV low alloy steels listed in Table 1*

Sl No	LOP (min) MPa	0.2% PS MPa	UTS (min)	% Elongation (min)	% Reduction in Area (min)	Impact toughness (min) J/sq.cm	Fracture Toughness MPa√m (min)
1		850 (min)	1020	10	26	23.5	
2		950 (min)		10	35	34.3 at 233 K	
3	1177				20	24.5 at room temperature 19.6 at 223 K	
4		950-980			35	41.2 at 233 K	
		980-1050			30	34.3 at 233 K	130

4. FORGING PRACTICE ORIGINALLY FOLLOWED

The stepped shaft forgings most often produced were approximately 7 meters in length; they are stepped and the largest and smallest diameters were about 340 and 300 mm respectively. The production of shafts starting with the 600 mm ϕ ESR ingot involved a reduction of ~50% by hot forging. One ingot yielded one stepped forging. Even a single crack occurring anywhere along the length of the shaft would result in rejection of the entire shaft. In Phase 1, for fear of rejections occurring due to such cracking, the forge master chose to shape the material under conditions of high plasticity, *viz.,* relatively high forging temperatures and limited amount of reduction in a given heat. The forging was completed in 4 heats, the typical reduction in each of the first three heats working out to ~15%. To start with, the ESR ingot was heated to 1200°C, soaked for temperature to become uniform over the cross section, and forging taken up. The reheating temperatures were also relatively high, even though progressively decreasing temperatures were adopted for reheating through successive heats. Figure 1(a) gives hereinafter called as Phase 1. Figure 1(b) gives the schematic of the forging schedule adopted during Phase 1.

Soak the 600 mm ϕ ESR ingot at 1200°C
↓
Hot forging to effect 15% reduction in area
Stock temperature after reduction ~1050°C
↓
Reheat at 1200°C
↓
Hot forging to effect 15% reduction in area
Stock temperature after reduction ~105°C
↓
Reheat at 1150°C
↓
Hot forging to effect 15% reduction in area
Stock temperature after reduction 1000-1050°C
↓
Reheat at 1100°C
↓
Finish forging involving 5% reduction in area
Stock temperature at the end of forging ~950°C

FIG. 1(a) HOT FORGING SCHEDULE FOLLOWED IN PHASE 1

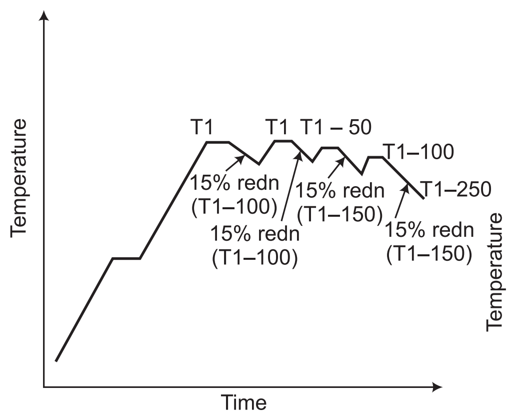


FIG. 1(b) SCHEMATIC OF HOT FORGING SCHEDULE FOLLOWED IN THE BEGINNING (PHASE 1)

5. HEAT TREATMENT AND EVALUATION OF MECHANICAL PROPERTIES – SPECIFIED LOP NOT REALISED

The forgings were taken up for heat treatment, consisting of normalizing, hardening (austenitizing followed by quenching) and tempering in two stages. The limit of proportionality (LOP) is specified for the steel forgings in question as a measure of strength. Evaluation of mechanical properties, importantly the LOP, was carried out on test material drawn from both ends of the forging. Cylindrical tensile test specimens were prepared from test pieces cut out with their axes lying in the transverse section of the forging and oriented in the tangential direction at mid radius location. Failures were encountered in realizing the specified strength levels. An LOP of 1177 MPa is the minimum specified as shown in Table 2. The governing specification allowed a relaxation of 30 MPa, with the result that LOP values higher than 1147 MPa are still considered acceptable. However values lower than even 1147 MPa were often encountered. Values as low as 1080 MPa were obtained.

6. REPEAT HEAT TREATMENT

In view of the low LOP values obtained, repeat heat treatments were carried out in several instances to improve the LOP value. When the second heat treatment also did not yield the desired LOP level, a third heat treatment was carried out. There was generally some improvement in LOP value after repeat heat treatment, but there were instances where the specified value of LOP could not be attained even after third heat treatment, resulting in rejection of forging. This is because the governing specification allowed a maximum of three heat treatments. In view of the failures encountered in Phase 1, a number of shaft forgings had to be rejected.

7. LOW TEMPERING TEMPERATURES ADOPTED TO REALISE THE SPECIFIED LOP

The recommended tempering temperature, as per the governing Standard was 520-580°C. In view of the low LOP values being obtained, relatively low temperatures (400-450°C) were adopted with the objective of meeting the specified LOP value. The inspiration for this decision came from the known relationship between the strength and the tempering temperature for the NiCrMoV low alloy steels [1]. As there was incidence of LOP values <117kg/sq.mm even after adopting a relatively low tempering temperature (400-450°C), tempering at even lower temperatures (350-400°C) was then resorted to. Production and supply of the shafts to the user agency tempered at relatively low tempering temperatures continued for some time.

8. PROBLEM OF BURSTING OF FORGED AND HEAT TREATED SHAFTS – FAILURE ANALYSIS

Serious problems of bursting of the shafts during service were soon reported. Over a dozen shafts burst into fragments during proof testing. A few shafts failed early in service (in the first quarter of their rated life). Consequently about 400 shafts manufactured in this manner and supplied to user agency were withdrawn from the field. The activity of manufacture and usage came to a standstill.

Failure Analysis was then taken up by competent agencies.

8.1 Findings of Failure Analysis

Many burst shafts were investigated. Optical Microscopy and SEM were extensively used in addition to checking of chemistry and mechanical properties. Their main findings were (i) Fracture surfaces showed a brittle mode of material separation. Fracture occurred by intercrystalline or quasi cleavage mode. (ii) Material was found to have poor resistance to propagation of cracks. (iii) In one shaft tin was present at a high level and promoted temper embrittlement. (iv) In another shaft, evidence was found for inclusion-facilitated brittle fracture. (v) Extensive banding was seen in the microstructure. Maropoulos et al [2] have also observed dark and light bands in forgings of NiCrMoV low alloy steels in hardened and tempered condition. Reference [3] elaborates on some of these findings.

8.2 Tempered Martensite Embrittlement (TME)

Many shafts were heat treated with tempering carried out in the range 350-400°C, trying to realize LOP values ≥1147 MPa. However, it was subsequently realized that this approach is beset with serious problems on the toughness front. In NiCrMo type low alloy steels, Tempered Martensite Embrittlement (TME) sets in when tempering is carried out in the temperature range 250-400°C [4]. As such, tempering in the temperature range 350-400°C is expected to result in a metallurgical condition with relatively low toughness levels. In forgings tempered in this range, one has to reckon with a brittle state with low resistance to crack propagation.

8.3 Summary Findings of Failure Analyses

Based on failure analyses carried out and an analysis of the published information on similar steels as brought out in Section 8.2, a broad consensus was reached on reasons for failure:

- Steel was tempered at too low a temperature
- 350-400°C range is not recommended as resulting toughness is expected to be poor; a toughness trough is reported in the literature for this type of steel when tempered in this temperature range
- Brittle fracture was a result of poor toughness state of steel.

9. MODIFIED FORGING SCHEDULE TO IMPROVE THE LOP

In view of the failure encountered in attaining the specified LOP level, in subsequent campaigns hereinafter called Phase 2, major changes were brought into the hot forging practices to produce the shafts. The entire reduction of ~ 50% was given in one heat, in typically three passes; reheating in the furnace during forging was avoided. Figure 2(a) gives the process steps involved in the modified forging process followed in Phase 2. Figure 2(b) shows the schematic of the modified forging schedule followed in phase 2. With the changed forged practice, there was no more the problem of realizing the specified LOP value in the heat treated condition. In fact, acceptable LOP value could be obtained in all cases after the very first heat treatment. It is to be emphasized that the heat treatment given to forged shafts produced in Phase 2 was identical to the one given to shafts produced in Phase 1. With the modified forging schedule, there was also an improvement in the impact toughness values. The mechanical properties obtained in the two phases are compared in Table 3.

Soak the 600 mm ϕ ESR ingot at 1200°C

↓

Hot forging to effect 25% reduction in first pass
Stock temperature at the end of first pass 1050-1100°C

↓

Hot forging to effect 20% reduction in second pass
Stock temperature at the end of second pass ~1000°C

↓

Hot forging to effect 5% reduction in finishing pass
Stock temperature at the end of third pass ~900°C

FIG. 2(a) MODIFIED FORGING SCHEDULE (PHASE 2)

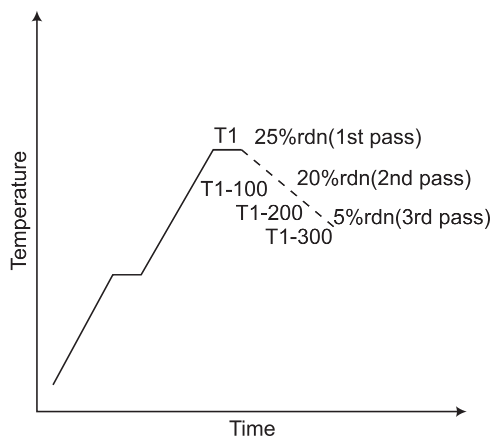


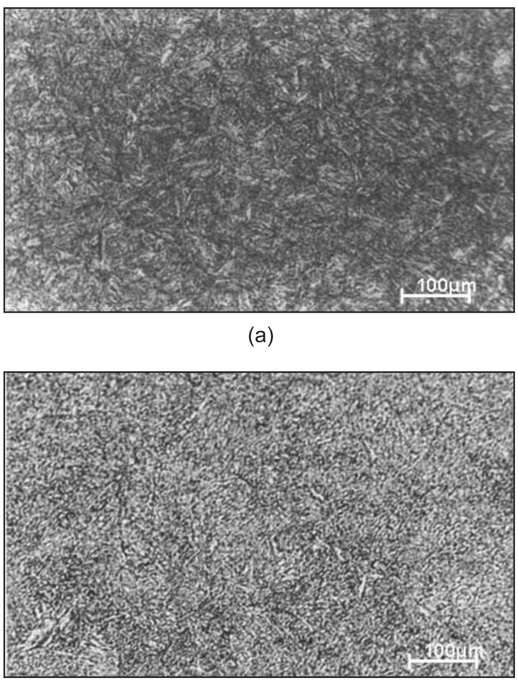
FIG. 2(b) SCHEMATIC OF HOT FORGING SCHEDULE FOLLOWED AFTER INCORPORATING MAJOR CHANGES

Table 3. *LOP and impact toughness of shaft forgings (after heat treatment) as a function of forging schedule*

Sl. No.	*Forging schedule*	*LOP (MPa)*	*Charpy Impact (J/sq.cm.) RT-40C*		*Remarks*
1	Phase 1 – Forging of shaft in 3 to 4 heats	1080-1140	23-32	19-27	Repeat heat treatment resulted in some improvement in LOP value
2	Phase 2 - Forging carried out in single heat (modified practice)	1180-1230	35-45	30-40	Acceptable LOP obtained after the very first heat treatment

9.1 MICROSTRUCTURAL CHANGES BY SWITCHING OVER TO MODIFIED FORGING PRACTICE

Switching over from Phase 1 to Phase 2 resulted in refinement of the martensite sub-structure. Figure 3(a) is a representative microstructure of the shafts from Phase 1 in the forged and heat treated condition. Figure 3(b) is corresponding microstructure from Phase 2. While no systematic prior austenitic grain (PAG) size measurements were carried out, the data available from a few melts in the forged and heat treated condition indicate that a grain size finer by about three counts on ASTM scale resulted in the forgings by moving over from Phase 1 to Phase 2.



(b)

FIG. 3 MICROSTRUCTURE OF SHAFT FORGINGS AFTER HEAT TREATMENT (a) ORIGINAL FORGING SCHEDULE (b) MODIFIED FORGING SCHEDULE

9.2 Explanation for the Finer Grain Size Obtained with Modified Forging Schedule

In Phase 1 some reheating steps formed part of the forging schedule. The reheating temperatures were also relatively high, even though decreasing reheating temperatures were used for successive heats during forging. Since % deformation in any heat was small, there was no scope for dynamic or metadynamic recrystallisation [5]. Static recrystallisation was taking place; in view of the relatively high temperatures used for reheating and smallness of strain, recrystallised grain size would be relatively large. Vanadium carbides in this family of steels have been shown to strongly retard the movement of grain boundaries and thus restrict the grain growth [6, 7]. Since these carbides completely go into solution on reheating to a temperature of ~1020°C [8, 9], considerable amount of grain growth is expected when reheating temperatures higher than 1020°C are used. For example, when the first reheating is done at 1200°C, a temperature much higher than 1020°C, considerable amount of grain growth is expected. Since the starting grain size before the second stage of deformation is large, the grain size after static recrystallisation during second reheating would also be large as has been demonstrated for 304 type austenitic stainless steel by Towle and Gladman [10]; added to this, the relatively high second reheat temperature (1150°C) would cause significant grain growth. Similar considerations apply to the remaining part of the forging schedule. Net result is that the final grain size at the end of forging would be quite coarse. The grain size after the ensuing heat treatment is expected to be correspondingly coarse.

Even with the modified schedule adopted in Phase 2, no dynamic or metadynamic recrystallisation is expected, because of the small amount of reduction in any given pass. But with the relatively low temperatures prevailing, one has a situation where higher strain is being given at relatively low temperatures resulting in a relatively smaller grain size after static recrystallisation. The scope for grain growth after recrystallisation is much less in this schedule, as reheating at temperatures > 1020°C does not figure in this schedule. The overall result is a microstructure with a relatively fine grain size after the ensuing heat treatment.

The observed decrease in PAG by moving over from Phase 1 to Phase 2 can be explained based on the analysis given in the preceding two paragraphs. This decrease in PAG/refinement in martensite substructure in Phase 2 is believed to have contributed importantly to the improved strength and toughness levels obtained in this phase, as elaborated in the following sections.

9.3 Hall-Petch Type Relationship in NiCrMoV Steels

A Hall-Petch type relationship has been reported [11] for the NiCrMo steel AISI 4340 between 0.2% yield strength and prior austenitic grain size. As per this report, a refinement of grain size of 4 on ASTM scale would mean an improvement of ~60 MPa in yield strength. However, the slope of the straight line would depend on tempering temperature. An increased tempering temperature may bring down the slope, as demonstrated for Fe-0.2%C steel [12]. Further the NiCrMoV low alloy steel under discussion has higher levels of Ni, Cr and Mo. While the relationship for the steel in hand and for the tempering temperature of ~400C is not available, it appears reasonable to account for the observed improvement in LOP based on observed refinement of microstructure resulting out of changed hot working practice.

9.4 Boundary Strengthening in Heat Treated NiCrMoV low alloy Steels

The role of boundary strengthening in steels with a tempered martensitic structure has been studied by the previous workers. In low and medium carbon steel, the martensite laths are arranged in packets whose size is directly related to austenitic grain size [13]. There is much discussion in the literature about the role of packet boundaries and the interlath boundaries in causing strengthening. Maropoulos and Ridley [14] carried out studies on strength of steel forgings of steels, whose composition is very similar to the steel under discussion. They analyzed the results obtained based on the premise that both packet and interlath boundaries cause strengthening. The contribution from lath boundaries, as per their analysis, seems to be important and in fact much higher than that from packet boundaries. It has been suggested by other workers also that both types of boundaries contribute to strengthening [14].

9.5 Dislocation Strengthening

Dislocation strengthening is another contributing factor to the limit of proportionality. Several studies showed [14] that dislocation density and therefore the strengthening resulting from dislocation interactions changes considerably during tempering. Identical tempering treatments were adopted for forgings produced in Phase 1 and Phase 2. However some difference in the dislocation density could have been inherited due to the difference in thermo-mechanical processing history, i.e., difference in the forging schedule adopted. Study of this aspect was not part of the scope of the present study.

9.6 Particle Strengthening

Difference in the size, distribution and volume fraction of cementite and vanadium carbide particles arising out of the differences in prior processing history might also have contributed to the observed difference in strength. This aspect has to be studied further.

10. SECONDARY HARDENING IN NICRMOV LOW ALLOY STEEL

Figure 4 shows the relative tempering behavior of martensite in Fe-0.36% C and Fe-0.36% C-3.3 Ni-1.4 Cr-0.4 Mo-0.15V steel. The curves have been synthesized from the data published by Grange et al. [15] bringing out the tempering behavior of plain carbon martensites and how individual alloying elements influence the tempering behavior. The martensite present in alloy steel gets softened at a much lower rate with increasing tempering temperature. In fact governing specifications for the steel Fe-0.36% C-3.3 Ni-1.4 Cr-0.4 Mo-0.15 V stipulate tempering temperatures in the range 520-580 C and the relatively high LOP (≥1147MPa) with improved forging schedule and tempering at these relatively high tempering temperatures is associated with the secondary hardening role played by Mo and V.

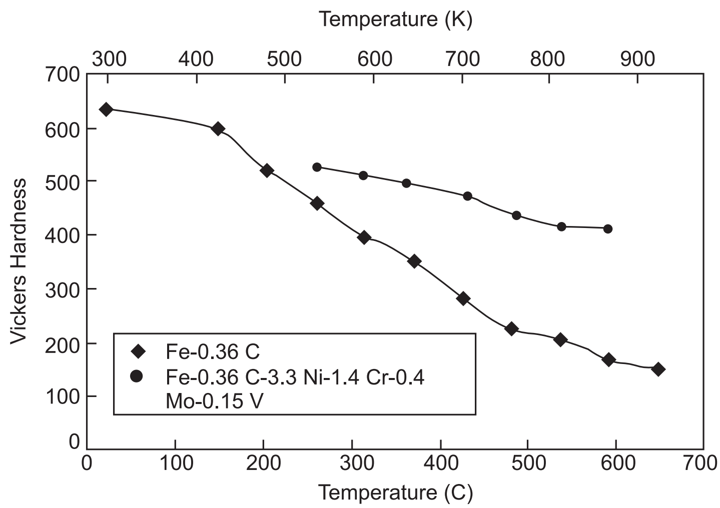


FIG. 4 RELATIVE TEMPERING BEHAVIOR OF A PLAIN CARBON STEEL AND A NICRMOV LOW ALLOY STEEL, BOTH HAVING THE SAME CARBON LEVEL

11. HOW TOUGHNESS IMPROVES WITH MODIFIED FORGING SCHEDULE

One may also attempt an understanding of how the modified forging schedule leads to improved impact toughness. According to Maropoulos et al [14], the transition temperature of low alloy NiCrMoV steels can be described by the relationship 50% FATT (C) = $-31 + 0.16(\sigma_d + \sigma_p) -9.5\ d^{-0.5}$.

Where

σ_d = dislocation component of the yield strength

σ_p = precipitation component of the yield strength

d = cleavage size.

With modified forging schedule, d values came down and accordingly 50% FATT (C) comes down. This could lead to improved impact values.

12. TEMPER EMBRITTLEMENT IN NiCrMoV STEELS

Another concern with the NiCrMoV type low alloy steels when manufactured as relatively large cross sectioned products is the temper embrittlement (TE). It occurs after tempering or cooling through the temperature range 375-575°C. TE manifests as intercrystalline fracture. Impurity elements (P, As, Sb and P) during such treatment can segregate to grain boundaries and weaken them resulting in preferential fracture along grain boundaries. Even though steel under discussion has been produced aiming at very low trace element levels, it is possible that some of the heats produced with scrap from sources other than integrated steel plants had somewhat higher levels of trace elements. In fact, one of the failed shafts investigated had 'Sn' level as high as 200 ppm.

Further the levels of trace elements were not monitored in the initial production phase by way of systematic chemical analysis. There is a possibility that there were a few heats with somewhat high level of trace elements and which have dwelt in the temperature range 375-450°C, during tempering. Tendency for intercrystalline fracture seen in the failure analysis carried out can thus be explained.

13. FRECKLES IN STEPPED SHAFT STEEL FORGINGS

Macro examination of opposite faces of transverse slices cut from different locations from bottom part of the forging revealed that the defects are channel-like with the channels inclined at an angle to the longitudinal axis of the ingot. Figure 5 illustrates the situation schematically. A and B are two transverse slices cut for macro examination, A towards bottom end of the forging and B further away from the bottom end. Both faces of slice A (A1A2 and A3A4) are macro-etched and locations of spots on the two faces were often such that they are points of intersection of a channel (running through the thickness of the slice at an angle to the longitudinal axis of the forging) with the two faces. Similarly faces B1B2 and B3B4 of slice B are macro-etched and a similar relationship was noticed between locations of dark etching spots on the two faces.

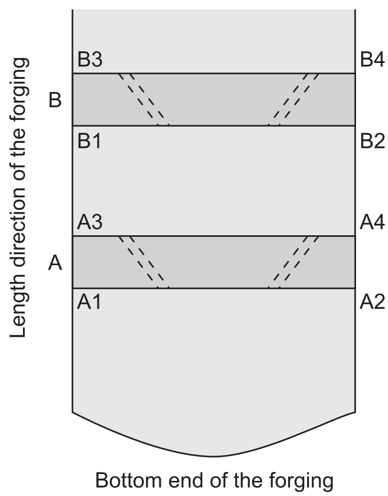


FIG. 5 SCHEMATIC OF FRECKLE-LIKE DEFECTS IN ESR QUALITY FORGINGS

14. EPILOGUE

India has come a long way with reference to establishing the technologies for manufacture of large cross-sectioned NiCrMoV steel forgings. Today melting and remelting/refining facilities are available in the country to routinely produce these steels with very low levels of deleterious trace elements and gas levels. Further hot working facilities, such as long forging machine, have been installed which enable optimal thermo-mechanical processing so as to give rise to well-conditioned microstructure responding excellently to the ensuing heat treatment. Production of stepped shafts well conforming to specifications has become order of the day.

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FINFREE SCARFING AT LD2 & SC

SHANTANU CHAKRABARTI[1]

1. INTRODUCTION

Scarfing is a mechanical operation carried out on steel slabs with the help of a high power flame, in order to take care of the surface defects in hot rolled and cold rolled coils, originating from the slabs. The objective is to produce cleaner steels for demanding applications such as automobiles. However, scarfing tends to leave the surface with metallic fins and flashes, which need to be removed to ensure quality product thereafter. Formation of the fins on scarfed surface depends on the nature of the liquid that is formed when the flame hits the slab and localised melting takes place (started by dosing iron powder).

Below Fig. 1 shows liquid metal flowing down the slab, placed at an angle to the horizontal. Part of the liquid is blown away by the 'forward drive' of the scarfing torch. while the remaining liquid on the slab finally solidifies into fins and flashes.

FIG. 1 SCARFING NOZZLE IN OPERATION: MOLTEN METAL FLYING OFF

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2. THE IRON-OXYGEN PHASE DIAGRAM AND FUNDAMENTALS OF SCARFING

The Fe-O phase diagram is important with regard to scarfing. If scarfing is carried out in an ‘oxygen-deficient’ condition, the liquid is rich in iron with a small amount of oxygen in solution, such as point A in Fig. 2. On increasing the supply of oxygen in the scarfing zone, the nature of liquid changes. The composition then falls in a region of two immiscible liquids—liquid iron with dissolved oxygen and liquid iron oxide as in point B. On further increase of oxygen in the scarfing zone, only liquid iron oxide is formed, as indicated by point C.

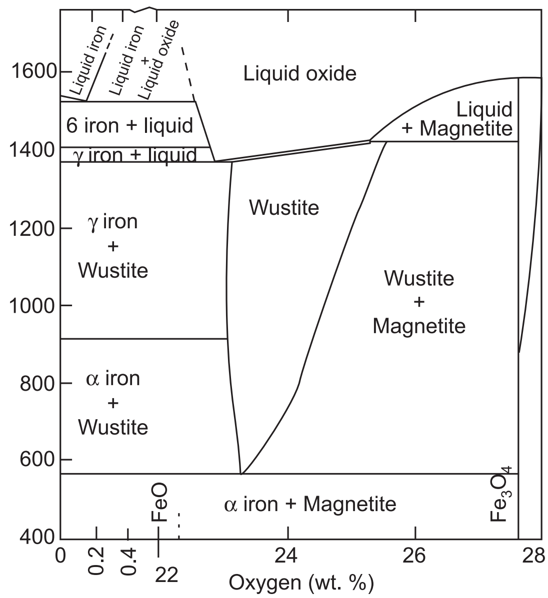

FIG. 2 IRON-OXYGEN PHASE DIAGRAM

The liquid solidifies into delta-iron and **wustite;** on cooling down to the ambient temperature, the product is alpha-iron and **magnetite** in all cases, as seen in the figure. The conversion of wustite to magnetite takes some time and any sample is likely to have presence of unconverted wustite. The content of metallic iron is high when it starts around point A, the low oxygen case. As the scarfing process moves to point B and then to point C, iron content reduces. Metallic iron percentage can be precisely calculated using the ‘lever rule’. The less the content of metallic iron in the solidified mass, the more brittle/‘self-separating’ is the scale.

3. BACKGROUND

The automatic slab scarfer with Oxy-propane flame cutting facility [Fig. 3] was commissioned in the slab-scarfing yard of LD2 & Slab Scarfer in Tata Steel, in January 2004. Problems of hard metallic and sticky scales on the scarfed surface became recurrent in the first Six months. This

FIG. 3 SCARFING OF SLABS BY AUTOMATIC SCARFER

required heavy grinding giving rise to surface defects during subsequent rolling. It became a severe bottleneck for the IF & EDD grade of steel, meant for autosector.

3.1 Theoretical Understanding of the Problem

The quality of the scarfing vis-a-vis the fins generated depends on several factors. The most important of them lies in the interaction of the fuel (propane in this case) with oxygen, which is supplied in stages dictating the geometry of the flame and its intensity The first stage oxygen, that comes through the first set of concentric holes around the central gas nozzle of the oxy-propane burner supplies the basic need of the flame to form and just sustains it. The second stage oxygen, coming through the second set of concentric holes, gives the flame its shape and intensity to scarf. The third stage oxygen, coming through the last set of concentric holes near the outer periphery of the burner, which was kept unused for long, gives extra oxygen to stabilise the flame, to enable the molten scales to oxidise and get dislodged from the surface of the slab.

The other factors affecting the quality of scarfing include the angle between the nozzle and the slab: a lower angle gives more momentum to the molten scale and pushes them forward to fall off. Distance between the nozzle tip and the slab also has a bearing, as too-short or too-long a distance makes cutting control difficult. The angle of inclination of the slab on the car also affects the removal of fins, as a steeper angle increases the gravity force on the molten scales, which fall down easily. Scarfing speed in addition controls the depth of scarfing.

3.2 Observations and Experimentation at Site

With the oxygen pressure set at values prescribed by the manufacturer, **(6.5/2.8/5.0 bar** in three stages respectively) as well as the changed set (6.5/2.8/0), the fins that were generated were

FIG. 4 A STICKY SCALES ON SCARFED SLABS

found to be hard and difficult to remove Some trials with a newer set of values (5.0 /0.7/ 1.6) as later suggested by the manufacturer, were later taken without any improvement. (**Fig. 4**). The high oxygen pressure in the 2nd and 3rd zone, as originally recommended, failed to achieve the desired results, as the residence time for reaction was inadequate. Hence, modifying them to lower compatible values yielded the desired results.

3.3 Characteristics of Fin/Scale

Fins consist of metallic Fe & FeO_x. Fins containing over around 70% metallic iron require extensive rework on the slabs. Brittleness of fins varies directly with FeO_x%. See (**Fig. 5**).

4. REMEDIAL JOURNEY

Taking cue from the fact that the scales need extra oxygen to get oxidised to become self-separating from the slab, we changed the settings of the nozzle to **6.0/5.0/1.5 bar,** opening up the third stage of peripheral supply of oxygen. The nozzle-angle was changed, by tilting the nozzle more towards the slab. The slab inclination angle on the left hand car was also increased from 63° to 75°, as in the right hand car.

These changes (oxygen pressure sequencing, nozzle angle change and slab-tilt) along with a marginally slower speed (10 m/minute from 12 m/m) produced encouraging results, in changing

FIG. 4B DIFFICULT REMOVAL OF STICKY SCALES FROM SLAB SURFACE

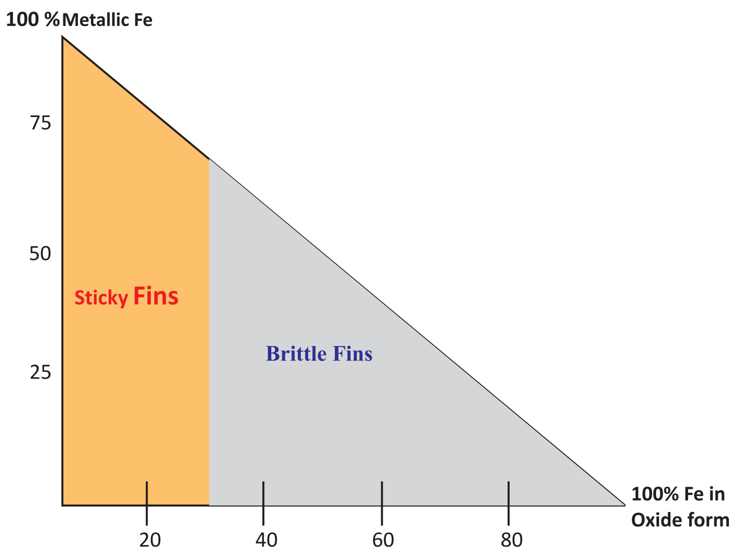

FIG. 5 PERCENTAGE OF METALLIC FE & FE IN OXIDE FORM AFFECTING FIN QUALITY

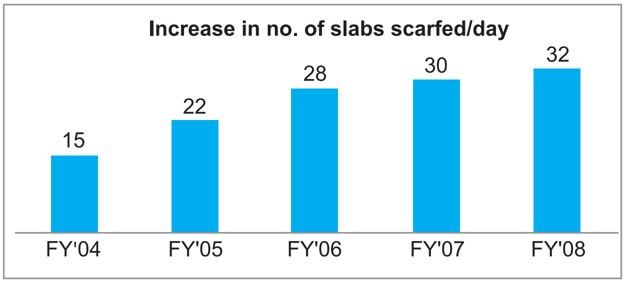

FIG. 6 INCREASE IN NUMBER OF SCARFED SLABS PER DAY OVER THE YEARS

the quality of the scales generated. It was immediately noticed that the fins produced were shorter (less than 15 mm high compared to 40 mm & higher earlier) and most of them were breaking off on their own. Thus the job of manual scale removal became simpler reducing the subsequent grinding operation in the yard. All these resulted in the number of machine scarfing of IF + EDD slabs increasing from 15 to 32 per day. **Figure 6** depicts the improvement; in recent years the need for scarfed slabs has come down to a maximum of 25 slabs/day.

4.1 Evidence

Fins are produced after scarfing which are brittle and hence get dislodged from the slab on their own. Such pieces were collected from the slab yard and blended into a representative sample. Similarly, a sample from a firmly sticking fin was collected from a slab. These were analysed for metallic iron and FeO. The results tabulated below **(Table 1)** are commensurate with the concept.

Table 1

		Fe	*FeO*	*Other Oxides*
Case1	Brittle and self-separating fins	2.1	31.7	Rest
Case2.	Fin firmly sticking to slab	92.3	6.7	-Do-
Case3.	Typical scarfing ‘slag’ *(Data from the machine manual)*	44	33	-Do-

The Case-1 and Case-2 are extreme situations; if the machine produces fins containing over 60% metallic iron, the slabs require extensive reworking/grinding. It is likely that typical operation of this kind of scarfing machines generates fins/flashes with less than 50% metallic Fe as seen in the 3rd row of **Table 2**. The fins from some of the scarfed slabs with varied pressure settings of oxygen were analysed to find out the proportions of metallic iron and iron in oxide form; results show scales produced with the revised arrangements have a remarkably higher amount of oxides over metallic Fe. This substantiated the brittleness of the fins and their propensity to separate out easily.

Table 2. *Composition Of Scales Collected From Scarfed Slabs*

Sample	*%Metallic Fe*	*%Fe as Oxide*	*Nature of Scale*
S1	62	38	Hard
S2	94	6	Hard and sticky
RECOMMENDED	42	58	Moderately brittle
B1	32	68	Moderately brittle
B2	**16**	**84**	**Brittle**
B3	**10**	**90**	**Very Brittle**
B4	**14**	**86**	**Brittle**
B5	36	64	Brittle with some hard pieces
B6	5	95	Powdery
B7	12	88	Very brittle

4.2 Recommendations

The scarfing zone and specially the liquid that flows down the slab must receive more oxygen so as to produce oxide-rich liquid, ultimately producing brittle and self-separable fins. Even if such oxide mass temporarily sticks to the slab surface, they do not pose quality hazards. These are loosened in the reheating furnace and are washed away during high pressure de-scaling during hot rolling.

Reports from the Coil Dividing Line (CDL) on the scarfed slabs also show that the number of slivers and blisters came very much under control. See **Fig. 7** and **Fig. 8**. However, the data set is not large enough to conclude a better performance, but surely shows, that the purpose of scarfing is fulfilled.

FIG. 7A IMPROVED SCARFED SURFACE (1)

FIG. 7B IMPROVED SCARFED SURFACE (2)

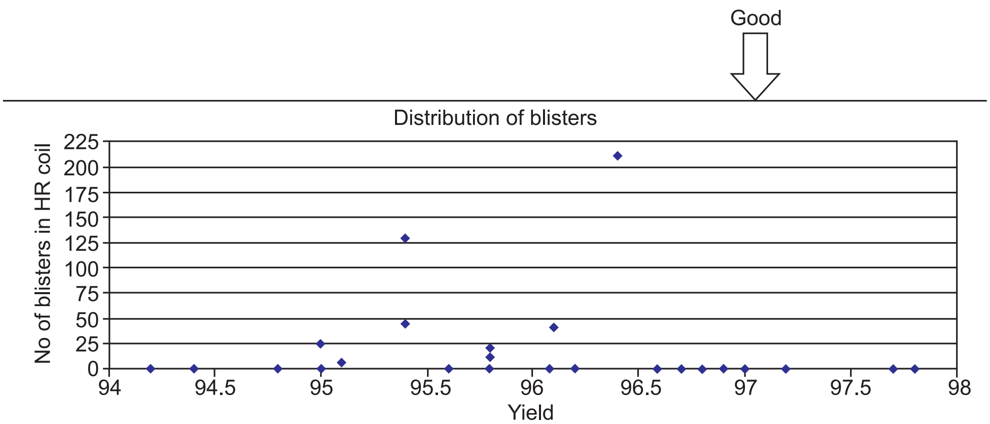

FIG. 8 OCCURRENCE OF BLISTERS IN SCARFED SLABS

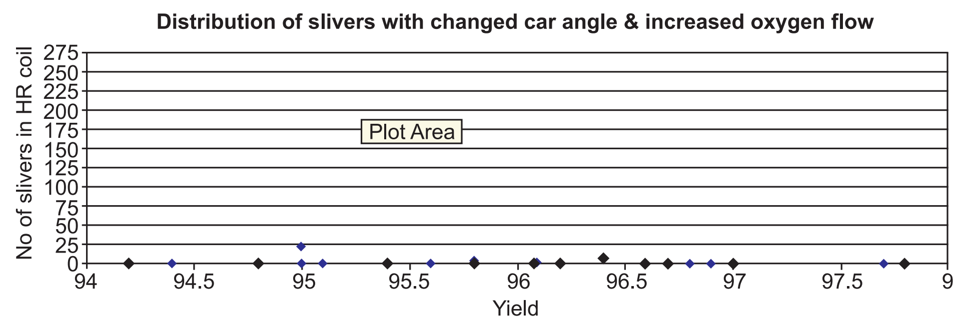

FIG. 9 SLIVER DISTRIBUTION AS A MEASURE OF THE EFFECTIVENESS OF IMPROVED SCARFING

5. CONCLUSIONS

Generation of sticky metallic fins on IF and EDD steel slabs at the Slab-caster yard of Tata steel works during scarfing led to a substantial problem of productivity. Differentially adjusting the oxygen pressure of Oxygen in the three stages of the Oxy-Propane burner, especially opening up the third stage of oxygen supply, helped immensely in converting the scales into brittle scale, easily removed from the surface. The output from the machine also increased from 15 slabs per day to 30 slabs per day without any fresh investment. This added more than ₹90 million to the bottom line of the company in a year. Moreover the quality of scarfed slabs remarkably improved after the practice was started to be followed.

Acknowledgement

The author would like to thank the authorities of Tata Steel for using the non-classified information in this article and also the team led by Mr Ravi Ranjan of Flat Product Group (Head, LD Operations) for the work that produced this remarkable achievement.

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HOT DIP GALVANISING: FEATURES AND FUTURE

SHANTANU CHAKRABARTI[1]

1. INTRODUCTION

Hot Dip Galvanising for cold rolled steel is one of the most popular and well understood techniques of protecting steel from atmospheric and other forms of corrosion like chipping and perforation. The reason for the extensive use of this process is the dual nature of the protection of the coating; it provides a metallurgically bonded tough zinc coating covering the steel surface and its sacrificial action protects the steel in case of minor damage to the coating.

2. PRODUCTS IN THE HOT DIP GALVANISED BASKET

GI, or Galvanised Iron, contains zinc along with a miniscule quantity of aluminium, which improves the adherence by forming an inhibition layer between the steel and the coating. Other alloying elements deliberately added to the coating at times are Pb, Sb, Sn (and Fe by virtue of the process). Sn adds to the shine while Pb/Sb is added mainly to generate the flowery patterns known as spangles, preferred in low end application such as roofing. High quality zero spangled skin-passed GI (produced from a bath containing no Pb/Sb) has gained universal popularity with the white good manufacturers and has of late found extensive applications in automobiles.

GALVALUME, which is hot dip coated steel with 55% Al, 1.5% Si and the rest Zn, is noted for its high resistance to atmospheric corrosion compared to that of GI. This resistance arises from the joint effect of barrier protection offered by Al and the galvanic effect of zinc. Though it is mainly preferred in construction industry for its bright appearance and trouble-free life, it has potential for use in the automobiles in the exhaust system and as structural members.

GALFAN, used mainly in roofing and panelling, containing 95% zinc and 5% Al has good formability and corrosion resistance.

An improved version of hot dip galvanised steel, EXTRAGAL, with stringent control on substrate, quality, coating chemistry and surface finish has been promoted by ARCELOR-Mittal.

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Meant for high end usage like automobiles and white goods, this has better formability, paintability and weldability than ordinary GI.

GALVANNEALED (GA) steel is an improved version of coated steel produced by hot dipping in zinc bath, followed by diffusion annealing. This product has gained ground in Japan and some other countries because of its higher corrosion resistance, better weldability (than GI), and better paintability (than GI & EG), mainly for automobile industry.

2.1 Development of GA: Process Basics

The process is an on-line diffusion annealing process in which the desired grade of steel coated with zinc on both the sides by continuous hot dip process is subjected to an on-line heat treatment. This converts the entire coating to a zinc-iron alloy (the iron diffusing into the coating). The diffusion process results in the formation of mainly columnar zinc-iron crystals growing in an outward direction and transforms the bright metallic zinc layer into a dull gray coating**.** The zinc layer gets completely converted into a combination of intermetallic phases of zinc and iron, (like eta, zeta, delta and gamma) containing varying proportions of iron (8-12%) and zinc.

2.2 Basic Steps in GA Process

The steps involved in the GA process are:

- Cleaned cold rolled steel strip is immersed in the molten zinc bath containing a predetermined quantity of Al (0.10-0.13%).
- The alloy layer begins to form on the strip in the bath
- As the strip emerges, it drags excess zinc with it, which is wiped off by the air knives to get the desired coating thickness
- The moving strip with the molten zinc coating is passed through a heating furnace to heat it to 500-550°C
- It is soaked along the path in the same furnace and ultimately comes out of the enclosure, and follows the same route as other coated steels, like cooling & quenching
- By this time, the desired phases have formed and the main intermetallic layer of $FeZn_7$ is in place and the surface assumes a grayish appearance.

The properties of GA coatings are strongly influenced by the Fe content. While galling, corrosion resistance and weldability are improved by the presence of Fe, the application properties that deteriorate with Fe content are powdering, shear strength of the gamma layer interface and occurrence of crater-like defects on painting.

The characteristics of the intermetallic phases in GA are tabulated below:

2.3 Intermetallic Phases in Galvannealed Steel

Phase	*Composition*	*Fe%*
Zinc [η]	Zn	0.008 max
Zeta [ζ]	FeZn13	5.5-6.2
Delta [δ]	FeZn19/FeZn7	7-11.5
Capital gamma1 [Γ_1]	Fe5Zn21/FeZn4	18-22
Capital Gamma [Γ]	Fe3Zn19/FeZn3	24-31

3. ADVANCES AND FUTURE CHALLENGES FOR HOT DIP GALVANISED STEEL

From 1837 when the first patent for "…means for preserving iron from rust by galvanising" was granted to M Sorel in France, till 2011 when the largest triennial International Conference [GALVATECH] on Coating of steel was last held in Genoa, Italy the driving forces have been economic profit through material design, flexibility, robustness and productivity, and environmental conservation through resource protection and pollution prevention. The notable challenges in the field of hot dip galvanised steel products in different stages of development are production of

- High strength GI & GA (unto 1000 MPa YS) with excellent formability
- GI/GA with higher corrosion resistance and hence lower maintenance
- Chromate-free passivation mainly for electrical & electronic appliances
- Advance functionalities like noise reduction, electro-magnetic wave shielding, solar radiation reduction
- Coatings with less zinc or zinc alloys, like MagiZinc or ZincAM but with equivalent or better properties, in order to conserve z_n
- Thin Organic coating, compatible with subsequent forming & welding
- More stringent surface quality for exposed automotive applications
- Building solutions for resource conservation and aesthetics
- Improved roofing material with properties of heat and noise insulation
- Recovery of zinc from scrapped galvanised products.

Other challenges include selection of the right representative tests for assessment of corrosion resistance for coated steel, as the commonly used Salt Spray test or humidity tests fail to predict the expected life of the product in actual situations.

The targets of operational improvements are higher productivity, trouble-free operation of bath and associated hardware, smooth operation of the furnace and other line equipment, handling of dross, an innovative system of vertical galvanising (CVGL) without pot rolls and the most sophisticated system of On-line defect analysis. In view of the increasing demand from the automobile sector for coated steels with DP/TRIP/CP substrates, the challenge of producing a perfect surface looms large, as the elements responsible for strength enhancement are prone to easy oxidation leading to poorer adhesion and other surface defects.

Driven by the efforts towards resource conservation by mitigating corrosion of steel vis-à-vis the fast depleting global zinc reserves, galvanised steel will still enjoy the preference of manufacturers of automobiles, white goods and affordable roofing solutions. Optimised developments with newer usage will charter the path towards a sustainable future.

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UNUSUAL METALLURGICAL BEHAVIOR OF NICKEL-BASE ALLOYS IN CHEMICAL PROCESS INDUSTRIES

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ABSTRACT

Nickel base alloys are well known for their resistance to corrosion in aqueous solutions of different corrosive conditions. In addition, they possess good resistance to high temperature phenomena like scaling, oxidation, chlorination, carburizing, creep etc., likely to occur in chemical process equipments. In spite of careful selection of these alloys for specific services, metallurgical phenomena such as premature corrosion, cracking, creep etc., have occurred unusually in the recent past in these alloys in chemical process industries. The present paper attempts to describe three such occurrences in the form of detailed case studies conducted by the author. The industries involved are petrochemicals and fertilizers. The materials involved are Incoloy 800HT (UNS N08811) and 27/35 Cr/Ni proprietary alloy (W. Nr. 1.4852). The phenomena experienced are localized deep corrosion, cracking, pitting and accelerated creep. Each phenomenon was independently studied in detail, the problem diagnosed and remedial measures recommended. These alloys should not be taken lightly with respect to their resistance to operational transients and their metallurgical quality.

1. INTRODUCTION

Nickel base alloys form an important class of materials of construction (MOC) among "metals and alloys for chemical industries". They are considered for applications where the common carbon steels and stainless steels cannot be used from the points of view of both corrosion resistance and high temperature strength. Nickel base alloys excel these conventional materials for such situations.

Pure nickel is normally used for caustic services, upto moderately high temperatures. It is not suitable for high temperature services and for highly corrosive acidic conditions. Alloying with chromium, iron, aluminium and titanium induces high temperature strength, creep resistance and

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also resistance to high temperature corrosion phenomena like oxidation, carburization, chlorination etc. Similarly, alloying with molybdenum, chromium, tungsten and controlling levels of impurity elements such as carbon, sulphur, phosphorus etc., induces resistance to corrosion by highly corrosive reducing acids such as sulphuric, phosphoric and hydrochloric acids.

There is a general paradox in the spectrum of materials of construction for the chemical process industries. When one goes up in this spectrum, namely from carbon steels to stainless steels and other corrosion resistant alloys, the resistance to general corrosion increases. However these latter materials become susceptible to localized corrosion phenomena such as pitting, crevice attack, stress corrosion cracking etc.. The present paper discusses three case studies where unexpected phenomena such as pitting corrosion, cracking, creep etc., have occurred in relatively short times in carefully chosen nickel base alloys.

Table 1, on page 339 gives the chemical composition of the alloys considered in this paper. For comparison purpose, the chemical compositions of conventional stainless steels such as Type 304 and 316 are also included. One can notice the substantial amounts of nickel and chromium and intentional presence of specific alloying elements like aluminium, titanium, niobium etc., in the nickel base alloys.

2. CASE STUDY NO. 1: CORROSION OF INCOLOY 800HT FURNACE TUBE

The case involves Incoloy 800HT coil (seamless pipes of size 152.4 mm OD by 12.5 mm WT) in the radiation zone of a cracking furnace used for cracking an organic chloride to produce a petrochemical organic monomer. The process involves cracking the organic chloride in the vapor phase at temperatures well above 250°C producing the monomer and hydrogen chloride gas. The feed is preheated in a preheater coil from 35 to 160°C, vaporized in a vapor coil at about 240°C and then cracked in the radiant coil. The cracked products leave the furnace at about 510°C. The schematic sketch of the process is shown in Fig. 1. Incoloy 800/800HT is the normally accepted material of construction for the service of the radiant coil.

In the case under consideration, several portions of the bottom three turns of the radiant coil started leaking within 9 to 10 months of service. In several other places of the same coil, wall thickness came down to values less than 5.00 mm from the original 12.5 mm. Observations on cut samples established that the leakage and wall thickness reduction was due to general corrosion on the inside surface of the tubes, namely corrosion on the process side and not on the furnace side. A wall of 12.5 mm thickness resulting in leakage in 10 months through thickness reduction corresponds to a corrosion rate of 15.00 mm/year. This is an abnormally high corrosion rate, never expected of any material of construction, not even carbon steels. A high nickel alloy such as Incoloy 800HT exhibiting such a high corrosion rate is quite unusual and demands a detailed study.

Photograph 1 shows the inside (process side) surface of the coil near the leaked area. Heavy coke deposition, brownish corrosion product, gradual reduction in the thickness and the leaked hole can be noticed. Such features were not present on the outside (furnace side) surface of the coil. Photograph 2 shows the sample of a coke lump collected from the inside surface of the coil. Interconnecting network of cracks and heavy porosity can be seen.

Table 1. *Chemical Composition limits of major elements in nickel base alloys considered, along with that of 304 and 316 SS (wt %) (max, or noted otherwise)*

Alloy	*C*	*Cr*	*Ni*	*Mo*	*Fe*	*Ti*	*Al*	*Others*
304 SS	0.08	18.00 / 20.00	8.00 / 10.50		Base			
316 SS	0.08	16.00 / 18.00	10.00 / 14.00	2.00 / 3.00	Base			
Incoloy 800 H	0.05 / 0.10	19.00 / 23.00	30.00 / 35.00		39.5 min	0.15 / 0.60	0.15 / 0.60	
Incoloy 800 HT	0.06 / 0.10	19.00 / 23.00	30.00 / 35.00		39.5 min	0.15 / 0.60	0.15 / 0.60	Al + Ti 0.85 min
20/32 Cr Ni Nb	0.06 / 0.12	18.00 / 22.00	30.00 / 34.00	0.10	Balance			Nb: 0.06 to 0.12 (a)
25/35 Cr Ni Nb Si	0.40	25.00	35.00		Balance			Nb 1.5 (b) Si 1.5 Mn 1.5

(a) Sulphur 0.02 max, Lead 0.05 max, Tin 0.01 max

(b) Approximate nominal values.

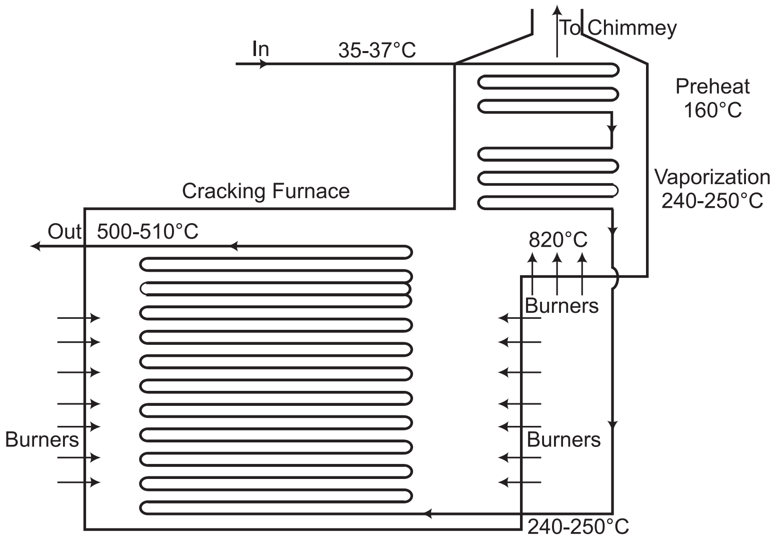
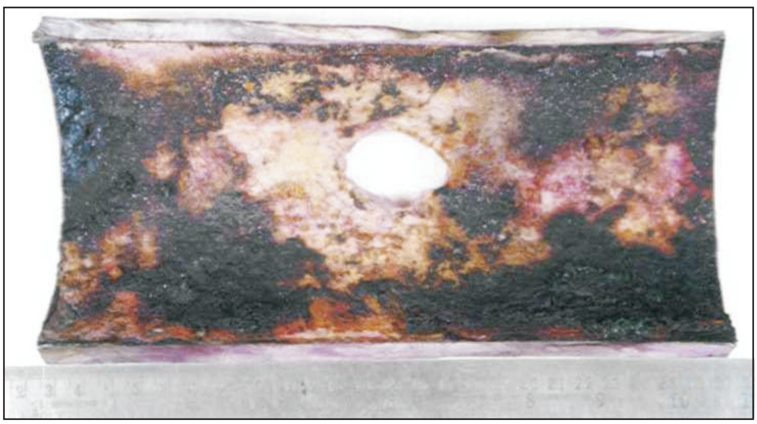
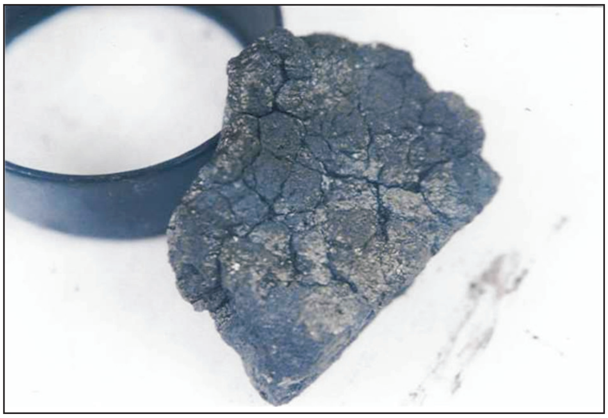


FIG. 1 FURNACE COIL FOR CRACKING ORGANIC CHLORIDE



PHOTOGRAPH 1 THE INSIDE SURFACE OF THE RADIANT COIL NEAR THE LEAKED AREA

While handling affected pipe samples and the coke lump, droplets of some liquid were oozing out from the pipe inside surface, from the cross section of the wall and from the coke lump. These droplets were very highly acidic as detected chemically. They also responded positively to the tests for acidity and chlorides. The following is the chemical analysis of the deposit collected from the inside surface:



PHOTOGRAPH 2 A SAMPLE OF A COKE LUMP COLLECTED FROM THE INSIDE SURFACE OF THE RADIANT COIL

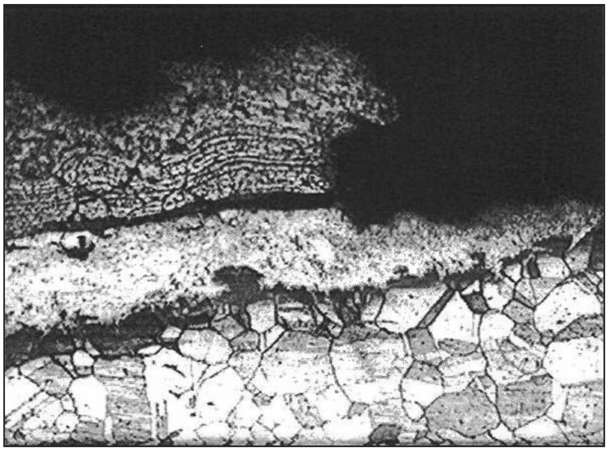
pH of 1% solution	3.7
Cr	0.035%
Ni	0.042%
Fe	0.058%
Chloride	0.048%

These observations indicate that liquid hydrochloric acid has been entrained in these samples.

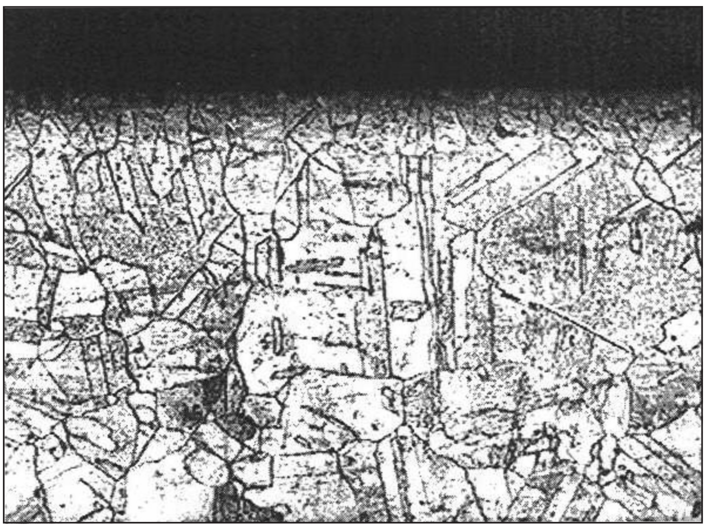
Photograph 3 shows a typical metallographic cross section across the leaked hole near the inside surface of the coil. Three layers can be seen. The bottom most layer is that of the parent metal. The next is a carbide layer with porosity of significant size. The next layer is that of the adherent coke deposit, also porous. Corrosive attack can be seen on the parent metal just below the carbide layer. The attack is general, uniform and not localized. Liquid hydrochloric acid from the process environment has trickled through the pores and attacked the base metal. *Incoloy 800HT is not resistant to corrosion by liquid hydrochloric acid. It is resistant to dry HCl gas, but not to wet HCl acid.*

The liquid hydrochloric acid has come-about in the following way: For some reasons, the auxiliary burners for the upstream vaporizer coils have not been in operation. This causes incomplete vaporization resulting in liquid organic chloride carry-over to the radiant sections of the furnace. A look at the operational history of the furnace showed the extent of vaporization in the feed to the radiant section was varying from 30 to 58% only while 100% is the satisfactory/expected value.

The moisture in the feed is about 50 ppm. In addition, steam is frequently used for removing coke deposit, the latter invariably forming during cracking operation. A part of the steam is entrapped as moisture in the porosity of the adherent coke deposit.



PHOTOGRAPH 3 PHOTOMICROGRAPH OF A CROSS SECTION ACROSS A LEAKED HOLE NEAR THE INSIDE SURFACE OF THE RADIANT COIL. (50X)



PHOTOGRAPH 4 TYPICAL ACCEPTABLE AUSTENITIC MICROSTRUCTURE OF AN UNFAILED REDUCER (100X)

In the radiation section, as soon as cracking starts, HCl gas is generated as a bye-product. This HCl gas dissolves in the moisture and forms liquid hydrochloric acid at the first few turns of the radiant coil where the temperatures are in the lower cracking range. This liquid hydrochloric acid attacks the coil wall from inside. Incoloy 800 HT is not a suitable material of construction for liquid HCl.

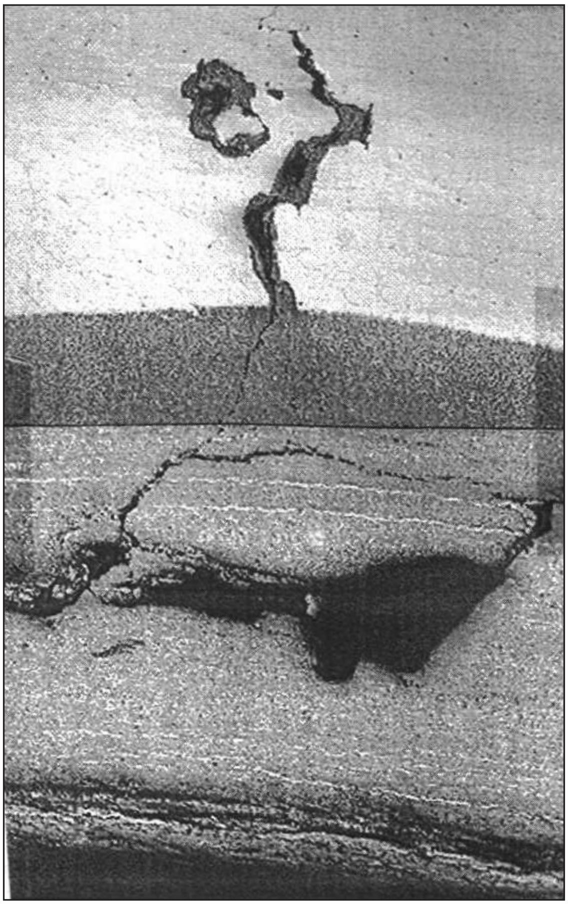
PHOTOGRAPH 5 GRADATION OF MICROSTRUCTURES, NON-ACCEPTABLE, ACROSS THE WALL OF A FAILED REDUCER FROM OUTSIDE SURFACE (TOP) TO INSIDE SURFACE (BOTTOM). (100X)

In the further turns of the radiant coil, because of increasing temperatures, the generated HCl gas and the moisture are both in the vapor form. Incoloy 800 HT is resistant to this vapor, being a material basically developed for high temperature service. Hence, there was no attack on the upper turns.

This is an unusual occurrence, because Incoloy 800HT has been a proven material for the said service under design conditions. Unfortunately during operation, conditions arose for which Incoloy 800HT is not suitable.

3. CASE HISTORY NO. 2: CRACKING OF ALLOY 800 H (20/32 CrNiNb) REDUCER

In the ammonia plant of a fertilizer complex, the primary reformer tubes are connected to the down stream pig tail tubes through reducers. These reducers are said to be made of "20/32 CrNiNb" or



PHOTOGRAPH 6 BLOW HOLES AND CRACKS NEAR THE INSIDE SURFACE ACROSS THE WALL OF A FAILED REDUCER. (50X)

"Alloy 800H as per ASTM B 408". After about 10 years of operation a few of these reducers (2% of the total number) suddenly cracked resulting in leakage of the hot gases from inside. This is a dangerous situation; hence a detailed diagnostic study was desired.

Figure 2 is a sketch of the reformer tube, reducer and the pigtail. The location of the crack in the reducer is indicated. The position of cracking in all the failed reducers was the same, namely just above the bottom weld connecting the outlet pigtail tube.

There was not any abnormality, either in the operating conditions or in the operating procedures, just before and well before the cracking incident, that could be attributed to the cracking.

One of the failed reducers and a typical unfailed reducer were taken up for detailed testing and analysis. Table 2 compares the results. The following diagnostic inferences are drawn from

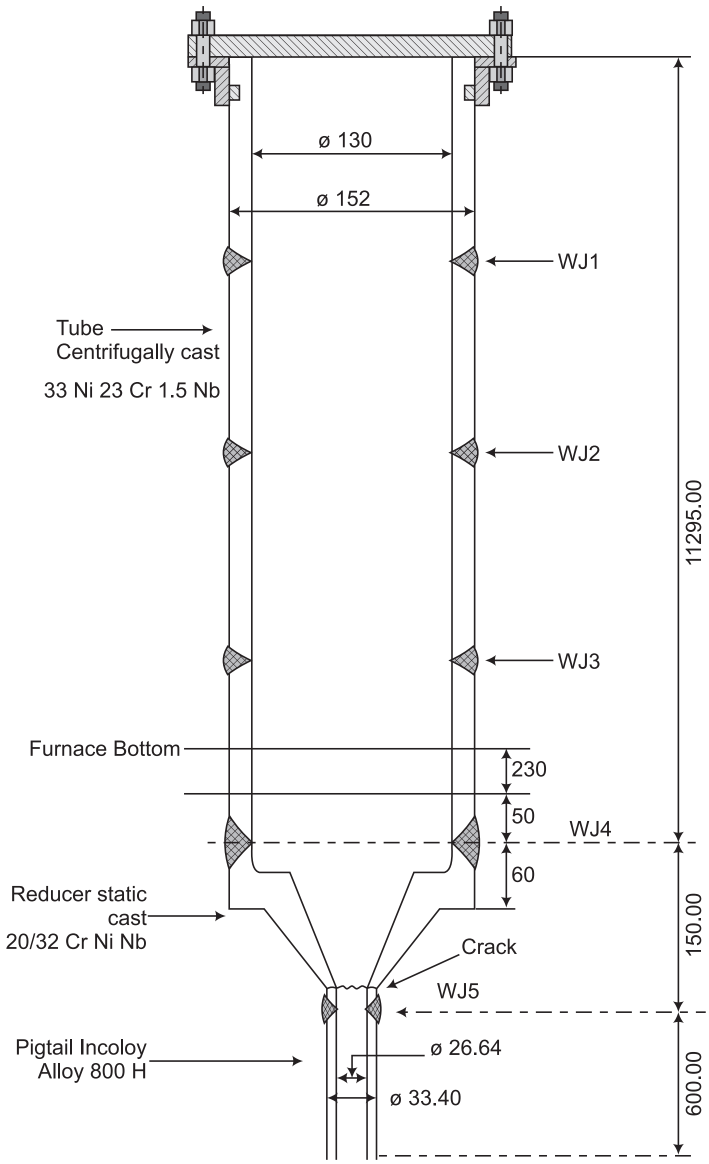


FIG. 2 PRIMARY REFORMER TUBE WITH REDUCER

this comparison: The observed cracking is basically due to carburization occurring on the inside surface of cast reducers and not wrought (forged) reducers. Carburization results in a brittle phase and is not acceptable in thin sections such as the outlet ends of the reducers. The carburized layer being magnetic responds to the testing by ferrite meter showing "high ferrite". Being hard and brittle, it easily initiates cracks under the action of thermal stresses that are common in reformer components.

Table 2. *Comparison of Test Results of Unfailed and Failed Reducers*

Test	*Unfailed*	*Failed*
1. Chemical Analysis	Conforms to specification	Fails as shown below: (wt %) Sulphur 0.032 (0.02 max) Lead 0.13 (0.05 max) Tin 0.04 (0.01 max)
2. Ferrite Content	0% - Inside 0.8% - Outside (Satisfactory)	51% - Inside 18% - Outside (Unacceptable)
3. Magnetic Characteristic	Non magnetic	Magnetic
4. Observation on the Inside Surface	Smooth and free from any foreign material	Thick greenish black carburized layer to about 50% of wall thickness from the inside surface.
5. Hardness	Uniform and acceptable. About 165 VHN.	• Unacceptably high • 190 VHN on the outside surface • 397 VHN on the inside surface
6. Microstructure	Acceptable Typical Austenitic 'step' structure throughout See Photograph 4	• Non acceptable • Gradation of structure • Cast structure on the outside surface • Carburization on the inside surface • See Photograph 5.
7. Soundness	Sound throughout	• Localized blow holes • See Photograph 6
8. Assessed manufacturing route	Wrought Forged and annealed	As cast with many blowholes

In general, between the cast and wrought forms of stainless steels of the same chemical composition, cast form is more prone to carburization. In the case under consideration, the big blowholes present in the casting have helped accelerate the carburization and the cracking process. Further, the excess quantities of low melting alloying elements would have formed weak spots. Cracks either initiate at these weak spots or propagate easily through these weak spots, particularly at the thin sections.

As before, this is also an unusual occurrence because Incoloy 800H has been in use successfully in similar service, but mostly in the wrought form, forged and annealed. The cast form has resulted in carburization and cracking and the blowholes in the casting have accelerated the process.

4. CASE HISTORY NO. 3: CREEP OF "25/35 CrNiNbSi REFORMER TUBE"

The primary reformer tubes in an ammonia plant are made of centrifugally cast thick pipes of wall thickness around 11.00 mm and internal diameter about 130 mm. The material of construction in the case under consideration is high nickel austenitic stainless steel "25/35 CrNiNbSi" containing high nickel (about 35%) and other intentional alloying elements Cr, Nb and Si as shown in Table 1. These elements are added to improve strength and resistance to oxidation and creep.

A typical reformer tube is similar to that shown in Fig. 2, without the crack, of course. These tubes operate with process gas inlet temperature at the top at 510°C and with the reformed gas outlet temperature at the bottom at 730°C. There was an unexpected fire during the eighth year of service affecting a few tubes. One of these tubes was found to be heavily bowed at the middle. The balance tubes had developed cracks in them necessitating immediate replacement. The bowed tube was not removed and was allowed to continue in service.

After a couple of years of further service, it was desired to assess the residual life of the operating reformer tubes. Four main types of methods are in use to estimate residual tube life in reformers:

(i) Measurement of changes in tube dimensions
(ii) Non-destructive testing
(iii) Creep rupture testing of the service-damaged tubes
(iv) Metallographic examination.

For the present case, a combination of the methods (i), (ii) and (iv) was adopted.

The heavily bowed tube was removed and used for testing. The following are the results:

(a) Dimensional measurements:-

• Maximum bowing	37 mm, in the middle portion, quite high, unacceptable
• Maximum occurred creep	1.07% in the middle, acceptable as per set standard

(b) Non-destructive testing: -

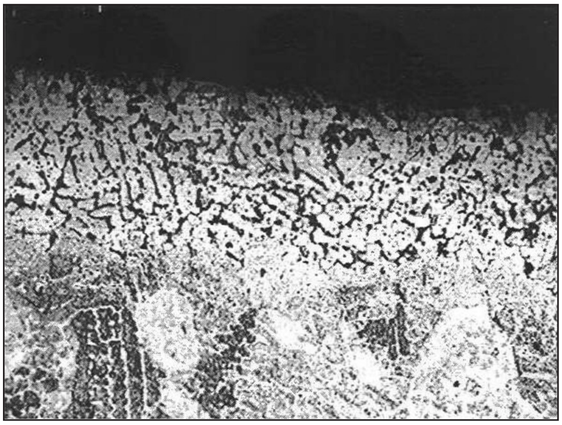
• Maximum attenuation in ultrasonic velocity: 22% at the middle portion. Though acceptable, but an indication of some finite defects across the wall of the tube.

(c) Metallographic testing: -

(i) Photograph 7 shows the cross section microstructure of the bowed tube near the outside surface at the bottom where the temperature is the highest. A thin layer to a depth of about 0.54 mm from the outside surface was found to be affected by creep. This is continuous normal creep occurring throughout the operating period of about 10 years.

(ii) Photograph 8 shows the cross sectional microstructure at the outside surface at the maximum bow position. Very deep creep cavities and hot worked recrystallised grains could be seen. This indicates that this portion got bent under exposure to very high temperature during the fire.

(iii) Photograph 9 shows the cross sectional microstructure at the outside surface at a place where maximum ultrasonic attenuation of 22% was seen. The structure is almost similar to that shown in Photograph 8 above.



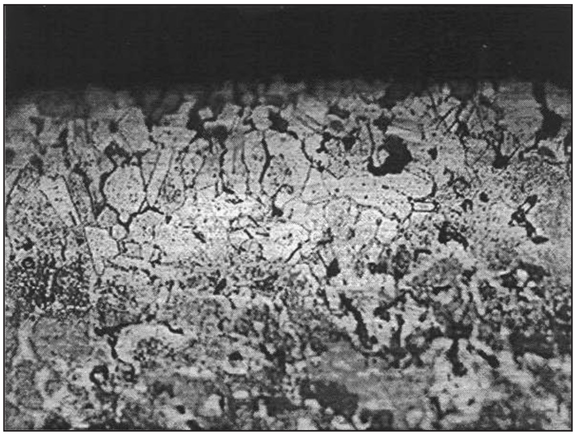
PHOTOGRAPH 7 MICROSTRUCTURE ACROSS THE WALL OF THE BOWED TUBE AT THE OUTSIDE SURFACE NEAR THE BOTTOM-MOST POSITION (100X)

PHOTOGRAPH 8 MICROSTRUCTURE ACROSS THE WALL OF THE BOWED TUBE AT THE OUTSIDE SURFACE NEAR THE MAXIMUM BOW POSITION (200X)

(d) Creep Analysis:

A study of the trend of creep values as obtained through OD measurements over the years gave the result shown in Fig. 3. The values correspond to those obtained during turn-around inspections at the respective years.

The figure can be divided into three regions I, II and III. Region I contain creep values obtained before the fire incident. Region III contains creep values obtained after the fire incident. Region II is the transition from Region I to III. One can notice that the average slope of Region I is equal to



PHOTOGRAPH 9 MICROSTRUCTURE ACROSS THE WALL OF THE BOWED TUBE AT THE OUTSIDE SURFACE AT A PLACE WHERE MAXIMUM ULTRASONIC ATTENUATION WAS 22% (200X)

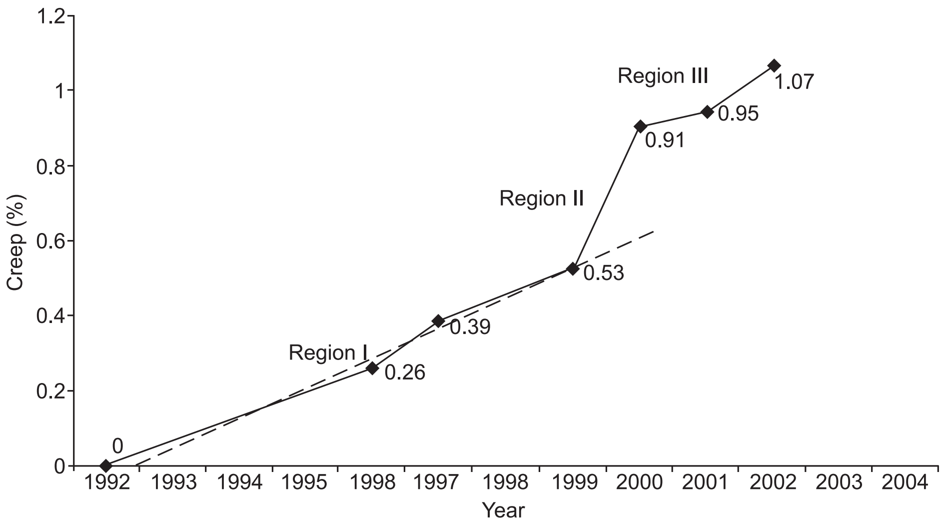


FIG. 3 PROGRESS OF CREEP OF THE BOWED TUBE

that of Region III. This means that the rate of increase of creep due to normal operating conditions is the same before and after the fire. However, during the fire, creep has occurred at a faster rate, corresponding to the very high slope of Region II, resulting in bowing. The net creep of 0.91% immediately after the fire is still within the acceptable value. Since bowing, due to lengthwise elongation, also has occurred, the tube had to be removed.

This is also an unusual occurrence because ‘25/35 CrNiNbSi” is a fully acceptable material of construction for reformer service with no carburization, good strength and acceptable creep rate. But for the fire, the affected tubes would have lasted for quite a few more years.

5. SUMMARY AND CONCLUSIONS

The paper has discussed three case studies of unusual metallurgical behavior in nickel-base alloys used as materials of construction in chemical process equipments handling petrochemicals, fertilizers and inorganic acids. The unusual behavior is the premature failure due to excessive corrosion, cracking and creep. The message conveyed by these case studies is the following.

Special materials of construction such as high nickel alloys are also liable to fail prematurely if the operating conditions happen to be different from the design conditions. Presence of liquid HCl in contact with Incoloy 800HT and intense fire striking the reformer tubes are the issues discussed. Lack of proper metallurgical quality in these alloys giving rise to premature cracking has also been discussed.

If precautions are taken at the appropriate time against the above diversions, the special properties of nickel base alloys can be put to useful and cost-effective service.

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CASE STUDIES OF TRACE IMPURITIES LEADING TO MAJOR CHEMICAL/ELECTROCHEMICAL CORROSION PROBLEMS IN CHEMICAL PROCESS INDUSTRIES

K. ELAYA PERUMAL[1]

ABSTRACT

In chemical industries, the process equipments should withstand the corrosive actions of the process media. The variations in the chemistry of the process environment are carefully studied and materials of construction for the equipments are so chosen that they withstand the corrosives under varying conditions. In spite of such a careful selection, unusual sudden corrosion problems occur leading to premature leakage and failure of the equipment. Reaction vessels, heat exchangers and piping are particularly affected by such unusual phenomena.

These phenomena are, in many cases, attributable to trace impurities which were either not expected to be present or assumed to be present in insignificant quantities. Three such impurities namely chloride, sulphide and microorganisms are discussed in this paper. Their corrosive attack, chemically and/or electrochemically, on materials of construction are presented through practical case studies conducted by the author.

The following specific case studies are discussed in this article.

Heavy pitting corrosion of carbon steel boiler tubes.

Stress corrosion cracking of stainless steel tubes used in alcohol evaporator/superheater.

Stress corrosion cracking of stainless steel column used for producing esters.

Heavy localized pitting corrosion of a natural gas preheater used as a feed for producing ammonia.

Heavy thinning of a plate type heat exchanger used for cooling concentrated sulfuric acid.

In each of the above case studies, the corroding impurity species are identified, the corrosion reaction explained and remedial measures are suggested.

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1. HEAVY PITTING CORROSION OF CARBON STEEL BOILER TUBES

In distilleries manufacturing alcohol, package boilers are in use for meeting steam requirements. The steam condensate from the plant is recycled to the boiler as part of the boiler feed water. The subject boiler is a fire tube boiler in which the fuel gas flows within the tube while the boiler water flows along the outside (shell-side) of the tubes. The tubes are made of boiler quality carbon steel.

After regular commissioning of the boiler, first major inspection of the outside surface (water-side) of the approachable boiler tubes was made after about 11 months. Heavy localized rust-trees (tubercles) were found to be present at several places. These were mechanically brushed-off to the extent accessible and the boiler was put back into operation. Tubes showed leakage after an additional operation of about 2 months, followed by further leakages after about 2 and 6 months of operation. At that time it was decided to replace the tubes with fresh ones and subject the leaked tubes to a detailed failure analysis study.

The outside surface of the affected tubes showed localized pitting corrosion. The pits contained loose brownish rust (corrosion product) along with grayish black metal (the steel of the tube) underneath. These localized pits have grown in depth and resulted in leakage. **Photograph 1** is that of the microstructure of a longitudinal section of an affected tube cut across a pit. Localization of pitting corrosion can be seen very clearly. Corrosion is occurring not uniformly throughout the surface but at localized spots randomly.

The depth of the pit seen in this micrograph is about 0.15 mm. Localization of corrosion resulting in deep pitting is typical of attack by chloride.

The brownish rust collected from the pits was chemically analyzed. The following are the results:

pH of 1.0% solution	3.5
Iron	67.62%
Calcium	0.14% (1400 ppm)
Sodium	0.074% (740ppm)
Chloride	0.030% (300 ppm)

These results indicate that the deposit is highly acidic and consists of corrosion product (iron oxide) along with appreciable quantities of calcium, sodium and chloride. Both these features, namely acidity and chlorides, are not expected to be present in boiler tube deposits and are not acceptable. Their presence indicates that there has been some ingress of acidic chloride salts into the boiler water circuit. The entered salts dissolve in water. Their solubility limits get exceeded on the hot surface of the boiler tubes resulting in localized deposition of salts. The water trapped under these deposits remains stagnant instead of flowing with the bulk water. If the deposits are acid-forming, which they are in this case, the trapped water becomes acidic and corrodes the tubes locally leading to leakage over a period. This is also called **"under deposit corrosion".**

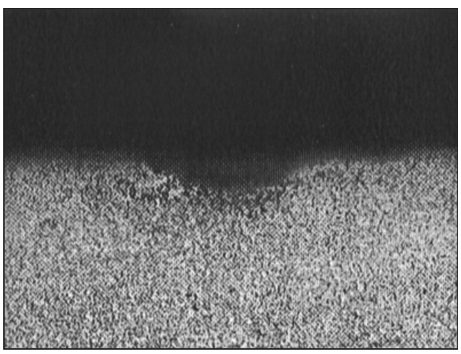
This would continue to occur until the deposits are chemically cleaned and the water chemistry is controlled to avoid entry of acid-forming salts, the chlorides.

The formation of acidic deposits in the boiler under consideration has occurred for a long period sometime prior to the first inspection at eleven months after commissioning. **Figure 1** shows the variation of daily average chloride level in the blow-down water in the month when leakage occurred. One can notice that the chloride has increased slowly from about 50 ppm in the beginning (first day of the month) to as high as 180 ppm on 11^{th} day of the month. Leakage has occurred on 15^{th} day forcing boiler shut-down. Attempt seems to have been made to reduce the chloride level. The boiler was commissioned again on the 26^{th} day of the month with about 30 ppm chloride in the blow-down water. This again slowly rises and then falls to a low value of about 20 ppm at the end of the month. One can draw the following inferences from this figure:

- There is a source of chloride contributing to the boiler water. The entire boiler feed water chemical treatment prior to the addition of condensate was found to be satisfactory without contributing chloride. Hence the chloride comes from leakage of distillery process chemicals into the condensate.
- High content of chloride in the boiler water leads to leakage in a short time.
- The plant personnel are capable of identifying the source of chloride and controlling it, but not to a desired low value (nil).

It is concluded that the leakage of boiler tubes was due to **ingress of chloride impurity** in small quantity to the boiler water through distillery process chemicals into the steam condensate which is recycled to the boiler feed water circuit.

It was recommended that this source of leakage within the distillery processes should be identified and plugged.



PHOTOGRAPH 1 MICROSTRUCTURE ACROSS ONE OF THE CORRODED PITS IN THE TUBE SAMPLE. LOCALIZATION OF ATTACK WITHOUT ANY EFFECT ON THE NEARBY OUTSIDE SURFACE OF THE TUBE. (50X)

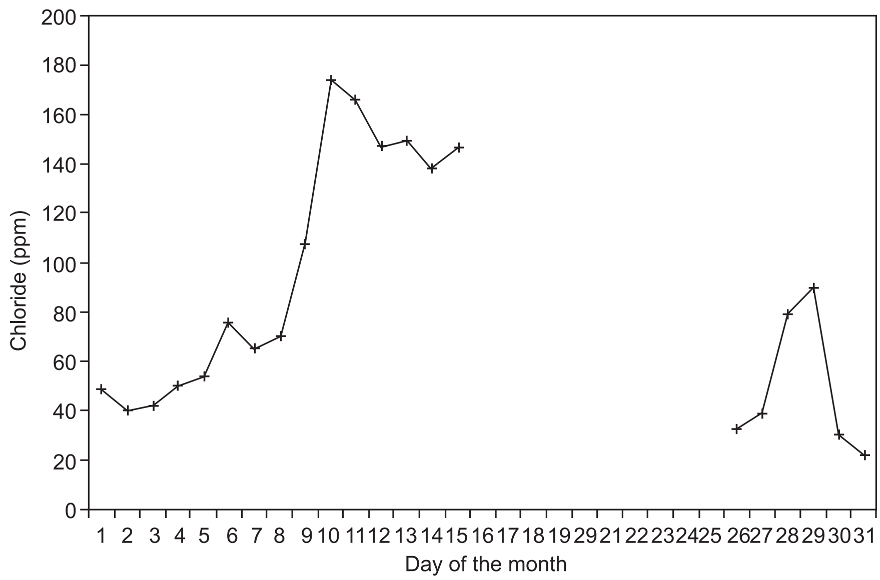


FIG. 1 VARIATION OF DAILY AVERAGE CHLORIDE LEVEL IN THE BLOW-DOWN WATER IN A MONTH WHEN LEAKAGE OCCURRED

2. STRESS CORROSION CRACKING OF STAINLESS STEEL TUBES USED IN ALCOHOL SUPERHEATER

In petrochemical plants where alcohol is used as a raw material, it is preheated, vaporized and also superheated in shell and tube heat exchangers. The equipment in this case is a vertical heat exchanger used for superheating alcohol vapor. The equipment was in operation only for seven months when leakage occurred in almost 30% of the tubes. Since this is a highly premature failure, a detailed failure analysis study was conducted.

The tubes are made of Type 304 Stainless Steel (SS) (UNS S30400), are seamless and manufactured as per specification ASTM A-213, size 19.05 mm OD, 2.77 mm WT, 2500 mm in length and 195 in number. The shell is made of carbon steel and the top and bottom tube sheets are also made of Type 304SS. Alcohol vapor enters the inside of the tubes at the bottom at about 115°C and leaves at the top at about 185°C. The necessary heat is supplied through high pressure steam flowing on the shell side (outside of the tubes) from top to bottom.

The positions of the leaky tubes were random, as shown in Fig. 2, without any pattern or preference to locations. On pulling out some of the leaked tubes it was found that all these had through and through circumferential crack at a height of about 5 mm from the top side of the bottom tube-sheet, as shown in Fig. 3.

The cracked tubes could be easily separated into two pieces along the cracked section. The fracture surface at the crack of one of the failed tubes showed that there is no thickness reduction on the wall of the tubes at the fractured section; the fracture does not belong to any mechanical overload ductile/brittle failure and the crack is not clean shear but is of step-wise grain breakage.

One of the cracked tubes was sectioned longitudinally and examined inside. There was heavy brownish rust deposit on the inside surface to a small length on either side of the crack. On lightly removing the rust by rubbing, localized deep pits and circumferential cracks could be seen on the inside surface. These features were not present on the outside (steam side) surface of the tubes. This means that cracks have initiated on the inside surface.

The process side input was said to consist of roughly 80% alcohol vapor and 20% steam. There is some carry-over of liquid alcohol and moisture droplets from equipment upstream, namely alcohol vaporizer. The raw alcohol obtained from distilleries is routinely checked for its purity and moisture content among others. A typical analysis is given in the following Table:

Test	*Result*	*Specification*
Purity (% by weight)	91.30	91.96 min..
Purity (% by volume)	94.06	94.68 min..
Moisture (% by weight)	07.64	Trace

One can notice that the particular batch of alcohol is short of the required specification with respect to both purity and moisture content. Similar quantity of moisture, 7 to 11%, was reported for certain months within the completed operating period prior to the failure.

A sample of the tube cut longitudinally across the leak location was microscopically examined under a metallurgical microscope. Photograph 2 shows a section of the inside surface, a little away from the main leaked crack. Localized deep pits can be seen starting from the inside surface and growing in depth and width. These are corrosion pits typical of chloride attack on austenitic stainless steels.

Photographs 3 and 4 show, in the as-polished condition, multiple cracks starting from several locations on the inside surface. Cracks initiate both on smooth portions and on the bottom of corrosion pits on the inside surface and propagate towards the outside surface. The locations where these cracks initiate are about 10 to 15 mm above the main leaked crack. Photograph 5 is a composite photomicrograph of two neighboring cracks in the etched condition showing initiation on the inside surface and propagation towards the outside surface. One can notice multiple initiation sites, transgranular path and branching of cracks during propagation. These features are typical of **chloride stress corrosion cracking (CSCC)** of austenitic stainless steels of which Type 304 is one.

The occurrence of CSCC in stainless steels requires the simultaneous presence of the following situations:

An operating skin temperature above about 60°C

Dissolved chloride ion in an aqueous phase even in a small quantity

Tensile stress, applied or residual, even at low values.

In the present case, the skin temperature on the inside surface just above the bottom tube-sheet is well above 60°C.

Due to carry-over of liquid alcohol with the associated water along with the vapor and steam, there has been an aqueous phase present in the areas where cracks have occurred. As the process fluid moves vertically up on the tube-side (inside), the water evaporates and there is no further problem in the remaining length of the tubes. Chemical analysis for the extent of chloride present both in the as received alcohol and in the process condensate somewhere downstream from the subject super-heater was carried out along with pH measurements of the corresponding liquids.

The following are the results:

Sample	*pH*	*Chloride(ppm)*
As received alcohol from tank	4.8	43.0
Downstream condensate	3.5	9.0

One can notice that the water associated with the inlet to the superheater under study is acidic in nature and contains appreciable amount of chloride. As soon as the evaporation within the superheater starts, the remaining liquid in contact with the hot tube surface at the lower portions would be much higher in chloride.

Regarding the presence of tensile stress, even a small level of stress, much lower than the mechanical code allowable level, is sufficient to initiate CSCC. Austenitic stainless steels crack by CSCC even at stress levels of about 0.1 to 0.2 times the ultimate tensile strength. In the present case, small amount of residual stress is present in the tubes at positions close to the tube sheet where the tubes are expanded to the tube-sheet. Stress also arises due to differential expansion of carbon steel and stainless steel. Though these are within the mechanical design limits, in the presence of chloride, these are sufficient to initiate stress corrosion cracks.

Thus, it was diagnosed that the problem is that of stress corrosion cracking due to chloride, an impurity which has been present in the feed alcohol.

The following are the suggested remedial measures:

- Avoid liquid (alcohol and the associated water) carry-over to the evaporator
- Change the source of alcohol to one free from chloride
- If the above two measures are not feasible, then change the material of construction to a cost-effective “duplex stainless steel” which has much higher resistance to CSCC than austenitic stainless steels.

3. STRESS CORROSION CRACKING OF STAINLESS STEEL COLUMN USED FOR PRODUCING ESTERS

In petrochemical plants producing esters, alcohol is one of the raw materials. It is reacted with acid in a reactor and the produced ester is distilled in a distillation column made of 316L stainless steel. One such plant has been in operation for a few years. After one of the yearly maintenance/turn-around operations the column was pressure tested for restarting. Suddenly heavy leakage was noticed in several places of the column, particularly near and at the various weld joints. Since this was quite sudden and premature, a detailed failure analysis study was conducted.

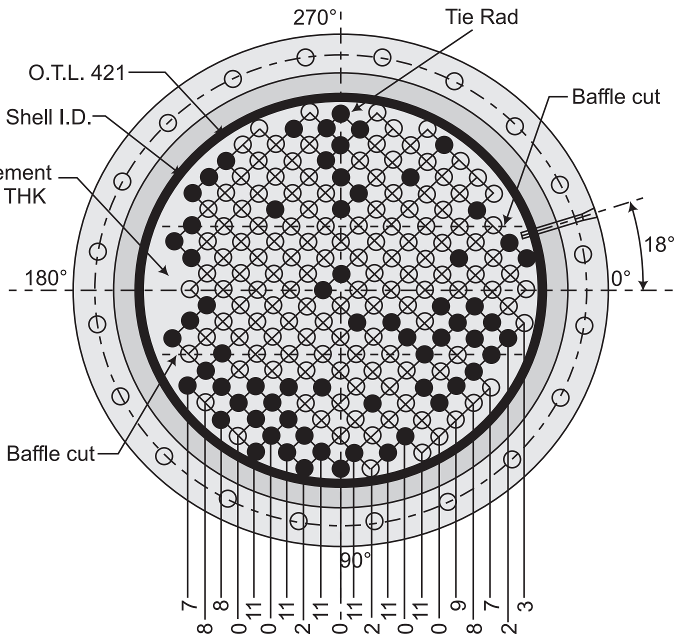


FIG. 2 CROSS-SECTION OF THE ALCOHOL VAPOR SUPERHEATER WITH LEAKED TUBES SHOWN AS FULL BLACK CIRCLES

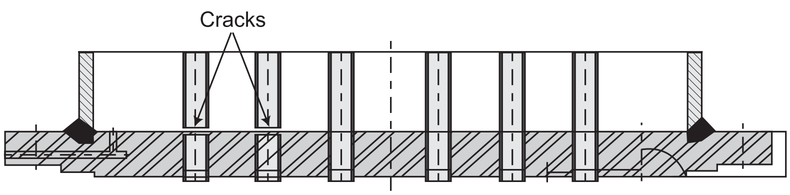
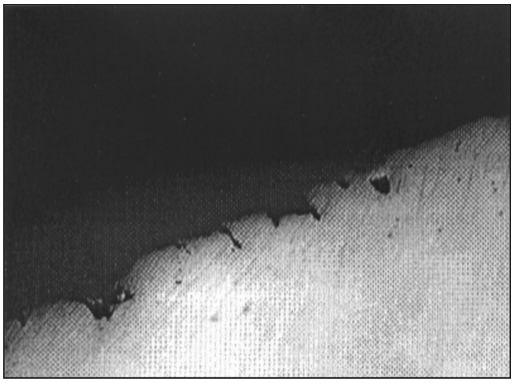


FIG. 3 A SKETCH OF THE ELEVATION OF THE BOTTOM PORTION OF THE ALCOHOL VAPOR SUPERHEATER. SHOWS CIRCUMFERENTIAL CRACKS ON THE TUBES JUST ABOVE THE TOP SURFACE OF THE BOTTOM TUBE-SHEET

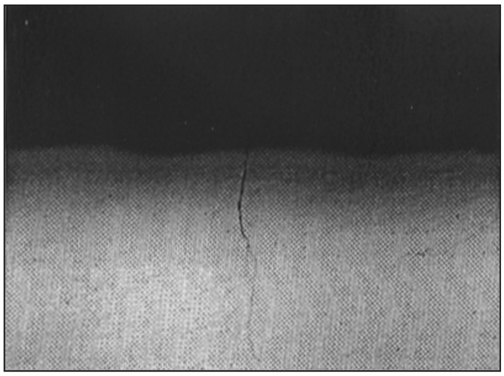
Visual examination of the column has indicated no mechanical damage and no visible corrosion which could be ascribable for the observed cracking. Loose to somewhat adherent deposits, grey in color, was present on most of the places of the inside surface.

Samples cut from regions having cracks were metallographically analyzed. **Photographs 6 and 7** show typical of the cracks observed. The following observations were made from these microstructures:

(i) The cracks have initiated on multiple locations on the inside surface, the process side, of the column



PHOTOGRAPH 2 LOCALIZED DEEP PITS ON THE INSIDE SURFACE OF ALCOHOL VAPOR SUPERHEATER TUBES. AS POLISHED (200X)



PHOTOGRAPH 3 CHLORIDE STRESS CORROSION CRACK INITIATING ON SMOOTH PORTION OF THE INSIDE SURFACE OF THE ALCOHOL VAPOR SUPERHEATER. AS POLISHED (100X)

(ii) They have occurred both at the weld joints and also purely on the parent metal little away from the weld joints.

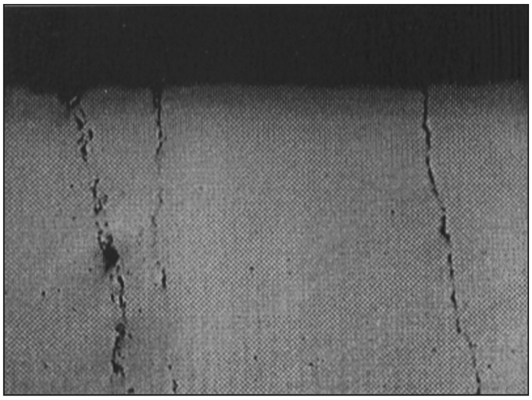
(iii) They propagate in a transgranular manner, cutting across the grains and not along the grain boundaries.

(iv) They show branching during propagation.

The above features indicate that cracks belong to the class of **Stress Corrosion Cracking (SCC).** The latter occurs either due to chloride, caustic or **Polythionic acid.** The first two are ruled out because of the following reasons:

(i) Chloride has not been detected at all at any of the batches of the input reactants.

(ii) The process conditions are such it is not possible to have caustics.



PHOTOGRAPH 4 CHLORIDE STRESS CORROSION CRACKS INITIATING ON MULTIPLE PLACES ON LOCALIZED PITS ON THE INSIDE SURFACE OF ALCOHOL VAPOR SUPERHEATER TUBE. (50X)

PHOTOGRAPH 5 COMPOSITE PHOTOMICROGRAPH OF A CHLORIDE STRESS CORROSION CRACK INITIATING ON THE INSIDE SURFACE AND PROPAGATING TOWARDS THE OUTSIDE SURFACE, TRANSGRANULAR WITH BRANCHING (100X)

(iii) Cracking has not occurred at all in previous years prior to the particular turnaround after which they were detected.

Thus it boils down to polythionic acid SCC as the cause of failure. Polythionic acids ($H_2S_nO_6$ where n is 2 to 5) are formed by the interaction of sulfur compounds (H_2S, SO_2 and inorganic and organic sulfides), moisture and air at ambient temperatures. Surfaces covered with a sulfide coating can produce polythionic acids at ambient temperatures when this sulfide coating comes into contact with moisture and air during a shut-down when the latter enter into the vessels/ columns. The following is the apparent chemical reaction of formation of polythionic acid from FeS coating:

$$8FeS + 11O_2 + 2H_2O = 4Fe_2O_3 + 2H_2S_4O_6 \text{ (tetrathionic acid)}$$

In the present case, the following additional information gives support to this suggestion of polythionic acid SCC as the cause of failure.

(i) The grey thin coating was identified as iron sulfide.

(ii) Sulfur has been found to be present as an impurity in the particular batches of alcohol which were processed just prior to the failure.

(iii) Cracks have not occurred during regular operation at elevated temperatures but during shut-down at ambient temperatures.

The iron sulfide coating forms during operation. During shut-down, atmospheric moisture and oxygen enter the system and react with the iron sulfide coating and form polythionic acid. The acid thus formed cracks the SS column wherever residual stresses are present, like welds, weld joints and parent metal close to the welds.

Thus this is a case of major corrosion failure due to the impurity sulfur present in the alcohol.

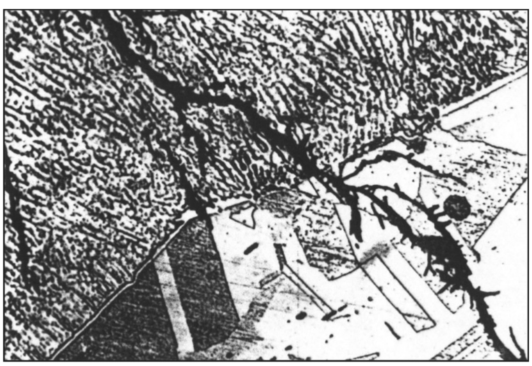
The following remedial measures, one or more, are suggested.

(i) Alkaline wash of the equipments immediately after shut-down before exposure to atmospheric air and moisture.

(ii) Nitrogen/Ammonia blanketing for short shut-downs.

(iii) Purging with a dry inert gas to avoid moisture condensation.

(iv) Use a material of construction having more resistant to polythionic SCC than Type 316L SS.



PHOTOGRAPH 6 TRANSGRANULAR STRESS CORROSION CRACK ON THE ESTER COLUMN BOTH AT THE WELD AND AT THE PARENT METAL AND CUTTING ACROSS THE BOUNDARY. (200X)

PHOTOGRAPH 7 BRANCHING NATURE OF PROPAGATION OF TRANSGRANULAR STRESS CORROSION CRACK ON THE ESTER COLUMN AT THE PARENT METAL (200X)

4. HEAVY LOCALIZED PITTING CORROSION OF A NATURAL GAS PREHEATER USED AS A FEED FOR PRODUCING AMMONIA

A fertilizer plant producing ammonia and urea uses Natural Gas (NG) as the feed-stock. The waste heat from the primary reformer is used to heat various streams for different purposes. One such purpose is to preheat the feed-stock NG from ambient temperature to some elevated temperature prior to different processing steps. The preheating is made in a set of parallel coils. The coils are made of seamless pipes of low alloy steel conforming to ASTM specification A-335/P-11, a chromium-molybdenum alloy steel containing 1.0 to 1.5% Cr, 0.44 to 0.65% Mo and 0.05 to 0.15% C. The pipes are of size 4.5" Outside Diameter (OD) and 6.03 mm Wall Thickness (WT). The pipes prematurely failed by leakage at several places after about 23 months of operation, considered as a premature failure.

The pipe is finned on the outside surface with carbon steel strips. The source of heat, namely the flue gas from the reformer flows along the outside surface of the pipe giving away the heat through the fins and the wall to the NG feed gas flowing along the inside surface of the pipe. The preheater was designed for NG feed inlet and outlet temperatures of 30 and 370°C respectively.

One of the leaky pipes was longitudinally cut, the inside surface examined and microscopically analyzed. Heavy scaling, its rupture after a certain thickness followed by leaky hole formation was seen on the inside surface. On closer examination, it was further seen that the hole is through and through and has initiated on the inside surface and propagated towards the outside surface.

The outside surface of the pipe showed warping of the fins at many places. At a few places where leakage has occurred, heavy scales could be seen. The latter is considered as a post-leakage occurrence.

The scale on the inside surface was collected, examined and analyzed. It was highly magnetic. Chemical analysis of the scale for certain elements gave the following results:

Elements	*Wt. (%)*
Carbon	19.56
Sulfur	10.06
Chromium	0.32
Molybdenum	0.25
Iron	60.00

From the magnetic nature of the scale and predominance of iron and sulfur, it is inferred that the scale is mainly iron sulfide. There are entrapment of hydrocarbon from NG and trace quantities of chromium and molybdenum from the pipe steel. **Photograph 8** shows penetration by some species of the NG gas into the metallic structure of the pipe through the inside surface. The species is apparently sulfur.

The sulfur content in the NG feed is not routinely measured. It is said to be about 0.3 ppm. This level is considered by the plant personnel as normal and was taken into account while designing the preheater with respect to choosing the MOC, the material of construction, sizing and fixing up the operating parameters.

Photograph 9 shows the microstructure of a longitudinal section of the wall of the pipe near a leaky hole. The pipe wall is seen in the bottom half with thickness reducing from right to left. Fin is shown on the top half covered with heavy oxide scale. Heavy grain growth can be seen on the outside surface of the pipe close to the fin.

Photograph 10 shows at a higher magnification excessive grain growth on the outside surface of the pipe at a place between the fins where there is direct flue gas contact.

This excessive grain growth indicates that there has been some continuous exposure for a long period of time to some elevated temperatures, much higher than the design value. A scrutiny of the records of the operating parameters has shown actual temperatures much higher than the design values as shown in the Table below.

Parameter, °C	*Design*	*Actual*
N.G outlet temperature	370	490
Flue gas inlet temperature	425	521
Flue gas outlet temperature	350	428

The readers' attention is drawn to the following three observations from those described above:

(i) The scale is mostly iron sulfide
(ii) Finite quantity of sulfur is present in the NG feed
(iii) Operating temperatures, and hence the pipe wall temperatures, are much higher than the designed ones.

From these three significant observations it is diagnosed that the leakage is due to **excessive sulfidation on the inside surface of the pipe** due to the operating temperatures being at values much higher than those of design. Direct reaction of organic sulfur compounds and elemental sulfur, present in the crude, with the metal surface is the predominant mechanism of high temperature sulfidation.

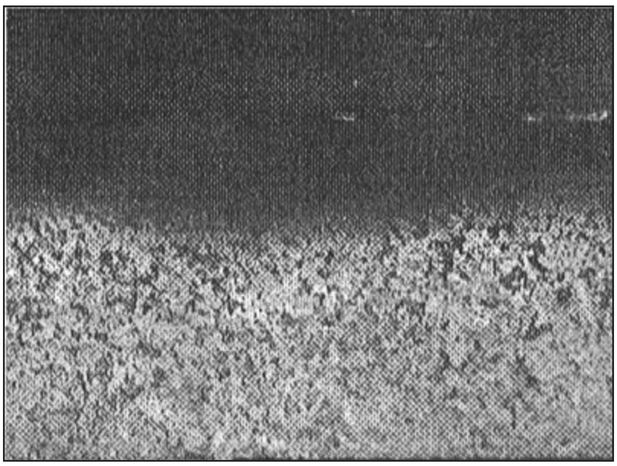
Iron sulfide film on steel surfaces is initially protective. But after a certain thickness, particularly at elevated temperatures, film breaks up locally exposing the base metal. More and more sulfidation takes place preferentially at these localized places. The film thus formed at these localized places breaks up after a certain thickness. This cycle continues leading to hole formation followed by leakage.

The following recommendations were made for remedial measures:

(a) Sulfur in the feed must be checked on a routine basis. Any abnormal high value should be noticed and corrective actions should be taken at the source of NG to reduce the level of sulfur to acceptable low values.

(b) Operating temperatures must be kept well below the design maximum values.

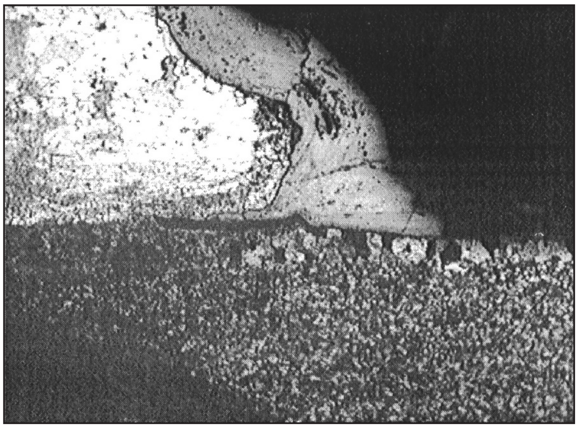
(c) As a long term measure, alloy steels with higher alloy content should be considered for replacement with a better MOC.



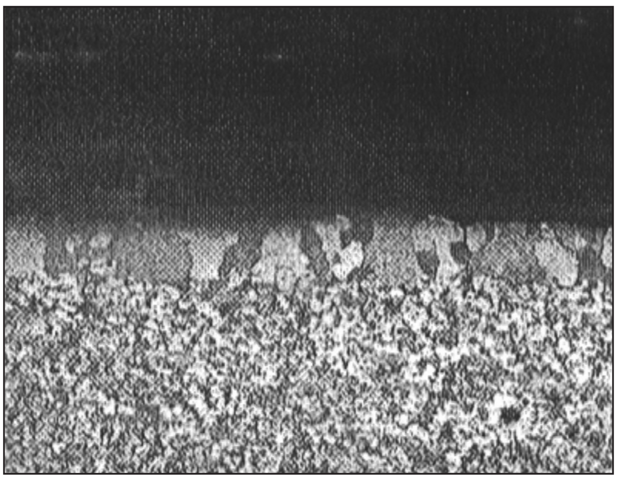
PHOTOGRAPH 8 MICROSTRUCTURE OF THE WALL OF THE COIL PIPE, NEAR THE INSIDE SURFACE SHOWING PENETRATION BY SOME SPECIES (SULFUR) FROM THE NG. (100X)

5. HEAVY THINNING OF A PLATE TYPE HEAT EXCHANGER USED FOR COOLING CONCENTRATED SULFURIC ACID

In plants producing sulfuric acid, the final product, the concentrated acid, is cooled either through a shell and tube cooler or through a plate-type heat exchanger (PHE). Alloy C-276, a nickel base alloy containing Mo, Cr, Fe, W and Co as major alloying elements corresponding to UNS



PHOTOGRAPH 9 MICROSTRUCTURE OF THE WALL OF THE COIL PIPE, LONGITUDINALLY CUT ACROSS A PLACE CLOSE TO THE LEAKY HOLE. GRADUAL WALL THINNING OF THE COIL, GRAIN GROWTH ON THE COIL OUTSIDE SURFACE, THE OUTSIDE FIN AND THE SCALE ON THE OUTSIDE FIN, ALL CAN BE SEEN. (50X)



PHOTOGRAPH 10 MICROSTRUCTURE OF THE WALL OF THE COIL PIPE, NEAR THE OUTSIDE SURFACE SHOWING EXCESSIVE GRAIN GROWTH ON AREAS BETWEEN THE FINS. (100X)

N10276, is a common acceptable MOC, material of construction, for such PHEs in sulfuric acid plants. This alloy has extremely good corrosion resistance to both concentrated sulfuric acid and cooling water. In the case study under consideration, plate elements of Alloy C-276 of 0.63 mm thickness developed pin-hole leaks within one year of operation, a very premature failure.

On one side of the plate elements of the PHE, concentrated sulfuric acid (92 to 99%) enters at 90°C and gets cooled to 70°C. On the other side of the element, cooling water enters at 32°C, extracts heat from the acid through the element and leaves at 43°C.

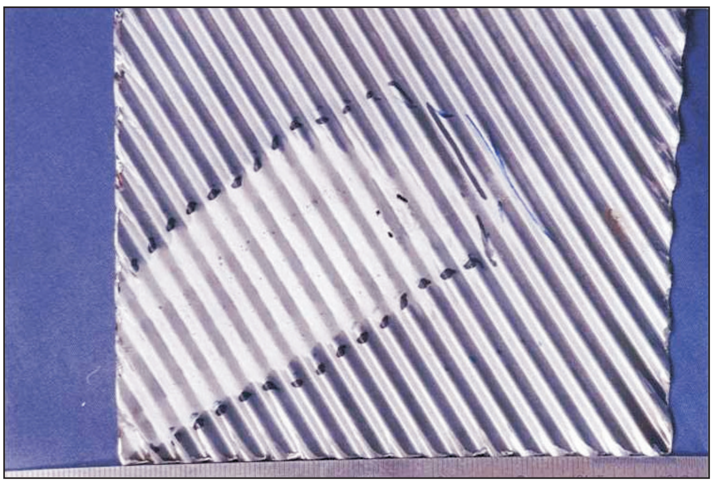
Within a year of operation, pinholes developed in the elements allowing water to enter the acid. On the acid side, immediately downstream of the leaky hole, mixing of water with acid made the acid dilute and increased the local temperature. Hot dilute sulfuric acid corrodes Alloy C-276.

Close examination of the area near the leaky holes in one of the elements on the acid side showed sharp holes and corrosive attack downstream of the holes. (**Photograph 11**) Other than this corroded region, the rest of the element area, which was also in contact with the acid, was corrosion-free.

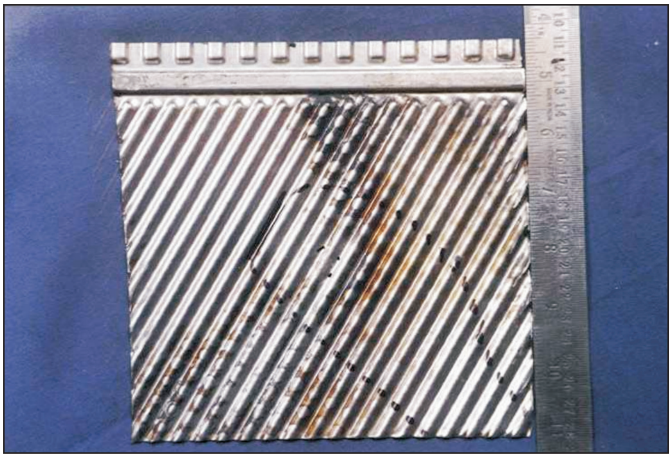
Interesting observations were made when the cooling water side of the affected plate elements near the leaky holes was closely examined. **(Photograph 12)** Thin deposit like appearance interspersed with white circles was present. Within each of the white circles, shiny central spots could also be seen. **(Photograph 13**)

These shiny white areas are **bacterial colonies** on the cooling water side. Microscopic bacteria thrive in these colonies generating highly acidic secretions. Since bacteria strongly cling to the metal surface, these acidic secretions remain stagnant and initiate and propagate pitting corrosion of the underlying metal very fast leading to pin-hole leaks. These pinholes are the starting points of the leakage problem.

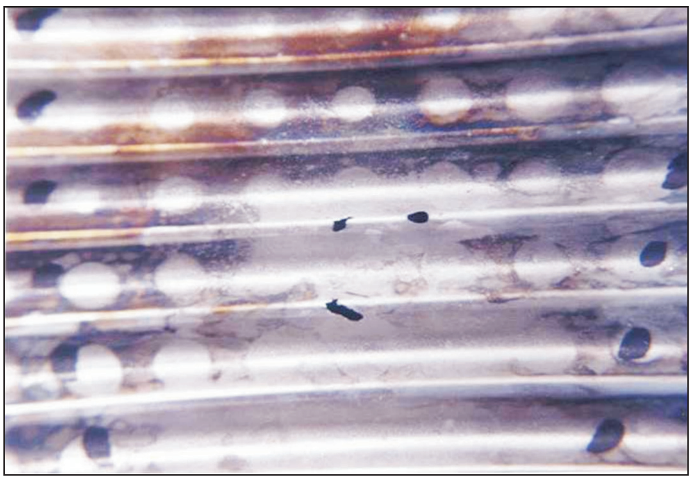
The cooling water used for industrial purposes is a good medium for thriving of micro bacterial organisms. These organisms, in the process of thriving, grow to big sizes and lead to fouling and also to localized pitting corrosion as mentioned above.



PHOTOGRAPH 11 SHARP HOLES AND CORROSIVE ATTACK DOWNSTREAM OF THE HOLES ON THE ACID SIDE



PHOTOGRAPH 12 COOLING WATER SIDE OF THE AFFECTED PLATE ELEMENTS NEAR THE LEAKY HOLES



PHOTOGRAPH 13 CLOSE-UP VIEW OF THE COOLING WATER SIDE

The usual preventive action against these problems is to kill these microbial organisms through adding biocides, both gaseous chlorination and addition of proprietary chemical biocides.

Apparently, the cooling water used in the plant under consideration has not been treated properly against microbial organisms. Proper chlorination with specially studied and formulated biocide treatment would have prevented the experienced problem. Such actions were recommended as remedial measures.

6. GENERAL COMMENTS

Through practical case studies, it has been demonstrated that trace impurities in chemical process environments play a critical role in causing failure of process equipments. The particular impurities considered are chloride, sulfur and microorganisms. Care should be taken during the initial design stage itself for providing right steps for preventing any major problems due to these trace impurities.

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MONITORING OF SUPERPLASTIC DEFORMATION BY MEASURING CHANGE OF CAPACITANCE

ABHIJIT DUTTA[1]

A new method of measurement of change of capacitance has been introduced which enables monitoring of progress of deformation during superplastic forming. Instead of entirely relying upon the theoretically generated "pressure – time cycle", the forming can rather be controlled by following the "capacitance – time profile" which takes care of any eventual necessity of increase/ decrease of pressure due to hardening/softening during the progress of forming and suggests correction of the theoretically calculated pressure sequence instantly. Therefore, the process is likely to become more attractive and truly effective to the commercial forming community.

1. INTRODUCTION

Superplastic forming is the ability of some materials to undergo extensive elongation in tensile test. By utilizing this property the material can be blow formed to different shapes in a manner similar to glass blowing or thermoforming of plastic. For the success of gas pressure forming, however, depends heavily on the precise formulation of a "pressure – time cycle" through analytical or FEM approaches [1-6]. Dutta and Mukherjee [1] developed a simple and straight forward equation, as given below, for forming a hemispherical shape (Fig. 1),

$$\mathbf{P = 4\,\frac{S_0}{a}\,\bar{\sigma}\,\exp(-\bar{\dot{\varepsilon}}t)\,[\exp(-\bar{\dot{\varepsilon}}t)\,\{1 - \exp(-\bar{\dot{\varepsilon}}t)\}]^{1/2}} \tag{1}$$

where,

P = Required gas pressure at any time t

t = time

σ = Effective flow stress

$\bar{\dot{\varepsilon}}$ = Effective strain rate

S_0 = Initial thickness of the blank to be formed

a = radius of the hemispherical dia

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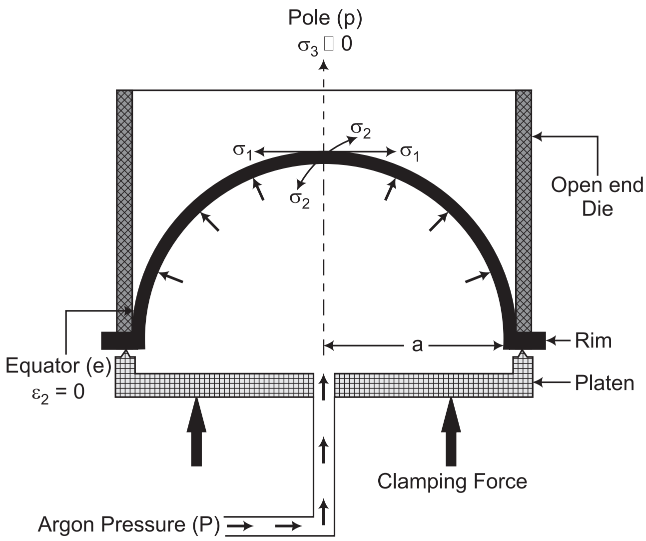

FIG. 1 SCHEMATIC GAS PRESSURE SUPERPLASTIC FORMING OF HEMISPHERE

The progress of deformation at any point of time can be described in the form of depth (d) or radius of curvature (ρ), as given below:

$$\mathbf{d} = \rho - \sqrt{\rho^2 - \mathbf{a}^2} \tag{2}$$

where,

$$\rho = \frac{\mathbf{a}}{\mathbf{2[exp(-\bar{\dot{\varepsilon}}t)\ \{1 - exp(-\bar{\dot{\varepsilon}}t)]^{1/2}}} \tag{3}$$

Since the gas pressure forming is carried out at high temperature, the progress of deformation cannot be monitored easily, as the complete die-blank assembly is covered by the furnace. Therefore, the change in radius of curvature of the dome can only be predicted through computation of equations e.g. Eq., (2) or Eq., (3). However, in the event of unanticipated hardenings e.g., strain hardening, precipitation hardening, grain growth hardening, multiaxial strain hardening, the prediction of the progress of forming might go wrong. Attachment of LVDT or laser beam for measuring the actual depth or radius of curvature might be expensive and complicated. In the published literature, the problem has hardly been addressed. Kahandal and Yasuri [7] have described a method of controlling the strain rate directly through regulation of gas mass by fitting a flow controller in the line. In the present investigation the property of change of capacitance between forming blank and the die has been chosen as the parameter to describe the progress of deformation.

2. THEORETICAL ANALYSIS

From the knowledge of elementary physics, the capacitance between two parallel plates of area A, separated by a distance l, as shown in Fig. 2, can be expressed as follows:

$$\mathbf{C = K\varepsilon_0 \frac{A}{I}} \tag{4}$$

where,

C is the capacitance,
K is the dielectric constant (1.00054 for air) and
ε_0 = permittivity constant = 8.85×10^{-12} F/m.

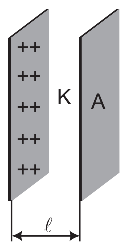

FIG. 2 PARALLEL PLATES CAPACITOR OF AREA 'A' AND SEPARATED BY A DISTANCE'I'

As shown in the Fig. 3, the blank was insulated from the die by means of a coating with high dielectric constant. The deformable circular blank SQT, as represented by a broken line in Fig. 3 turns to a dome shape after gas blowing for time t as described by arc SPT. The hemispherical die surface is described by arc SRT. In order to calculate the capacitance (C_{blank}) between the dome SPT and the hemispherical die, two parallel annular discs AA′ and BB′ of thickness dx and radius x are considered. The distance AB between them can be expressed as follows

$$\mathbf{AB = \sqrt{a^2 - x^2} - \left(\sqrt{\rho^2 - x^2} - \sqrt{\rho^2 - a^2}\right)} \tag{5}$$

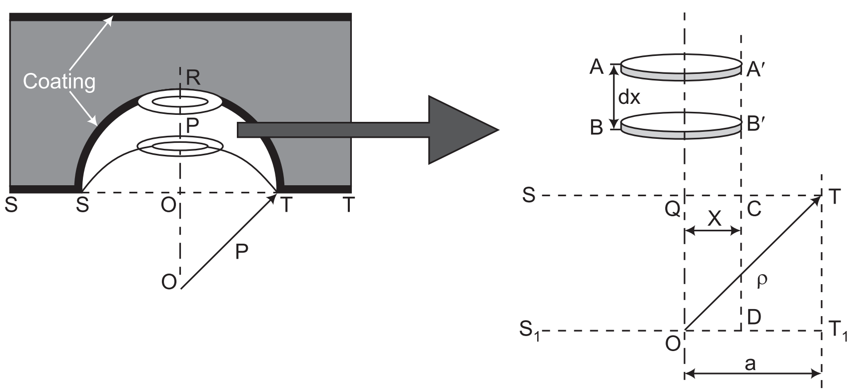

FIG. 3

The surface areas of both the annular discs are 2πxdx. Then the capacitance C_{blank} can be written in the form of following integral

$$C_{blank} = K_{air}\,\varepsilon_0 \int_a^0 \frac{2\pi x dx}{\sqrt{a^2 - x^2} + \sqrt{\rho^2 - a^2} - \sqrt{\rho^2 - x^2}} \tag{6}$$

The integral was numerically solved by writing a computer program.

The capacitance of the capacitor formed between the flange SS′ (or TT′) and the die face can be expressed as follows:

$$C_{flange} = \frac{K_{coating}\,\varepsilon_0 \pi [QS)^2 - (QS')^2}{t_{coating}} \tag{7}$$

where, $K_{coating}$ is the dielectric constant of the coating and $t_{coating}$ is the thickness of the coating. The total capacitance C_{total} can be expressed as the summation of the two capacitances

$$C_{total} = C_{blank} + C_{flange} \tag{8}$$

Throughout the blow forming operation the capacitance C_{blank} would continue to vary while C_{flange} essentially remains constant. Therefore, a decrease in radius of curvature ρ or an increase in depth 'd' of the formed dome at any time 't' would lead to an increase in capacitance according to the Eq. (6).

3. EXPERIMENTAL

A die with hemispherical cavity of 40 mm dia and also a flat matching die were machined from 316 stainless steel. A stainless steel pipe was attached to the flat die for blowing argon gas as shown schematically in Fig. 1. The die blank assembly was held tightly between the rams of a hydraulic press. The die surfaces were plasma coated so as to create an electrical insulation between the dies and the forming blank and also between the dies and the rams of the hydraulic press.

An eutectic composition of Pb-Sn, with 60% Sn & 40% Pb was cast and rolled at room temperature to a sheet with approximate thickness of 2mm. Tensile samples were tested with incremental cross head velocity technique to determine the strain rate regime of optimum superplasticity from the stress – strain-rate plot. The pressure – time cycle was then computed theoretically from Eq. (1), as described in the previous section. The depth (d) vs. time, which is calculated for the chosen constant strain rate of deformation following Eq. (2). Corresponding to the depth change the capacitance change with time was also estimated. The initial capacitance between the flat blank and the die was made as "zero" through instrumentation. The applied pressure was so varied as to closely follow the pre-estimated capacitance vs. time curve. The change in capacitance was continuously measured through an in-house-developed capacitance bridge. The photograph of the indigenously developed instrument and the complete blow forming set-up has been shown in Fig. 4.

FIG. 4 SUPERPLASTIC BLOW FORMING SET-UP ALONG WITH THE CAPACITANCE BRIDGE

4. RESULTS AND DISCUSSIONS

The incremental cross head velocity test data for the Pb-Sn alloy was converted to stress vs. strain-rate and 'm' vs. strain-rate plots as illustrated in Fig. 5. It may be noticed that strain rate sensitivity (m) increases progressively with decreasing strain rate. However a strain rate of 1.1×10^{-4} sec^{-1} corresponding to an 'm' value of 0.6 was considered to be suitable for applying to gas pressure forming that can be completed within a reasonable length of time. A circular disc shaped blank of 80 mm diameter and 2 mm thickness was machined from the rolled Pb-Sn alloy sheet. The required pressure vs. time cycle for blowing the blank to a hemisphere was determined by putting the stress, strain rate values, blank thickness and the die diameter in Eq. (1). The theoretical curve so generated has been shown in Fig. 6. Change in depth was also calculated theoretically and was plotted against time in the same figure. The corresponding change in capacitance with time was also plotted in Fig. 6.

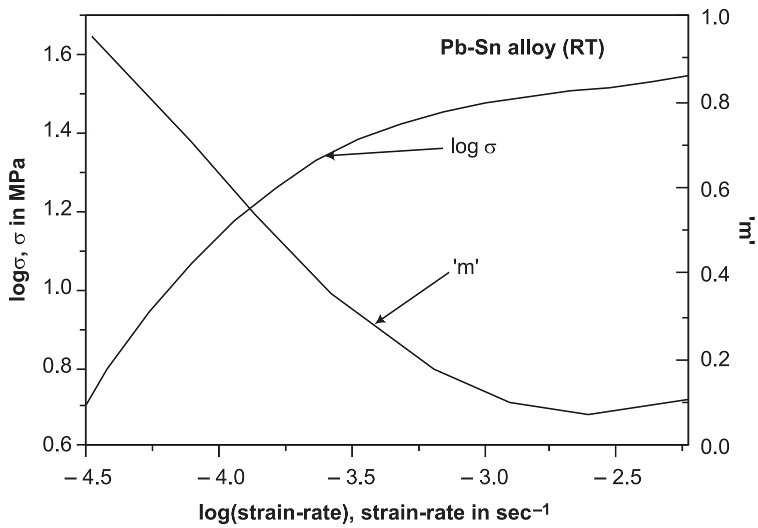

FIG. 5 PLOTS SHOWING "STRESS VS. STRAIN-RATE" (ON LOG-LOG SCALE) AND "'M' VS. STRAIN-RATE (LOG SCALE)" FOR Pb-Sn ALLOY AT RT

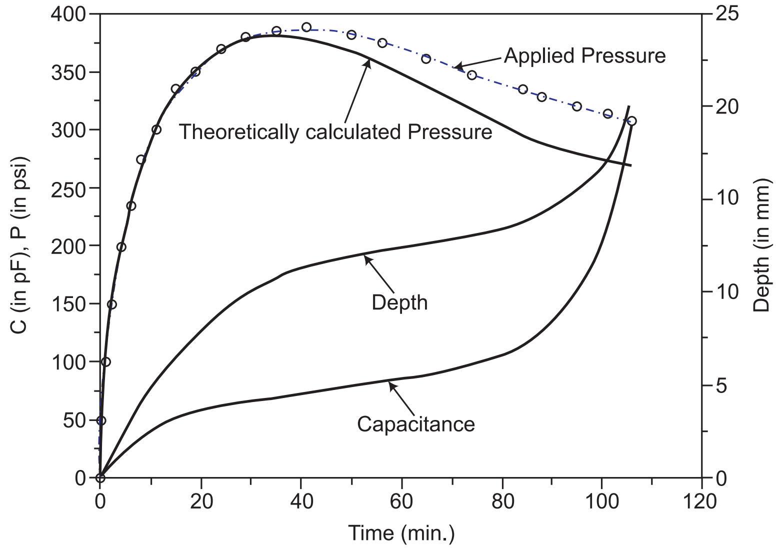

FIG. 6 PLOTS SHOWING THE VARIATIONS IN CAPACITANCE DEPTH, THEORETICAL PRESSURE AND ACTUALLY APPLIED PRESSURE WITH TIME

The Pb-Sn alloy blank was fixed between the top and the bottom dies which were insulated from the blank. Argon gas was then blown over the blank in such a way, as to closely follow the capacitance profile. The actual pressure needed to maintain the capacitance profile (or, in turn the depth profile) was noted and the plot of actually applied pressure has been shown in Fig. 6. It may be noted that the actually needed pressure to deform the blank according to the aimed strain rate is slightly higher than the theoretically calculated pressure rate. This indicates that strain hardening might have taken place with progress of time and deformation. The present observations show that superplastic blow forming can be performed without the knowledge of flow stress data. Moreover, any error in determining the flow stress data and difficulties in obtaining the multiaxial hardening data may lead to the generation of a faulty theoretical “pressure – time” profile. On the other hand, application of gas pressure according to the need as guided by the “capacitance – time” profile, ensures successful forming. The latter method also ensures the constancy of strain rate which is so important in superplastic forming. Progress of deformation can also be followed without interrupting the experiment.

5. CONCLUSIONS

(1) An inexpensive method of monitoring of superplastic gas pressure forming has been discovered, which needs measurements of capacitance.

(2) The present method also ensures successful forming of the complete shape, without prior knowledge of the flow stress.

(3) The method physically ensures complete filling of the die cavity at any particular strain rate, without depending on the complicated material flow behaviours.

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ISSUES IN MIX PROPORTIONING OF FLY ASH BASED SELF COMPACTING CONCRETE

SUBRATO CHOWDHURY, SANDEEP D. KADAM AND PRABIR C. BASU

ABSTRACT

An experimental exercise is undertaken to study issues related to mix proportioning of fly ash based self-compacting concrete. The issues are inadequacy of ingredient's characterization procedure using its physicochemical characteristics, effect of ingredients characteristics on mix composition and criteria to determine ingredient quantities to meet target performance on rheology, strength and robustness of the mix. Outcome of the exercise suggests that rheological characterization of ingredients is necessary in addition to a rational method to proportion optimum SCC mix based on explicit criteria to meet target performance considering ingredient characteristics. Higher powder content and the powder composition that slows hydration are favorable for robustness of the mix.

Key words: Self-compacting concrete (SCC), mix proportioning, rheology, strength, ingredient characterization, robust mix, powder. fly ash, micro-mortar.

1. INTRODUCTION

The objective of concrete mix proportioning is to determine the quantities of ingredients so as to meet specified performance requirements pertaining to engineering properties of concrete and its constructability with minimum cost. Slump, considered as measure of workability, and 28 days compressive strength are taken as the specified performance requirements at fresh and hardened state respectively for traditionally placed concrete (TPC) mix. After placement, TPC mixes like conventional normal strength concrete [1, 2] and high performance concrete (HPC) [3, 4] is compacted by means of external energy input from vibrators, tamping or similar action. Such external compaction is not necessary for self-compacting concrete (SCC) as the mix is so proportioned that it gets compacted within the mould of formwork by its self-weight. The hardened concrete should also satisfy the specified strength and durability [5].

For an intended use in structure, the performance requirements of a concrete mix in the hardened state are same irrespective of whether it is TPC or SCC. SCC can be viewed as a class of HPC with special attributes of self-compaction/consolidation during placement. For mouldability, a fresh SCC mix shall have appropriate workability to fill all the space within the formwork (filling ability), passing through the obstructions caused by reinforcement and/or embedment (passing ability) and maintaining its homogeneity (resistance to segregation) by virtue of its appropriate rheology [6]. These are the three principal functional requirements in fresh state of SCC. The desired rheological characteristics of fresh SCC mix are low yield strength together with adequate plastic viscosity [7]. Such characteristics are not only necessary for achieving desired mouldability but they also help in achieving target strength and durability at the hardened state [8].

Ever since the concept of SCC has evolved, mix proportioning of SCC has been attracting the attention of research workers and still the trend is continuing. Ideally, the mix proportioning methodology should be directly based upon explicit criterion for satisfying all the target functional requirements of rheology, strength and durability simultaneously. Such ideal situation does not exist principally for three reasons. Firstly, the mechanism of transition of a concrete mix from fresh state to hardened state through hydration is quite a complex process and perhaps still not fully understood [1, 2, 3]. Secondly, concrete in hardened state, is a heterogeneous three phase composite and correlations between the phases and their mechanical properties are still subject of intense research [1, 2, 3]. Finally, the requirements resulting from the performance demand often result in contradiction with the requirements of mix proportioning method. Proportioning of a concrete mix under the effect of the above still remains a technique of art rather than science.

Ingredients of SCC mix are similar to those used in TPC mixes. On some occasions, viscosity-modifying agent (VMA) becomes an additional ingredient. A number of methods for proportioning SCC mix have been proposed over the years. In view of more elaborate as well as stringent requirements on rheology, most of the methods are principally concerned with achieving rheology in order to produce self-compacting properties. For a mix proportioning method to result in optimal SCC mix, economical quantity of ingredient (locally available) is to be determined meeting the specified performance requirements with minimum trials. At the same time, the mix should have attributes of robustness. Robustness is the ability of SCC mix to retain its properties against external variability [7, 9]. Sources of external variability are ingredient characteristics, changes in ingredients quantity during batching, mixing and character of mixture. This is a time dependent phenomena. Lack of robustness adversely affects rheological composition and durability of mix [10].

There are quite a few issues related to development of a good mix proportioning method for robust SCC mix. This is obvious from the fact that a large number of mix proportioning methods for SCC have been published till date [11-18]. The present paper addresses some of these issues. The issues cover principally three areas of mix proportioning: i) Ingredients characterization; ii) approach to determine ingredients' quantity satisfying the target performance on rheology, strength and durability as well as taking into account the ingredients' characteristics; and iii) robustness of mix. Experimental program was taken up to bring out the related issues and investigate them. The issues concerning approach to determine ingredients' quantity and robustness of mix were examined by the experiment of reproducing SCC mixes, selected from literature, with local ingredients. While, the issues related to ingredients characterization was studied by conducting tests for rheology of mortar mixes created by the authors. All experiments were conducted on SCC mixes having powder consisting of different types of ordinary Portland cement (OPC) and fly ash (FA) as supplementary cementitious materials. It is expected that the outcome of this exercise will help in future work in the quest for proportioning optimal mix of SCC.

3. BRIEF OVERVIEW OF SCC MIX PRPORTIONING METHODS

SCC mix can be viewed to have two phases. When it is considered as a suspension of aggregates in paste, the two phases are solid phase consisting of coarse and fine aggregates, and paste phase (also known as liquid phase) made of powder, water and chemical admixture [11]. Another way to view the two phases are aggregate phase (solid particle of size > 4.76 mm) and mortar phase consisting of powder, chemical admixtures, water, air and fine aggregates, i.e., aggregate up to the size of 4.76 mm. Irrespective of how the different phases of SCC mix are viewed, ingredients of mortar or paste are to be so proportioned that they become compatible in a SCC mix. Different mix proportioning methods available in literatures attempts to determine ingredient quantity so that an optimum balance between two phases, irrespective of their definition, is achieved in order to that the resulting concrete mix possesses desired rheology of SCC by satisfying certain criterion [19]. Saak et al addressed such criteria, in terms of yield strength and viscosity of paste, to be compatible for SCC [12]. Another important aspect is that a minimum quantity of micro-mortar (fine-grained mortar), involving all particles less than 125μ, water and admixture is necessary in a SCC mix [13].

A number of SCC mix proportioning methods are available in literature. In general, the SCC mix proportioning methods consider volume as the key parameter because of the importance of the need to fill over the voids in-between the aggregate particles by the paste [20]. These methods can be grouped into two categories. The basic steps involved in the first category are determination of quantity of coarse aggregate, and then deriving appropriate quantity of mortar required for the SCC mix [6]. The second category involved evaluation of the suitable quantity of mortar mix and then finding out the quantity of coarse aggregates [21. Proportioning of mortar plays important role in developing successful SCC mix, which in turn greatly depends on quantity and composition of powder. Powder of a SCC mix is the mix of solid ingredients having sizes 125μ or less. It primarily consists of OPC and supplementary cementitious materials such as fly ash, plus fines particles (size < 125μ) from aggregates.

The mixes proportioned by both these categories can further be subdivided into three types; powder type, VMA type and combined type [22]. In first type, powder content is high, typically 475 kg/m^3 or above, with adequate superplasticizer and almost no VMA. The second type involved are of lower powder content, as low as around 350 kg/m^3, sufficient superplasticiser and high quantity of VMA that is required for maintaining homogeneity in view of reduction in powder content. Third type is a combination of the two, wherein small quantity of VMA support is necessary for decrease in powder content (as compared to the first method) to maintain homogeneity.

The credit for developing the first SCC mix proportioning method goes to Okamura and Ozawa in 1995 [6, 23]. Their method falls under first category (powder-type). Coarse aggregate proportion was set at 50% of the dry rodded weight and the mortar volume is determined taking into consideration the air content in the mix. The water/powder ratio and superplasticizer dosages of the mortar were adjusted until the minimum relative flow area of 5 and relative flow rate between 0.9-1.1 are achieved using mortar spread and V-funnel test respectively [5]. A good number of first category methods that produce powder type mix have been developed over the years [10, 24-29]. Jonasson et al developed similar SCC mixes for cast in place concrete for industrial usage [30]. Nawa et al proposed a first category of SCC mix proportioning method [31] that can produce all the three types of mix powder, VMA and combined. They suggested ranges of quantities for coarse aggregate, unit water, powder, and w/p ratio in tabular form. The ranges are applicable for coarse aggregates size of 20 mm or 25 mm and different VMA. Oh et al suggested a similar category method, which produces combined type of mix [32].

Saak et al [12] presented a segregation resistant model for SCC mix proportion. Authors introduced the concept of self-flow zone where the segregation resistance is optimized for SCC at the highest yield stress and viscosity, yet the concrete has high workability. Quantity of water, superplasticizer and VMA were determined by trials till the paste's rheological characteristics fell into the self-flow zone. This method may be viewed as belonging to the second category, one that could produce all three types of mixes. Billberg [13] described a second category method that proportioned combined or VMA type SCC mix. This method assumed fresh concrete as a system of particles suspended both in micro and macro mortar and sought to optimize the mix proportion in terms of minimum micro mortar volume meeting the rheological requirements. He proposed a model to determine total aggregate content for avoiding blocking, V_c/V_{agg} falling within the range of 0.4-0.55. Bui et al [21] introduced a mix proportioning method that can essentially be classified under the second category and can produce both VMA and combined type SCC. The approach is based on the paste rheology model. Effect of aggregate properties and content were considered in developing the new paste model for SCC. Examples of second category method of producing powder type of mix are given in references [33 through 37].

Khayat et al studied the utility of statistical model in proportioning self-consolidating concrete [38]. Their method could be classified under both categories and predominantly proportioned VMA type of mix. Ghezal et al described category two type methodologies that proportioned SCC mix with low binder content and mineral additives[39]. The mix produced from this method was either combined or VMA type.

Moosberg described the approach to characterize filler material for SCC mix [40]. Nachbaur et al developed concrete equivalent motor method for proportioning of SCC mixes with minimum trial mix [41]. The objective was to find a mortar mix, linked to the concrete mix, whose properties can be co-related to the workability and early age compressive strength of concrete. This is a second category mix proportioning method using VMA. Rodriguez et al adapted the mix proportion method of conventional HPC for developing optimum SCC mix [42]. They proposed two steps of optimization, (i) paste optimization using the result of Marsh cone and mini slump test, and (ii) aggregate optimization by achieving minimum voids.

Liberato Ferrera et al [18] presented the rheological paste model applicable for the design of steel fiber-reinforced self-compacting concrete. The method includes the fibers in the optimization of the solid skeleton through the concept of the "equivalent specific surface diameter". Optimization of rheological properties of cement paste and the appropriate choice of its volume ratio are the keys of the method. The model proved to be an efficient tool for designing fiber-reinforced concrete mixtures with selected fresh state properties, employing different ratios and types of steel fiber reinforcement [18].

Though available information specifically on mix proportioning methodology of high volume fly ash based SCC (HVFA-SCC) is little, investigation on the properties of HVFA-SCC has been reported in literature. Dinakar and Babu studied durability of HVFA-SCC by conducting experiments on eight mixes with cement replacement level (CRL) ranging from 0% to 85% [43]. HVFA-SCC exhibited higher permeable voids and water absorption than similar vibrated normal concrete of the same strength. However, weight losses and chloride ion diffusion is significantly lower in case of HVFA-SCC. Mustafa Sahmaran et al observed from experimental investigations that HVFA-SCC exhibited improved self-healing characteristics as compared to that of similar SCC without fly ash [44]. Self-healing attribute was characterized by recovering in compressive strength and permeation properties of cylindrical specimen with pre-existing cracks. They conducted experimentation on fly ash based SCC mix with 0%, 35% and 55% CRL having a constant w/p of 0.35.

4. ISSUES RELATED TO PROPORTIONING OF SCC MIXES

Literature survey presented in the preceding section reveals that there is a host of literature on mix proportioning of SCC. Most of the methods principally differ on determination of ingredient quantity to meet the requirements on rheology without concern for strength. There are a number of methods based on rheological model, which takes the rheological characteristics of ingredients into account indirectly. Publication of so many methods clearly indicates that there exist issues to proportion SCC mix meeting demand on both rheology and strength. Some of these issues were studied through a series of experiments. The physical and chemical characteristics of fly ash and OPC that were used in the experimental study are summarized in Table 1 and that of aggregates in Table 2. Relative density of VMA and two types of superplasticizer whose base materials were sulfonated naphthalene formaldehyde (SPR) and poly-carboxylic ether (SPG) were 1.031, 1.241 and 1.084 respectively.

Table 1. *Characteristics and particle size distribution of Fly Ash and OPC*

Parameters	*OPC*		*Fly Ash*	
	OPC1	*OPC2*	*FA1*	*FA2*
SiO_2 (%)	21.04	20.82	59.52	61.5
Reactive Silica (%)	–	–	29.34	28.9
Al_2O_3 (%)	5.1	4.88	32.55	32.12
Fe_2O_3 (%)	4.66	3.88	3.10	2.81
CaO (%)	63.62	62.85	2.23	1.87
MgO (%)	0.98	2.70	0.25	0.34

Contd...

Contd...

LOI (%)	1.93	1.78	0.63	0.40
SO_3 (%)	2.24	1.58	0.38	0.18
Total alkalies as Na_2O (%)	0.5	0.69	0.75	1.45
Fineness (m^2/kg)	298	361	538	309
Particle Median size D50(μ)	24.4	26.42	23.15	60.16
Particle Size Range: percentage				
300μ-125μ	0	0.26	3.4	19.23
125μ-90μ	1.03	2.74	5.54	14.50
90μ-45μ	20.71	21.62	19.53	25.86
45μ-5μ	68.77	68.35	56.58	32.25
Below 5μ	9.49	7.03	14.95	8.16
Lime Reactivity (MPa)	–	–	6.2	4.0
28 days (cube) compressive strength (MPa)	63.0	62.0	–	–
Specific Gravity	3.18	3.16	2.22	2.10
Initial setting time (minutes)	150	210	–	–
Final setting time (minutes)	215	265	–	–

Table 2. *Physical Characteristics of Aggregates*

Characteristics	*Fine Aggregate*			*Coarse aggregate*	
	RS1	*RS2*	*CS*	*CA10*	*CA20*
Fineness Modulus	2.89	3.62	3.05	5.72	5.99
Specific Gravity	2.64	2.69	2.71	2.78	2.78
Water Absorption (%)	0.26	2.9	2.1	2.05	1.8
Particle size ≤ 125μ (%)	0.0	1.5	12.0	–	–

Note: RS: river sand: CS: crusher dust: CA10: maximum size of aggregates 10 mm; CA20: maximum size of aggregates 20 mm.

4.1 Ingredient Characterization

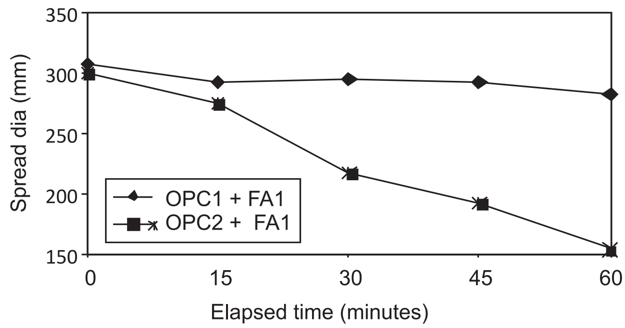
Characterization of ingredients is an essential pre-requisite of proportioning any concrete mix. It is a procedure by means of which ingredients of appropriate quality (characteristics) are selected so that resulting concrete mix satisfies the target performance. Two mortar-mixes M1 and M2 were proportioned with OPC1 and OPC2 cement respectively while fly ash (FA1), SNF based superplasticizer and fine aggregate (RS1) were common for both the mixes. In the mixes, fly ash content was 40% of the total powder content, and the powder to fine aggregate ratio was maintained at 1: 1.45 by weight. The water to powder ratio (w/p) of the mortar mixes was 0.3.

Both the mixes are examined through mortar flow test and mortar V-funnel test [6, 19]. Results of these two tests were plotted, Fig. 1. Spread diameter and flow time of mix M1 remained about 300 mm and 5-11 seconds respectively which was within acceptable zone all along 60 minutes elapsed time, indicating that the mortar had appropriate yield strength and viscosity compatible to SCC mix. In case of M2, the spread diameter fell below 250 mm after elapsed time of about 20 minutes though flow time remained within acceptable range over 60 minutes of elapsed time. The results indicated that M2 could retain sufficient viscosity but not yield strength necessary for SCC. Similar mixes with FA2 fly ash with cement OPC1 and OPC2 were tested. In both the cases, the mix could attain necessary flow diameter for about two minute of elapsed time and it became very sticky with very low rate of deformation. Mix, in the second case, is just like cake. The content of particle size of less or equal to 125 µ was considerably lower in FA2 as compared to that of FA1, which resulted in less micrometer content in the mix with this fly ash.

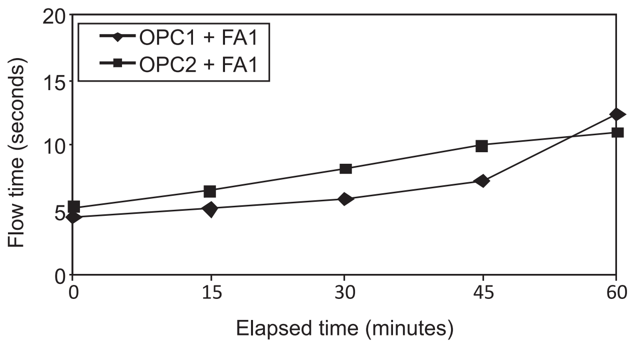
These simple experiments brought out one important issue related to characterization of ingredients for SCC. All ingredients, especially OPC1 and OPC2 cement as well as FA1 and FA2 fly ash satisfies the specification of physical and chemical characteristics suitable for TPC mix. Only OPC1 and FA1 are found suitable to produce mortar of SCC quality. Conventional procedure of characterization only was not found suitable for ingredients of SCC. The scope of characterization procedure needs to be extended to the level of rheological characterization. By the term rheological characterization, it is meant that the procedure of selecting the ingredients that can produce concrete mix of SCC rheology. A detailed discussion on this issue is given in references [45, 46 and 47]. Rheological characterization is important for cement, supplementary cementitious material and fine aggregate. Conducting tests on mortar and/or paste to assess yield strength and viscosity could do this.

4.2 Determination of Ingredient Quantity

Suitable approach to determine the ingredient quantity satisfying the target performance on rheology, strength and durability is the most important area of SCC mix proportioning. Issues in this regard are investigated by conducting experiments to reproduce example SCC mixes taken from published literature. Two mixes, designated J1[3] and J3[3], were selected from the publication of Ouchi and Nakamura [48] for this purpose and are given in Table 3. There is no special reason to select these two mixes excepting, probably, that they were adopted for construction of structures. The trial mixes were cast with OPC1 cement and FA1 fly ash, which are found suitable after rheological characterization. Durability aspect is not dealt directly in this experimental program.



(a) Variation of spread diameter with elapsed time for mixes with (OPC1 + FA1) and (OPC2 + FA1)



(b) Variation of funnel flow time with elapsed time for mixes with (OPC1 + FA1) and (OPC2 + FA1)

FIG. 1 RHEOLOGICAL TEST RESULTS OF MORTAR MIXES M1 AND M2

It is expected that a SCC mix, with rheologically characterizes ingredients and supplementary cementitious material as a constituent for powder, would accomplish the requirements on durability if it meets the demand on rheology and strength.

4.3 Requirements of Rheology

Total four trials on J1 mix and three trials on J3 mix were conducted to achieve an acceptable mix from the consideration of rheology. The test results of the trial concrete mixes and corresponding mortar content are shown in Table 4. Functional performance (rheology) of the mixes was evaluated conducting L-box test, slump flow test and concrete V-funnel test. The rheology of mortar component was examined using mortar funnel and mortar slump flow test [19].

The first trial J1-1 of J1 mix was conducted following the mix proportion of Table 3. Information on the characteristics of ingredients is not available in reference [46]. Composition of powder and unit water content for first trial remains identical with the mix J1[3]. River sand was used as fine aggregate and coarse aggregate composition was 67% of 20 mm down and 33% of 10 mm down.

Table 3. *Details of Trial SCC Mixes*

Trial mix Desig	*Mix Proportion*									
	Mortar Component								*Coarse Aggregate*	
	Powder		*Fine Aggregate*		*Admixture*			*Water (kg)*	*CA10 (kg)*	*CA20 (kg)*
	OPC1 (kg)	*FA1 (kg)*	*RS2 (kg)*	*CS (kg)*	*Super plasti cizer*		*VMA (%)*			
					Type	*Qty (%)*				
J1[3]	530	70	751	–	HRW RA	1.5	–	175	789	–
J1-1	530	70	798	–	SPR	1.5	–	175	281	560
J1-2	530	70	810	–	SPR	2.5	–	175	272.6	542.7
J1-3	530	70	650	163	SPR	2.038	–	195	255	511
J1-4	530	70	649.4	162.3	SPG	1.75	–	194.6	258.4	511
J3[3]	298	206	702	–	HRW RA	2.1	0.1	175	871	–
J3-1	298	206	751	–	SPR	2.1	0.1	175	307	612
J3-2	298	206	667	167	SPR	2.5	0.1	175	274	555
J3-3	298	206	270	641.6	SPG	3.25	0.1	181.9	361.4	361.4
SSC-1	354	354	426	426	SPG	2.5	–	170	618	–
SSC-4	340	340	548	235	SPG	1.93	–	170	533	186

Note: 1. Ingredients quantities are given for unit volume (1 m^3) of fresh concrete mix
2. HRWRA - high range water reducing admixture, VMA - Viscosity Modifying Agent.
3. 3-Mix proportion from reference 48.

Fine aggregate and coarse aggregate quantities were increased by 7% compared with original mix for achieving the unit volume of the concrete. The mix thus produced did not exhibit the characteristics of SCC. It was very stiff and did not flow through V-funnel. The mortar had initial spread diameter of 180 mm and it did not flow through mortar funnel; it was not compatible for SCC mix. Though, first trial J3-1 of combined type mix J3 exhibited better initial rheological characteristics both for the mix and mortar component, the mix became sticky and non-flowable after a short elapsed time. Cement, fly ash and fine aggregate used in the experimentation were characterised with respect to rheology. Failure to reproduce the mix confirms that relative quantity of ingredients for proportioning of concrete mix with desired rheology for SCC was very sensitive to the ingredients characteristics.

To improve the flowability, superplasticizer dose was increased to 2.5% in the second trial, J1-2. The quantities of cement, fly ash and water were kept same. Small adjustment in the aggregates quantity was done; coarse aggregate was reduced by 3% and fine aggregate was increased by about 1.5%. The rheology of the mix as well as mortar was improved at initial stage but still could

Table 4. *Rheological Properties of Mortar Component of Different SCC Trial Mixes*

Trial Mix Desig.	*Mortar*				*Concrete*				
	Volume (%)				*Slump Flow Test*		*V-Funnel Test*		*L-Box Test*
	Micro-mortar	*Paste*	t_m *(s)*	d_m *(mm)*	d_c*(mm)*	*t-50(s)*	t_m*(s)*	t_5*(s)*	h_2/h_1
J1-1	38	38	–	180	–	–	83	–	–
J1-2	39	39	–	220	–	–	54	–	–
J1-3	41	40	14.4	285	785	4	7.5	8	0.82
J1-4	41	40	7.9	326	797	2.47	5.6	6	0.95
J3-1	37	37	12.1	230	570	18	22	–	0.70
J3-2	38	37	7.4	280	740	4.8	8	9	0.91
J3-3	41	38	9.7	298	727.5	3.35	9.03	9.7	0.97

Note: t_m = mortar V-funnel flow time; d_m = mortar slump spread diameter;
t_c = concrete V-funnel flow time; d_c = concrete spread diameter.

not satisfy the requirements of a SCC mix with elapsed time. Further modification in the mix proportion was made in the third trial, J1-3, keeping the quantities of OPC and fly ash same. The unit water content was increased about 11.5% and superplasticizer dose was adjusted downward taking into account of the increased quantity of water. River sand was of coarser quality in the trials J1-1 and J1-2. About 20% of this coarse sand was replaced by crushed sand to make the fine aggregate further finer. The coarse aggregate quantity of mix was reduced by 6%. All these changes resulted in an increase in micromortar content in the mix. The rheology of the mix and the mortar component improved substantially to the acceptable quality but this was retained for a lesser time. With the elapsed time of less than 60 minutes, funnel flow time was sharply increased, spread diameter was decreased and L-box ratio comes down to 50% of the initial value indicating that the mix losses all the rheological requirements of SCC. For retention of rheology, main change made in next trial J1-4 was superplasticizer SPR was replaced by SPG.

Based on the experienced gained from the trials of J1 mix, the quantity of fine aggregate was increased, its composition was changed to make it more finer, and superplasticizer dose was increased marginally in the second trial, J3-2, to improve the flow. In addition, the quantity of coarse aggregate was reduced by 10% and fine aggregate quantity was increased by 11% for reduction of inter-particle friction. These changes resulted in an increase in micromortar content and the rheology of concrete and mortar was well within the acceptable range, but the acceptable rheology could not be retained. In the third trial J3-3, the proportion of crusher dust was increased substantially and coarse aggregate composition was changed. The superplasticizer SPR was also replaced by SPG. The modification resulted in an increase in micromortar content in the mix. The mix, thus produced, had rheology of acceptable quality, Table 4, with retention period more than 60 minutes.

Results of above experimentation conducting trials for reproduction of SCC mix bring out some important issues in connection of SCC mix proportioning method. These are summarized below.

1. It is expected that some adjustment of ingredient quantity is necessary to make any concrete mix amenable to ingredients of different characteristics. This is okay in case of TPC. But the influence of ingredient characteristics is strong on determining the ingredient quantity of SCC mix to achieve desired rheology. Consideration of ingredient characteristics is necessary to be incorporated in the mix proportioning methodology.
2. SCC mix should have minimum unit water content and superplasticiser dose needs to be around a threshold value for the given unit water content. Here, the issue is the determination of suitable combination of unit water content and superplasticiser dose by the mix proportioning method. This is possible if the method incorporates an explicit criterion on rheological characteristics adopted by conducting test on superplasticizer powder compatibility.
3. Micromortar content in both J1-4 and J3-3 is 41%, Table 4. This indicates that irrespective of mix type i.e., powder (J1) or combined (J3), a SCC mix should contain a minimum quantity of micromortar. Importance of micromortar in SCC is well addressed in literature [21]. It may be noted that influence of micromortar on rheology is also found in the experimentation on characterization. Issue, here, is to ensure the required quantity of micromortar in the mix through the mix proportioning method.
4. The volume fraction V_f/V_p is maximum in J1-4 among the J1-trials and in J3-3 in J3-trials and its value is around 1.5 for both the cases. Again V_c/V_f is minimum in J1-4 and J3-3 and their values are 0.971 and 0.771 respectively. This indicates that, for given aggregates and powder quantity, there exists optimum packing of aggregates to achieve desired rheology of the SCC mix. Such optimum level also depends on the characteristics of aggregate. Defining optimum packing of aggregates in order to satisfy required rheology is a challenging task. This evolves another issue, how to arrive at quantities of aggregates by a mix proportioning method to achieve the desired aggregates packing.

4.4 Strength Requirement

Values of w/p in the initial trial J1-1 and J3-1 were 0.292 and 0.347 respectively, which were finally changed to 0.327 and 0.361 respectively, Table 3. The desired rheology was achieved by changing the ingredient quantity; no attention was paid to the strength of mix at hardened state. Strength would obviously be reduced due to increase in w/p. It is observed from literature survey that emphasis of most of the mix proportioning methodologies of SCC is normally to produce self-compacting properties with less or no attention being given on subsequent hardened properties like strength and durability. This is an important issue in SCC mix proportioning.

It is not only the w/p, but the quantity of powder element other than cementitious material also has influence on strength. Fine particle of size ≤ 125μ contributes to strength and other hardened properties as filler material [3, 4]. Though cementitious content and w/p value of mixes SCC-1 and SCC-4 of Table 3 are close, their strength differs. Filler material contributed from fine aggregates in SCC-1 and SCC-4 are 58 kg and 35 kg respectively. Increase in the quantity of filler material along with slightly lower value of w/p contributed to the higher strength of SCC-1.

The presence of fine materials (particle size) plays an important role in micro mortar formation and thus rheology of the mix. This brings out the importance of considering rheology and strength together in the method to proportion an optimum SCC mix.

4.5 Robustness of Mix

Another requirement of SCC mix, which is of concern in recent time, is robustness of the mix [8, 9, 49]. In general, robustness could be enhanced by increasing viscosity, addition of VMA, increasing mortar density, and decreasing coarse aggregate size. This is achieved by proper characterization of ingredient and appropriate mix proportioning. Mixes with higher powder content are potentially more robust [9].

The viscosity of mortar and concrete mixes for both J1 and J3 during the process of trials changed with water content, type and quantity of superplasticizer as well as compositional variations. This is evident from the test results, [Table 4]. The flow out time determined by V-funnel test reduced from 83 second to 5.6 second for J1, and 22 seconds to 9.03 seconds for J3. Low viscosity of J1-4, as indicated from the V-funnel test results, may give rise to the issue concerning robustness of the mix. This is because of an increase in the quantity of water as well as superplasticiser dosage and type. Another reason for J1-4 mix having lower viscosity as compared to that of J3-3 is the difference in powder composition. In the first case CRL by fly ash is about 12%, while it is around 40% n the second case.

A SCC mix is expected to be robust, if viscosity level of the mix falls within the appropriate range of values. Robustness is vulnerable to external variability. The mix should be proportioned with such ingredients whose contribution to the performance of the mix is not vulnerable to external variability. VMA is often used in SCC mix for attaining desired viscosity; the quantity being quite small as compared to superplasticizer. Effect of VMA is susceptible to the external variability, especially the small changes in quantity during batching. Whereas, such changes in quantity of powder does not matter much. It is always desirable to attain viscosity in the mix by virtue of appropriate ingredient characterization and appropriate powder composition and its quantity [7, 9, 48]. This is another issue, which a mix proportioning methodology must take care of.

5. DISCUSSION

Experimental work presented in this paper has two distinct parts. The first part deals with the SCC mix developed by the authors to investigate the aspects related to ingredient characterization. The experimental result indicates conventional approach of physical and chemical characterization of ingredients alone is not sufficient, rheological characterization is necessary. Such characterization procedure would select ingredients so that paste or mortar proportioned with them possesses yield strength and viscosity required for SCC, like the case of mortar mix M1.

Second part of the experimental work is concerned with reproduction of two selected SCC mixes with local ingredients. The mixes could not be reproduced with the original proportion of the ingredients. Desired rheology could be achieved with modified quantities of ingredient by trial and error method without paying attention for target strength. The trials were conducted without any explicit criteria though tests were carried out to ensure that desired rheology was achieved. This led to relatively higher number of trials to reproduce the mixes even though rheologically characterized ingredients were used. Four trials were required for J1 and three for J3 mixes. Moreover, these trials do not guarantee whether the finally arrived proportions of J1-4 and J3-3 are optimal combination to achieve the desired rheology and robustness of the mix.

Another important observation is that risk associated with robustness was higher in J1-4 mix as compared to J3-3 mix though former one had higher powder content. The composition of power was different in these two mixes; fly ash content in the J3-3 mix was almost three times higher than that of J1-4 mix. It is a known phenomenon that fly ash slows down the rate of hydration of the powder. The mix J3-3 contained higher fly ash and its hydration rate would have been slower than that of J1-4. The above finding leads to the inference that composition of powder resulting in slower hydration rate is beneficial for SCC mix. Here lies the advantage of using fly ash in powder for SCC mix.

All these raise an umbrella issue of outlining mix proportioning method to produce optimal SCC mix based on criteria to meet the target performance requirements.

A rational mix proportioning method to produce optimum SCC is expected to take care of the issues addressed in the preceding discussion. This is possible when the method is based on the explicit criteria on target performance and taking into account the rheological characteristics of ingredients. Requirements on both rheology and strength are equally important for deriving an optimal SCC mix. Criteria on the rheological requirements may be formulated in terms of yield strength and viscosity of mortar or paste along with aggregates packing by means of volume fractions. Procedure to determine ingredient quantities by means of tests on paste/mortar should be outlined on the basis of these criteria.

6. CONCLUSION

Issues concerning proportioning of SCC mix are studied. Experimental investigations are conducted in two parts to examine the issues. First part is related to the ingredient characterization using the mortar mixes proportioned in the study. The second part involves with reproduction of SCC mixes selected from literature. Following conclusions are drawn from this study;

1. Selection of ingredients on the basis of their physical and chemical characterization alone is not enough for SCC. Rheological characterization is necessary to ensure that paste or mortar proportioned with the selected ingredients possesses yield strength and viscosity compatible to SCC.
2. Rheological characteristics of ingredients have strong influence on relative quantities of ingredients to achieve desired rheology of the SCC mix. Mix proportioning methodology should take these characteristics directly into account to produce an optimum SCC mix.
3. Powder composition that results in slower hydration rate is desirable for SCC mix. Use of fly ash has beneficial impact in this respect. Use of inert filler material may also serve the purpose.

4. The explicit criteria for a rational SCC mix proportioning method shall be derived for both strength and rheology and should be used together. For strength, the criterion is based on relation between strength and w/p. In case of rheology, the criteria may be derived from the rheological characteristics of mortar or paste, and aggregates packing by means of volume fraction. It is important to ensure minimum quantity of micromortar in the mix.
5. SCC mix, resulting from a mix proportion method should possess inherent viscosity of acceptable level, preferably without VMA, to ensure robustness. SCC mix with high powder content is potentially more robust.

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INTERDISCIPLINARY ENGINEERING

Current Trends in Engineering Practice Vol. III
Editor: Sneh Anand

ENGINEERS AS DESIGNERS AND INNOVATORS

N. S. MOHAN RAM[1]

CREATIVITY, INNOVATION, DISCOVERY AND DESIGN

The terms: Creativity, Innovation, Discovery, Design and Invention are often interchangeably and loosely used. These concepts while interrelated are distinctively different. Engineers as a rule are more likely to be concerned with innovation and design. A few may invent something new. Even fewer are likely to discover new laws of nature. In day to day life, however, one uses creative faculties to varying degrees. It is important that one has a clear understanding what the terms mean. Let us look at the Oxford Reference Dictionary meanings of these terms.

Create- Originate or bring to existence, invent and imagine

Discover- Acquire insight or knowledge by chance or design

Design- Produce a general arrangement or layout of something to be made, often a manufactured product and develop detailed production instructions.

Invent- Create by thought or design something which did not exist before.

Innovate- Bring in new methods, ideas or making changes.

What are the differences between these concepts?

Creation and invention bring into existence a new idea or object, which did not exist before.

Discovery is concerned with a phenomenon or relationship which was not known before.

Design may or may not create something new.

Innovation is often a new arrangement or combination of known things, usually for a commercial purpose.

CREATIVITY

Creativity spans wider canvas than just engineering. Art, Music, Literature, Engineering, Philosophy, Even politics. The paintings of Da Vinci or Picasso, compositions of Mozart or Thyagaraja, plays of Shakespeare or Kalidasa, works of Tolstoy, Valluvar, Silappadikaram, poems of Bharatiyar are creativity at work. Mahatma Gandhi's Salt march or even"Aya Ram Gaya Ram"—floor crossing in vidhan sabha by Bhajan Lall were creative. Something new should come into being, surprise, excite and also be effective. Creativity produces ***Effective Surprise.***

[1]Capt. IN (retired), VSM, FNAE.

PICASSO SCULPTURE AT MOMA

Do you find anything unusual in this sculpture of an Ourang Outang carrying a baby by Picasso displayed at Museum of Modern Art, New York?

CLOSE UP OF SCULPTURE

The face is made up of two toy cars welded together! Only Picasso could see a monkey's face in a toy car. Only a mystic poet Bharati could see Lord Krishna's dark color in the wings of a crow! This is creativity.

DISCOVERIES

Some well known discoveries are

Archimedes Principle, Newton's Laws of Gravity, Bernoulli's equation in fluid mechanics, Pythagoras theorem, Faradays laws, Penicillin, Double helix structure of DNA and RNA, Theory of Relativity. Radium, X-Ray and Raman Effect.

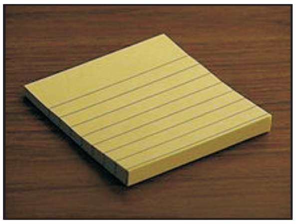
INVENTIONS

Inventions impact every day life and some of them are most commonplace today but were breakthroughs when initially conceived. Some examples with the names of inventors are

Safety Match-Gustav Erik Pasch of Sweden

Safety Pin-Walter Hunt

Internal Combustion Engine-Otto
Incandescent Lamp-Thomas Alva Edison
Zip Fastener-Gideon Sundblack
Intermodal Container-Malcolm Maclain
Television-Baird
Internet-Lawrence Roberts (Arpanet)



STRIPS

SONY WALKMAN

INNOVATIONS

Innovations differ from inventions as they are essentially commercial adaptations of elements already known. Shown below are some innovations which are commonplace today.

CHICK SHAMPOO SACHET

MICROWAVE OVEN

Post it strips, Sony Walkman, Chik Shampoo sachet, SMED process, Tata Nano, Toyota Production System, Microwave oven are essentially innovations as they effectively combine existing ideas or products, in a new way to make a marketable product or processes.

PRINCIPLES OF ENGINEERING DESIGN

Form and Function

Form follows function-principle states that shape of a building or object should be primarily based upon its intended function or purpose.

Examples are Tallboy" cars (Suzuki Wagon-R and Hyundai Santro) unlike Sports cars streamlined to minimize air resistance-City runabouts shaped for maximum passenger room and easy parking. Room for aesthetics within the concepts •Scooterettes for girls radically different from performance bikes for macho men. Indian and Japanese design usually follows this principle.

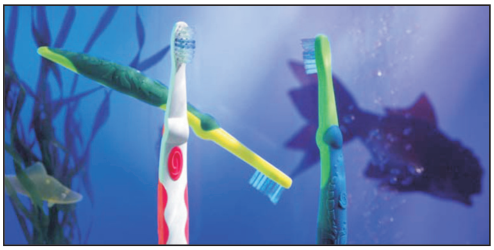
APACHE FOR BOYS

Sturdy outline of a Macho Motorcycle for boys!

SCOOTY FOR GIRLS

Sleek feminine lines for Scooty Pep aimed at girls.

A fine example of functional design was ca children's toothbrush designed by the Palo Alto design house IDEO, which won many awards for innovative design.



CHILDREN'S AWARD WINNING TOOTH BRUSH

Videos of children brushing teeth showed that they found it awkward to handle square shaped sharp cornered miniature versions of adult toothbrushes. Just making brushes smaller was not attracting kids to brush their teeth. Raised soft squishy ridges in the children's soft hands which will not rotate. Seductive colors and size re-proportioned for children's soft and pudgy palms won IDEO corp. US national award for product design.

Occam's Razor- The law of Parsimony in Design

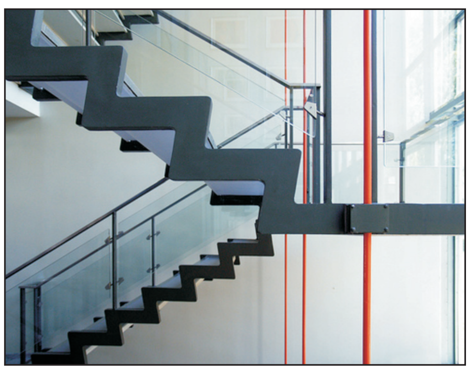
In design-Simplicity preferable to complexity. The law of parsimony postulated by William of Ockham postulated that entities should not be multiplied without necessity.

Nature operates in shortest way possible-Aristotle

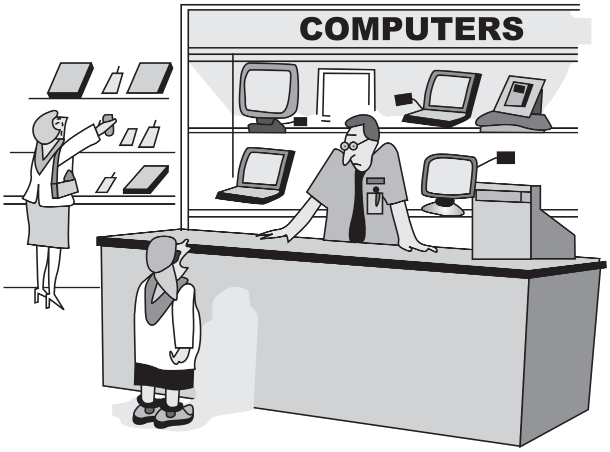
Everything should made as simple as possible but not simpler-Einstein

Unnecessary elements decrease design efficiency. Unnecessary weight: physical, visual or cognitive degrades performance. This principle can be used to evaluate competing functionally equivalent designs. Remove as many elements as possible without compromising function. E.g., computer display with fewest elements.

Some examples- A Scandinavian stool and an elegant stairway.



The cartoon below defines the ultimate vision of simplicity and user friendliness.



"Do you have something so simple that even my parents could use it ?"

LIBERATION OF FORM FROM FUNCTION

Electronics frees form from function.

Example -Apple I-Pod-shape or size does not evoke playing music! Beautiful by itself!

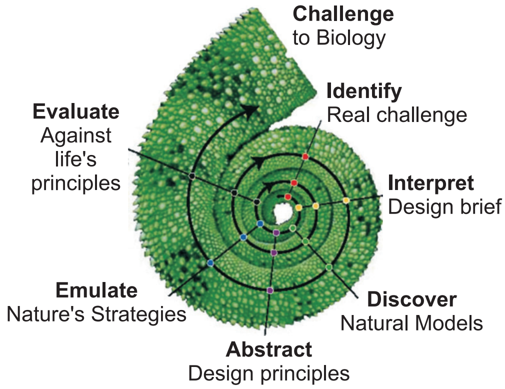
Apple Corporation is the undisputed leader in new paradigm in product design-aesthetic products with s

More and more free forms will enter consumer durables engineering designs also, as technology develops'

IPAD

Biomimicry—Imitating Nature in Design

Biomimicry is a tool for sustainable design by imitating nature. We can use Nature's wisdom for physical design, manufacturing process and logistics. The design spiral shown opposite summarizes the methodology. The design brief is "biologised"to understand how nature deals



BIOMIMICRY SPIRAL

with similar functions. Find out how organisms handle similar issues. Geckos climb vertical and overhanging surfaces. Robotics tries to mimic these lizards use for making robots move over such surfaces. Nature works with constant feedback, learning and adaptive loops. Natural systems operate at much higher efficiencies than mechanical systems.

Termite mounds are able to maintain stable temperatures inside their mounds at ambient ranging from –10 to +40 degree C. Adapting a similar approach, green buildings have been developed, using much less energy for air conditioning. Study of echolocation by bats in darkness resulted in development of a special cane for the visually impaired. The amazing hearing capability of Dolphins and whales is being studied for development of sonar's for anti submarine warfare. Biomimicry can provide techniques for optimizing engineering systems and structures. Murray's laws used for determining optimum diameter for blood vessels has been now reframed after studying biological analogies for determining pipe or tube diameters for minimizing mass engineering system.

The spider's web and beehive honeycomb inspired the genius Buckminster Fuller to develop the Geodesic Dome, which is a spherical or partial-spherical shell structure or lattice shell-based on a network of great circles (geodesics) on the surface of a sphere. This is commonly used in Planetarium and large domed structures.

DESIGN IN REAL LIFE

In school one is taught analysis – e.g., to calculate deflection or stability of a structure with known end conditions under specified loads. In real life loads or end fixity are not known. The structure does not even exist. The challenge is often in finding what questions to ask rather than finding answers to specific questions. Design a gradual progression from the abstract to the concrete in a spiral iterative process. Decisions taken at every stage become constraints later! Important to consider multiple options at the early stages and not to zero in on solutions too quickly. The quickest or obvious answer may not be the best!

Options available to the designer reduce as design progresses from abstract to concrete. For example, one may consider many options of crossing a river- bridge, tunnel, helicopter ride, boat ride, swimming across etc. But once an option is chosen constraints begin to appear. The designer should generate large number of ideas at the early stages, to arrive at optimal solutions

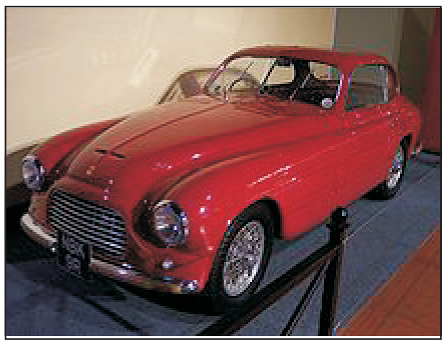
DESIGN IS FUZZY TO START WITH

Any new product design is very undefined and fuzzy to start with. One needs to devote time to understand customer needs and evolve specifications to meet them at product definition stage. One should also have frequent dialogue with customers at early stages and interchange information within the company to avoid costly errors, Organizations should associate designers with market research. "If you do not know where you are going, you are sure to get lost!" said Lewis Carroll in "Through the looking glass".

Let us look at how the concept of short stubby tall cars for urban use "Tallboy car" concept came up. The idea came from metaphor-"Automobile Evolution". Imagine city is jungle-cars are living beings jostling for space. How will the species evolve in Darwinian evolutionary terms? "Stop go" traffic, limited parking space, slow speeds and danger of being dented by other users are typical of urban usage of cars. If cars were living beings, the short, slow and maneuverable mutants will survive. Long, sleek and fast ones will disappear! This was followed by new metaphor, "man maximum, machine minimum". The outcome was a low powered car with good low end torque, short and easy to maneuver and park, liberal passenger and flexible luggage space, automatic gear shift and less space for engines. Results-Boxy design Suzuki Wagon-R, Hyundai Santro. Low power engine with good low end torque for taking off at traffic lights, what is the earthly use of a costly low slung Ferrari in crowded pot holed urban roads?

Contrast a tallboy city car with a sports car.

MARUTI WAGON-R

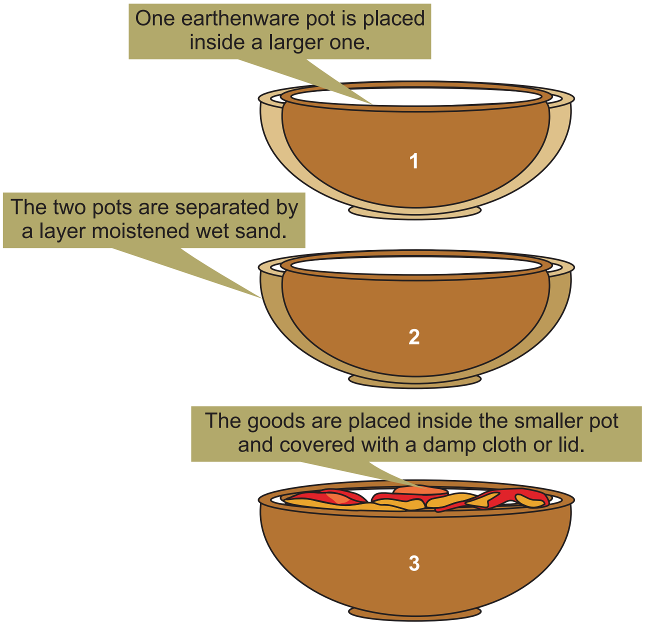


FERRARI

Low Cost Innovations

Storage of food for any duration was a big problem in sub Saharan Africa. Fruits, vegetables and meat were going bad very quickly in the dry and very hot desert climate.

"Zeer"– This was developed in Nigeria using the principle of –Matka –Surahi (Evaporative cooling). A low cost cooler-costing only 1.3 $! Is selling 30000 units per year. It increases storage life of food in Sub Saharan Africa-Tomatoes from 2 to 20 days and Meat from 1 to 14 days! It stores food fresh longer and reduces food related diseases. The economic benefit is that longer storage life leads to higher profits, better opportunities for women to sell food, greater



ZEER

rural employment and wider diet variety. This simple technology, which enriches daily life in an African desert, won Rolex and Shell awards for innovation. The two mud pots are separated by a layer of wet sand, which is periodically moistened.

A Liter of Light

In the slums of Manila, an innovative project is shedding light on the city's dim and dreary shanties. Plastic bottles jut from the roofs, bringing light to the dark dwellings below. Each bottle

LITER OF LIGHT

contains water and bleach. When placed snugly into a purpose-built hole in the roof, the home-made bulb refracts and spreads sunlight, illuminating the room beneath.

Sun light goes through the bottle, working as a window on the roof, and then goes inside the water. Unlike a hole, through which light will travel in a straight line, the water refracts it to go vertical, horizontal and 360 degrees. It provides 55 to 60 watts of clear light, almost ten months of the year. "A liter of light", brings sustainable energy practices to poor communities, from an idea originally developed by students at Massachusetts Institute of Technology.

Facilitating Innovation in Design

The first workable solution or the obvious is not always the best answer to any design issue. One should challenge status quo and learn to think out of the box. We need to understand that constraints are not God given. Blocks often exist only in our minds. We must learn to look for parallels from other fields. Often similar problems solved in other industries. The designer has to read widely, not just engineering books but other books and journals also. Such as the Economist, Popular Mechanics and Scientific American, books on creativity e.g., lateral thinking.

We must respect experts but be aware that their advice not gospel. Check yourself, as experts can also go wrong. One should never dismiss ideas from non experts. (An architect, on honeymoon in Crete, cracked the Minoan script, which had defied linguists for years.) Do not blindly rely on custom computer programs but check order of results by own calculations. Document work and share ideas with others. Design ultimately benefits from teamwork.

There is no greater satisfaction than creating something new, which works. Innovation in engineering is fun!

Current Trends in Engineering Practice Vol. III
Editor: Sneh Anand

ROLE OF ENGINEERS IN INDIA'S DEVELOPMENT

N. S. MOHAN RAM[1]

1. INTRODUCTION

In this lecture on the role of engineers in India's development, I plan first to discuss what motivates people take up engineering as a field of study. I go on to discuss India's growth and development in sixty-five years since we became independent, furnishing relevant data on GDP and employment. I then show how vital was the contribution of engineers to the nation's progress. I move on to discuss the charm and romance of engineering as a profession and the challenges and opportunities it affords to a young engineer.

1.1 Why We Choose Engineering as a Field of Study

Most of us have no idea of what we want to do eventually when we are at school. Our interests are changing all the time, Very few among us have any focus. We are guided by parental or peer pressure or entertain vague ideas of choosing safe options. Most of us drift into engineering studies, without any idea of what it involves.

Unfortunately, in India we do not encourage children to tinker with machines and gadgets. Usually they are prevented from indulging in such activities. They are asked not to waste their time but to study instead. When they land in an Engineering college, many might have never used a spanner or a screw driver! A few may have clear goals, most drift through college without any long term plan or idea of what they will do after graduation.

1.2 How do We Find Our Bearings as an Engineer?

In India we have two types of marriages- love marriages and arranged marriages. In the former, the boy meets and loves the girl before they tie the knot. In the latter, they learn to appreciate and love each other after their wedding! Those of you who came here without a clear idea of what you want to do can follow the latter model! One of our greatest mathematicians, Dr M. S. Raghunathan became one by default! You can learn to love Engineering, while you train to be one. I joined the Naval Architecture course at IIT Kharagpur in 1953 without a ghost of an idea of what it entailed! I went on to design India's first indigenous missile frigate and many other ships for the Navy!

Believe me, this system works well. You have chosen a fine subject. Learn to appreciate it and become expert in it. Allow me share with you the importance and romance of our chosen field.

[1]Capt. IN (retired), VSM, FNAE.

Engineering can be a rewarding and fun career! We can make a real contribution to a resurgent India and have a worthwhile career at the same time.

1.3 India's Economic Growth Since Independence

Let us look at some statistics of the economic growth of our nation over the six decades since independence.

After years of sluggish annual growth of 3 to 4 per cent, India's growth rate accelerated after 1990s, when the economy opened up. Now India grows at 8-9 per cent, doubling the size of its economy every eight years. It is the second fastest growing major economy in the world.

The investment bankers, Ms. Goldman Sachs in their famous "Building Better Global Economic-BRICs" 2001 report had forecast that India will emerge as the world's 3rd largest economy by 2050. Our growth since then has exceeded the forecasts of Goldman Sachs.

In the meanwhile the advanced nations are facing a serious recession. India and China are racing ahead, following different models of governance and economic models. We are leading in the services sector. China is now the manufacturing engine of the world. Our growth is led by private industry while China's growth is mostly driven by state run industries. Over half of China's population is engaged in manufacturing, 10% work in agriculture with the balance in services. Over 50% of our population is still engaged in agriculture with low productivity. Only about 10% is in manufacturing. Services can not provide the requisite number of blue collar jobs for our growing young population. Due to adoption of 'one child' policy, China will have an aging population soon. India has a much younger population, reaping what the economists call a 'demographic dividend'.

We are still a developing country with many difficult problems. Large sections of our population lives below the poverty line. The challenge before us to increase the share of manufacturing and industry in GDP and increase engineering employment to cater for our growing young population.

We need to increase the share of manufacturing in our GDP from 17% to over 30% and increase the pace of urbanization rapidly, if we want our demographic dividend to remain an asset and not become a liability. We engineers have a vital role in making it happen.

1.4 Engineer's Contribution to Our Growth

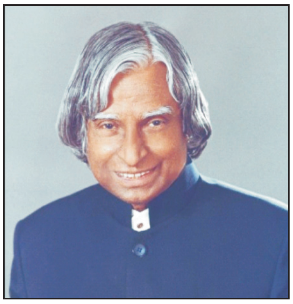
Engineers do not make headlines. Men like Visweswaraiya, Verghese Kurien, V. Krishnamurthy, Sam Pitroda and Sridharan have contributed immensely to our nation's progress. The media devotes more time and space to film stars, sportsmen and politicians than to these people. Alas, good news is boring. The commissioning of Delhi Metro or the launch of a warship gets less column inches than the goings on of Salman Khan or a gruesome murder!

Much of the growth I had mentioned earlier had come out of the work of a large number of unknown and unsung heroes, our engineers. As advised in the Gita, engineers work for the sake of work and not for the rewards and recognition it brings.

1.5 Some Builders of Modern India

Below are_portraits of some of the great engineers who contributed to India- Visweswaraiya, the doyen of civil engineers, Kurien of operation flood, Missile man and former president Kalam, Communication revolutionary Pitroda, Krishnamurthy of BHEL/SAIL/Maruti and Sridharan who built the Delhi Metro. There are many others like Homi Bhabha, Vikram Sarabhai etc., who are the architects of India as it is today.



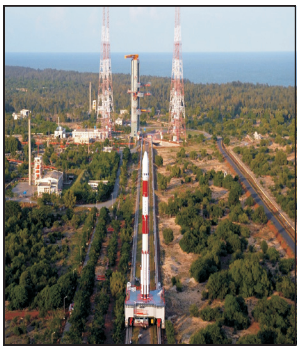
What urged people like this to serve the nation? Many of these people hailed from middle class families and were not from elite institutions like IIT's e.g., Infosys founder Narayanamurthy, Pentium Designer Vinod Dham. What drove these people was a desire to serve and a constant quest for excellence. The one thing they did not chase was money!

If one chases money, it becomes an obsession. If you chase excellence, money chases you! All these people were motivated by a strong urge to serve the nation.

1.6 Some Engineering Marvels

Bhakra Nangal dam, Polar Satellite Launcher Vehicle transporter, Reliance giant refinery at Jamnagar, Worli-Bandra Sea link, TATA Nano, Light Combat Aircraft for the Air Force and Navy's stealth frigate are some examples of India's growing engineering prowess.

BHAKARA NANGAL DAM



RELIANCE GAINT REFINERY JAMNAGAR

RELIANCE GAINT REFINERY JAMNAGAR

WORLI-BANDRA SEA LINK

TATA NANO

LCA IN FLIGHT

INDIAN-NAVY STEALTH FRIGATE

1.7 Engineering Enriches Ordinary People's Lives

Late CK Prahlad, the renowned Indian Management Guru wrote a seminal work "Fortune at the Bottom of the Pyramid". The "Economist" included it in its list of six significant management books of all time! He pointed out that the "poor" earning less than 2 $ (100 rupees) a day, were significant producers and consumers of goods and services. Meeting their needs can be profitable and serve society at the same time.

Frugal Engineering can serve their needs by using appropriate technology and reducing costs. Notable Indian examples are the TVS moped, Jaipur Foot, low cost mobile service, shampoo satchels and Arvind Eye Hospitals. Serving the needs of the poor is one our major challenges.

Carlos Ghosn the CEO of Nissan Motors and Renault identified "frugal Engineering" as one of India's core strengths. Frugal Engineering is the ability to develop and market products and services at low costs and with least investment, minimum use of materials and economic manufacture. TATA Nano, Indian two wheelers and three wheelers and the amazing Jaipur foot are prime examples.

The challenge before the Indian Engineers of tomorrow is to leverage our advantage to produce quality goods and services at the lowest cost in the world and to compete in the world stage. This is important on account of rapid depletion of fossil fuels, mineral resources and increasing ecological demands. While India's energy needs and production will inevitably show rapid growth, we have to take care of the environment and conserve resources.

1.8 Economic Mobile Telephony

Sam Pitroda made telephones affordable to the common man by introducing low cost STD and PCO booths. With the growth of mobile communication, costs have plummeted. One can get a basic handset for Rs. 1000 and a low end smart phone for as low as ₹ 5000. Mobile telephony in India is the cheapest in the world. The audio quality is also satisfactory.

The "Economist" estimated that the mobiles added nearly 1% to our GDP. The ITC I-Chaupal uses the power of mobile telephony to provide latest price of produce, cost of fertilizers etc., to farmers and increased their earnings. Mobile telephony has reduced waste of time and movement to a great extent. It is poised to enter banking in a big way following the African model.

1.9 UID- Aadhar Card Program

Government of India has envisioned AADHAR a Multi-purpose National Identity Card or Unique Identification Card (UID card) project.

Government will own and operate the Unique Identification number database. The aim is to provide a unique number to each Indian. The authority would create a national database of residents containing very simple data in biometrics, which consist of thumb prints and view of the irises of the two eyes. Conceived by Nandan Nilekani, the former CEO of Infosys who heads the authority, the plan is to cover 600 million of our population by the end of 2012. Enrolment is proceeding at 250,000 per day and will be stepped up to a million people per day.

It aims to provide proof of identity to poorer Indians, especially migrant labor, easy access to banking and financial systems and avoids the need for multiple proofs for access to services. The exercise is being done at a fraction of the cost of similar initiatives abroad. When it is up and running it will be a game changer for our country.

2. JAIPUR FOOT

Jaipur foot was invented in 1968 by a master craftsman Ramachandra Sharma and popularized by Dr. Sethi.

The foot was originally an artificial prosthesis foot made of vulcanized rubber quoted over wood, with multiple axis flexibility. The original design has been modified and improved over the years. Over half a million have benefited using the invention. Danseuse and actress Sudha Chandran continues to perform after losing her foots in an accident with the foot. It costs less than 30 $ (Rs. 1350/) against thousands of dollars of western models. The foot provides amazing mobility.

JAIPUR FOOT

2.1 Empowerment Through Mobility

Technology empowers the common man. It provides him mobility and access to information. It reduces transaction costs and delays. In the long run technology can reduce corruption- e.g., land registration systems. A classic example of the power of affordable mobility is the TVS 50 moped and its successors TVS XL and TVS XL Super. Over 75 lakhs of these iconic vehicles have been sold. On 7th of July 4 millionth XL Super was rolled out of our plant. We produce over 65000 mopeds per month and sell them all over India, confounding marketing experts who forecast their demise. These micro commercial vehicles which cost less than ₹ 28000, provide low cost commuting and movement of goods.

The amazing moped!

PROVISION CARRIER

MERCHANDISE CARRIER

3. ROMANCE OF ENGINEERING

Believe me, there is no feeling to compare with the happiness of an engineer when he or she sees her product or handiwork come to life.

I put pencil to paper in the design of INS Godavari in May 1974 and was on the bridge when the ship reached full speed of 29 knots on trials in the high seas. There is nothing to match that moment in my entire life. I see the same excitement in the eyes of young engineers who enjoy their work, wherever I go.

We engineers are the vanguard of mankind's progress. We should be proud we chose this profession which enriches life. India offers great opportunities to engineers as it is in the cusp of growth. There are opportunities aplenty waiting for you.

4. CHALLENGES AND OPPORTUNITIES

Technology is advancing at a blinding rate. Today's young engineers have to learn a lot more in a shorter time than we had to. If one is not continuously learning, one can become obsolete in no time. India is still a poor country and has to develop rapidly to become a developed nation as visualized by ex President Abdul Kalam in his vision 20-20.

Global warming and ecological factors greatly complicate engineering today. One has to keep in mind recycling at end of life to conserve depleting resources and to reduce carbon footprint. India imports over 80% of its crude oil. With greater development, our energy needs are increasing rapidly. We have to conserve and save energy to the maximum extent possible.

With globalization, we have to compete with the best in the world. Either we enter the global stage or we have no stage to play at all.

Today's engineers have to be versatile and learn to do more with less. There are severe challenges but there are also multiple opportunities

4.1 Final Word of Advice

Make full use of time while at the engineering college. Time available for study reduces after one takes up a job. This is the best time to learn.

Do not just chase grades or marks, Concentrate on learning.

One runs the danger of forgetting fundamentals due to the availability of customized software programs- losing the wood for the trees. Stress on fundamentals in all subjects.

Make use of vacations in internships or even working as a mechanic somewhere. Learn manual skills.

Do not think of the course as a mere passport to a job. View it as a doorway to continuous learning and personal advancement.

Never limit yourself and perceive yourself in a narrow manner.

Never underestimate your capabilities. If one has the ambition to succeed, one will develop capabilities and find the opportunities.

Current Trends in Engineering Practice Vol. III
Editor: Sneh Anand

ENGINEER AND THE SHOP FLOOR

N. S. MOHAN RAM[1]

1. INTRODUCTION

Many young engineers regrettably think that shop floor work is boring and routine. They prefer jobs in Marketing or R&D as more interesting and less strenuous. Some even leave the profession for software jobs or business studies.

The Shop floor is where real action takes place-where materials are made, metal is shaped, things are formed, parts are joined and products are created. It is where the ideas of Marketing, design from R&D and production processes from Engineering converge to create a product. This is where the rubber meets the road. This is the sacred space where men, machine and methods interact fruitfully.

Great companies like GE, Toyota Motor, Boeing, Du Pont and India's leading organizations, L&T, TATA group, TVS group, Mahindra & Mahindra group owe their leadership substantially to their superior shop floor practices.

2. COMMON MISCONCEPTIONS

Often engineering students carry some misconceptions about shop floor work. These are

1. Shop floor work is monotonous
2. It does not offer scope for originality, creativity or new learning. One just follows instructions generated elsewhere.
3. Working with blue collar workmen is boring and unpleasant. There is little scope for intellectual stimulation in day-to-day interactions.
4. Shop floor jobs are unglamorous dead-end jobs. There is no scope for growth unlike jobs in Marketing, Planning or R&D.

2.1 Recent Revolution in Manufacturing

In recent years, a sea change has occurred in shop floor practices. Production-friendly designs, new material technologies, advanced processes and superior methods have vastly improved workplace

[1]Capt. IN (retired), VSM, FNAE.

productivity. The creative power of the workmen who do the actual work has been recognized and harnessed. Control over their tasks and quality have been restored to the workers.

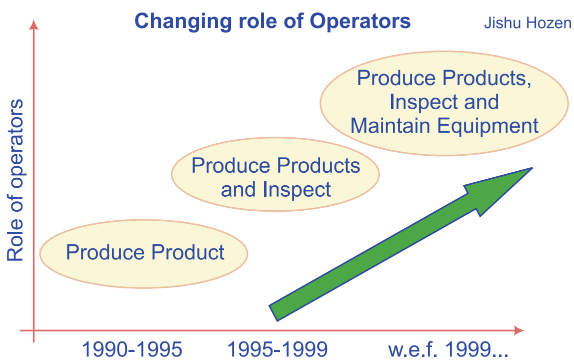
Production jobs are challenging and interesting for young engineers. They help to hone their interpersonal skills and prepare them for senior positions.

Outstanding CEOs of many successful companies worldwide had worked in the shop floor during their careers. They attribute their success partly to shop floor experience.

2.2 Working in Teams

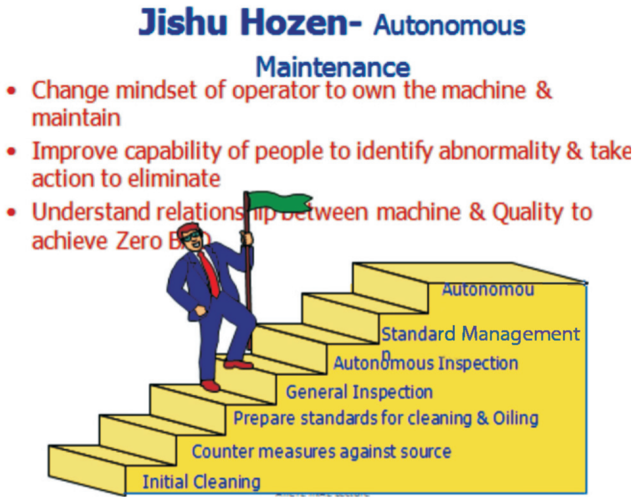
Shop floor improvements span four dimensions. Quality of products and processes Cost of production and products, Delivery of products to plan and Morale of work force. Most of the improvements are achieved by people working in teams. Improvements are best achieved by people working together to solve problems. Teams can work in four ways, depending on the scale and magnitude of the tasks: Quality control circles- where groups of workmen solve issues and effect improvements in their work place; Supervisory Improvement teams—where supervisors work together to solve problems in their department; Cross-Functional teams—where people from different departments solve problems which straddle functions and Task Forces—Temporary matrix structures set-up to tackle major challenges of the organization.

The role of operators is changing from just producers to producers, inspectors and maintainers of equipment.



The Japanese Jishu Hozen concept in Total Predictive Maintenance (TPM) gradually leads to a situation of autonomous maintenance of equipment, leading to increased availability, improved quality and superior performance.

In Quality circles—Small groups carry out improvements voluntarily in their own work place Group of 4-5 employees operate with an executive as a facilitator. They meet every week (in common areas like the canteen) after working hours. They are trained on use of problem solving methodology (QC Story) and 7 QC tools; they make presentations to the management on completion of the project. For a project to be successful, consistent quality, reliability and durability is essential.



3. SUGGESTION SCHEMES (TEIAN)

TEIAN is an idea proposed and implemented by an employee towards improving his/her own workplace. TEIAN aims to engage every employee to take interest in the organization, develop improvement orientation in the employee and induce creativity and use the full potential of employees.

This breaks drudgery in the workplace to perform just routines. When they implement improvements and adapt to it, they become open for improvements and change. Figure below illustrates a suggestion for reducing number of tools in crankcase machining operations.

Another simple suggestion halved the time for cleaning a fixture.

Workers can be motivated to offer suggestions by personal and public recognition by top management and cash awards. They can be informal during walk around or structured at major public functions of the company.

3.1 Task Forces and Cross Functional Teams

Major improvement projects require cross functional involvement at managers/executives level. The projects require rigorous application of problem solving methodology – QC Story and QC tools. For such teams, one selects members from relevant functions with required experience. The teams work on part time basis with a manager who owns the result as the sponsor. Typically, projects handled by such teams cover: Quality improvement – performance, Process capability, Durability and reliability, Productivity improvements and Delivery improvements.

A typical example was a process change in a moped shock absorber, changing chrome plating to powder coating to reduce costs and environmental damage.

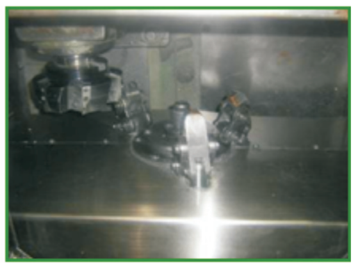
Suggestion sample : 4

Some examples of TEIAN....

Hard to clean   Machine: R2

Before

After



- Hard to clean the fixture
- Provided localized guard on fixture

Benefits:
Cleaning time reduced from 20 mins/day to 10 mins/day

Applicable Areas-1
Completed Areas-1

4. HOME KAIZEN

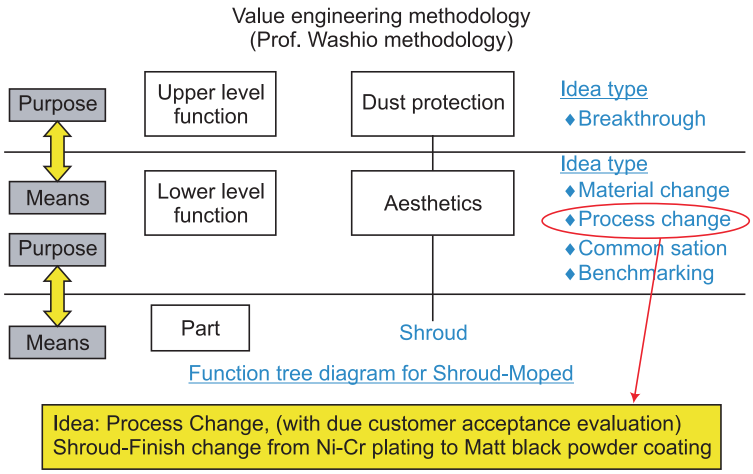
To ensure quality of products, industrial workmen are expected to maintain high standards of workplace hygiene and cleanliness. At the end of the day's work, theyoften go home to live in slums and unhygienic surroundings. There is a serious disconnect between the living conditions in their homes and the expectations of the workplace.

An interesting innovation carried out in TVS Motor Company required the families of workmen to be involved. Workmen's wives were trained in Japanese 5-S and Kaizen techniques and encouraged

Project Title

Value Engineering on Shock Absorber Model-XL HD

Function Tree

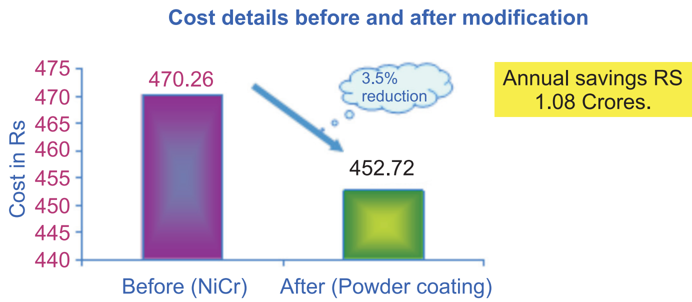


to apply the same to their homes. The improvements carried out by the families are showcased during the founder's day celebrations of the company. Most of the improvements cover safety at home, children's education, waste elimination and good housekeeping. The improvements done by the families are displayed in a large exhibition stall and top three improvements are recognized and rewarded by the chief guest at the function. Here is an example of a simple improvement done in a workman's home.

These changes in workmen's lifestyles and living conditions have definitely contributed to the impeccable cleanliness and organization of the workspace in TVS Motor Company, a Deming prize winning manufacturer of two and three wheelers.

5. SINGLE MINUTE EXCHANGE OF DIES. (SMED)

One of the innovations pioneered by Taichi Ohno of Toyota which has greatly increased productivity and flexibility in manufacture is SMERD, a technique by which complex dies in presses can be achieved in less than ten minutes, instead of hours it used to take earlier.



Before   After

SMED is a method of systematic approach for setup time reduction, according to quantified target.

Single Minute Exchange of Die = Exchange dies in less than 10 minutes.

Single Minute Means that necessary setup time is counted on a single digit.

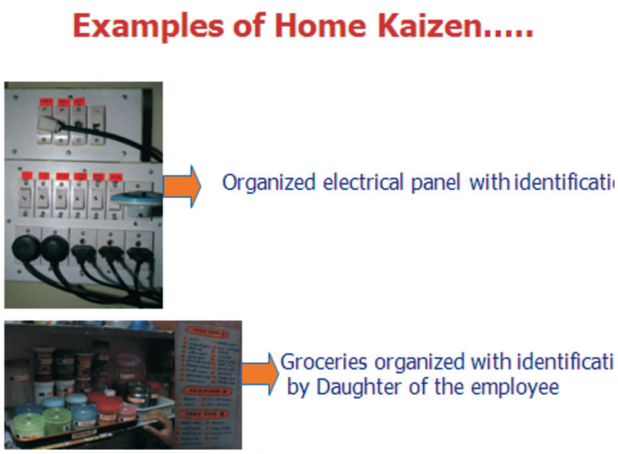
The four steps to SMED are

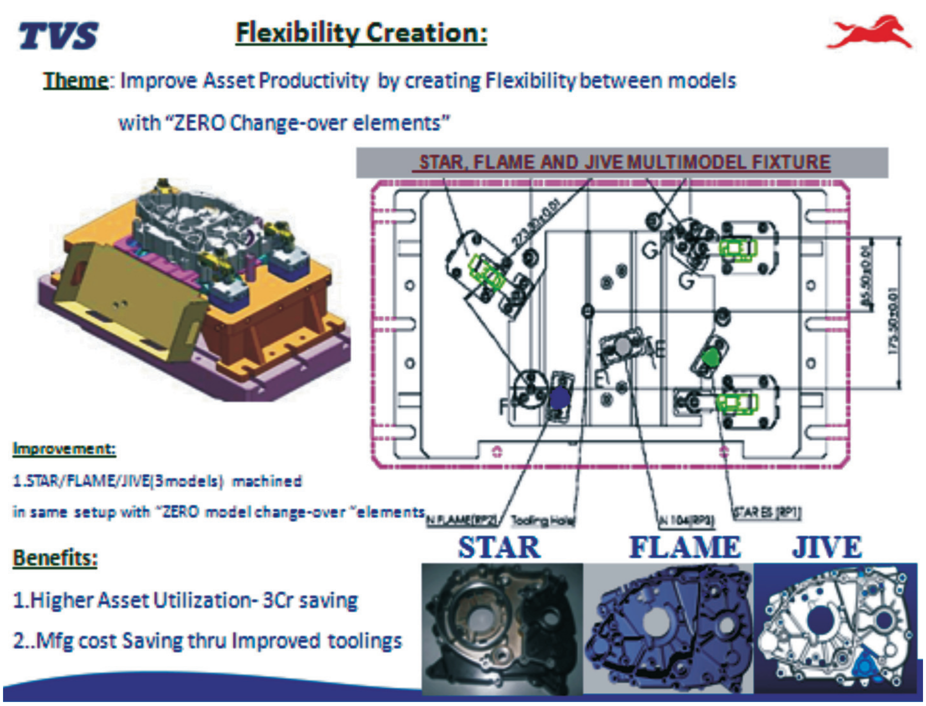
1. Discriminate operations that MUST be done while machine is stopped, called internal setup (IS), from those possibly done while machine runs, called external setup (ES), and useless operations.
2. Suppress useless operations, convert internal setup operations into external setup.
3. Simplify fittings and tightening.
4. Work together! And
5. Suppress adjustments and trials

A practical example of die change by making a flexible fitting is illustrated below.

6. AUTONOMATION (JIDOKA)

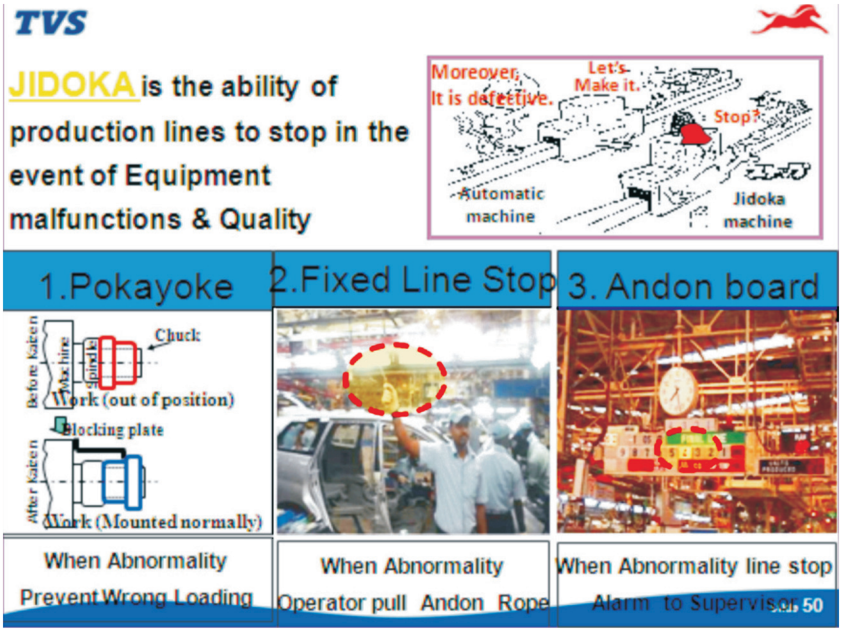
- Jidoka is providing machines and operators the ability to detect when an abnormal condition has occurred and immediately stop work. This enables operations to build-in quality at each process and to separate men and machines for more efficient work.
- Jidoka is one of the two pillars of the Toyota Production System along with just-in-time.
- Jidoka is sometimes called autonomation, meaning “automation with human intelligence”. It increases quality, lowers costs, Improves customer service and reduces lead time





The four steps in Jidoka are

1. Detect the abnormality
2. Stop the operation
3. Fix or correct the immediate condition and finally investigate the route cause and find a long term counter measure.



Poka yoke or mistake proofing- involves

- Visual control of quality
- Prevents defects from happening
- Example: A floppy disk can only be inserted into the drive in one orientation
- Andons
- Commonly lights to signal production line status
    - Red: line stopped
    - Yellow: call for help
    - Green: all normal
- Andon signals require immediate attention
- All of the mechanisms of lean manufacturing follow the same pattern
- They are designed to operate with the bare minimum (just enough, just in time) in order to detect abnormal conditions or system changes that might otherwise go unnoticed
- Detecting an abnormal condition does no good, though, unless there is follow-up
- Visual controls are just decoration unless they trigger action
- Bringing all production to a grinding halt until the problem is resolved can be difficult
- Depends on the nature of the problem. But stop is frequently simply a mental shift. It means "stop doing what you were doing because you need to do something different." It is an acknowledgement that some kind of intervention is required. That might mean shutting down a process or machine, or it might mean signaling for assistance.

6.1 Shop Floor work can be Challenging and Exciting

I have just provided you snapshots of the exciting things which are happening in shop floors around the world and in India. Working on the shop floor engineers deal with immediate live problems, work with people, and develop in depth knowledge and managerial capabilities. I strongly urge that time in the shop floor is the best investment one can make in one's career and for future advancement.

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MANAGING AN ENGINEERING CAREER (EXTRACTS)

N. S. MOHAN RAM[1]

(This lecture is a summary of a US lecture, which I had saved long ago. I am unable to trace the author's name for acknowledgments-anyway thanks to the unknown author!)

1. INTRODUCTION

This lecture is aimed at undergraduates, master's degree students and Ph.D scholars, who are aiming to enter industry to pursue an engineering career.

The first thing you have to understand is that a professional engineer's life is very different from that of a college student. You have to learn new skills and develop new abilities to succeed as an engineer. You have to

1. Learn to be business oriented
2. Handle tough, multi-disciplinary problems
3. Learn to work and network in multi-cultural and multi-national environments
4. Understand differences between academia and industry
5. Learn to differentiate oneself
6. Understand values and culture of the organization you have joined.
7. Be open to new ideas
8. Have total integrity
9. Make your boss a success
10. Support your University and Technical Society
11. Have fun and most importantly
12. Manage your career substantially by yourself.

2. DEVELOPING A BUSINESS ORIENTATION

Most engineering students have no clue of what business is about. In India, it is likely that some faculty members might also have not had exposure to industry, with all their experience confined

[1]Capt. IN (retired), VSM, FNAE.

to academia. One does not need a formal MBA degree to become business oriented. Instead one has to develop the mindset to learn what works in business and what does not and understand the Economics of business. The best way is to learn on the job quickly.

You must understand the cost of doing business and that business is increasingly getting globalised. One also must understand the importance and relevance of why companies need to make profits. One has to understand competition and learn to diagnose and manage the marketplace. One has to understand different types of money *viz.,* **"color of money"**- capital investments, administrative and overhead expenses, training expenses, R & D expenditure and surplus left over as profit. Mixing up different type of expenses can lead to errors and may even be illegal.

2.1 Learning to Handle Tough and Multi-Disciplinary Problems

Real life problems demand both technical and non technical knowledge- e.g., machine design, heat transfer, materials, purchasing, legal etc. Time bound college work on single topics is not designed to use multi disciplinary approaches. (Some colleges give projects which challenge and demand broader approaches - e.g., SAE formula car, design competitions etc.) One has to quickly learn disciplines not one's own and learn quickly on the job.

2.2 Learning When to Stop

We must learn to stop when more refinement adds cost but not value to customer. This also wastes time. Over refinement is usually caused by 1. Over-design- resulting in cost/manufacturing complexity increase. 2. Over-research- Ask yourself, is an answer needed? This is particularly difficult for advanced degree holders, trained in Ph.D. research techniques, stressing total understanding of underlying principles and 3. Over-analysis- The last 0.05 points in efficiency may not be real. This tendency is aided by modern computer capability.

One has to find out "value" as defined by customer and drive value into the product, stopping at the appropriate point. This disciplined approach is also known as listening to the 'Voice of the Customer' (VOC) and finding what is 'Critical to Quality' (CTQ).

2.3 Learning from Discrepant Events

A discrepant event occurs when information received differs from expected and past experience. Real progress stems from such events- e.g, discovery of Penicillin. Some times the unexpected event may not be bad data- could be new facts, a breakthrough. For example, Propeller blades became smaller after a broken blade showed greater efficiency. GE found huge gain in efficiency with variable stator prototype for axial compressors- which looked suspect initially but found to be a major breakthrough.

2.4 Learning to Network in New Environments

Networks are supportive systems sharing appropriate information and services among individuals and groups with common interest. One needs to devote time and effort to connect with others working in the field. Internet with open sources like professional social networking site, Wikipedia, email etc., facilitate networking. Networking with others in the field, through technical society work etc, may lead to promotion, job opportunities and advance careers. One can reap rich rewards from effective networking.

In industry one tends to work in reduced time scales to meet tight time schedules demanded by industry. One has to network as a team player. In colleges networking is mostly confined to association with people in the same discipline On the contrary in industry, engineers and others from different disciplines and conflicting demands work together to solve problems.

Take for example the design of wing for an aircraft or missile. The aero designer wants a complex airfoil shape and thinness, the mechanical designer wants thicker material, the materials specialist wants a particular material, which the marketing man say that it is too expensive and manufacturing says they can't manufacture that. How does one reach consensus?

In academia people mostly work alone- in industry work mostly together

One needs to develop networking communication skills, learn to write reports, summaries and make presentations.

Most importantly one should learn how to give a good "Lift speech". Say, you walk into a Lift with the VP of engineering who asks how is the project going. You have a few floors of travel to explain your work. He has no time to listen to details. Can you be concise, cut to the kernel of your work and give a good impression in 60 seconds?"

Always be concise but clear in communication. However, do not make things too brief, omitting essential detail. Einstein once said "Make things simple but not too simple!"

Most importantly, one has to work in multicultural environments with people of different ethnicities, languages and time zones.

2.5 Understanding the Difference between Academia and Industry

Generalizations comparing academe and industry

Academe	*Industry*
1. More individual oriented	1. More team oriented
2. Is it original work?	2. Can we leverage existing work?
3. Does it add to science?	3. Does it contribute to the business?
4. Will it be published?	4. Can it be produced efficiently?
5. Is it interesting to do?	5. Is it worthwhile financially?
6. Develop the equations. analysis from first principles	6. Fit a curve through the data and/or anchor the existing analysis
7. Is it Original and complete from scientific perspective?	7. Is it institutionalized from an engineering perspective?
8. Finish thesis- Graduate	8. Meet schedule and budget
9. Publish, publish, and publish	9. Customer, customer, customer
10. Sound scientific process templates	10. Design practices

11. Non-profit	11. For Profit
12. Solve roadblocks as they occur for risk abatement.	12. Has up front formal process
13. Professors are independent and free to do research.	13. Management accountable to shareholders

3. DIFFERENTIATING ONESELF

Make yourself different- Enhance your strengths, fix your weaknesses. Capture the four "E"s- Energy, Energize, Edge and Execute.

Energy - Develop high energy levels and enthusiasm for work. Become a dynamo accomplishing things.

Energize - Develop the ability to energize others around common goals.

Edge – Develop clear characteristics separating you from others in measurable, favorable ways and cultivate the ability to make tough yes-and-no decisions.

Execute- Deliver consistently on promises. It isn't that one never makes mistakes or takes risks but overwhelmingly one delivers.

3.1 Respect and Cherish the Values of Your Company

You have to understand the values and code of conduct that your particular company or organization promotes and lives by. Learn them and live by them (provided they are legal and moral).

For instance, in General Electric Corporation, they are called "GE Values" published, promoted and insisted upon by management. TVS Motor has its own way and values promulgated company wide. Similarly, you will have "your company or organization will have its own credo to follow.

It is great to have a benchmark and code of conduct against to measure one's and other's actions. Companies take these very seriously. They relate to honesty, trustworthiness, conflict resolution, fairness, safety, diversity, etc. If you can improve them, try to do so. If they need changing, be a catalyst for this change.

If you just cannot fit into them, move on. Otherwise you may be "moved on" faster than you think.

3.2 Be Open to New Ideas

You must develop an open and positive attitude. Avoid NIH (Not invented here) syndrome. History is full of detractors of good ideas. Here are some examples.

- "This 'telephone' has too many shortcomings to be seriously considered as a means of communication. The device is inherently of no value to us." Western Union internal memo, 1876.
- "Heavier-than-air flying machines are impossible" Lord Kelvin, president, Royal Society, 1895.
- "Everything that can be invented has been invented", Charles H. Duell, Commissioner, US Office of Patents, 1899.

- "Airplanes are interesting toys but of no military value",
- "Professor Goddard does not know the relation between action and reaction and the need to have something better than a vacuum against which to react. He seems to lack the basic knowledge ladled out in high school", New York Times editorial re Goddard's rocket work, 1921.

  The wireless music box has no imaginable commercial value. Who would pay for a message sent to nobody in particular?", The associates of David Sarnoff in response to his urgings for investment in the radio in the 1920's.
- "Who the hell wants to hear actors talk", Harry M. Warner, Warner Bros. 1927.
- "I think there is a world market for maybe five computers", Thomas Watson, Chairman, IBM, 1943.
- "There is no reason for any individuals to have a computer in their home", Ken Olson, president, chairman and founder of Digital Equipment Corporation, 1977.

On the flip side of the coin, there are also those who have doggedly persisted in advancing new ideas that violate the second Law of Thermodynamics, so be alert.

4. MAINTAIN UNYIELDING INTEGRITY

Most organizations these days have formal "integrity" statements, spelling out clearly company policies. A few integrity statements one meets are market-driven. One may, over time, become numb to the constant messages. But this does not in any way detract from their validity and from the necessity for you to maintain high integrity throughout your career. Whether you get caught or not, cheating is wrong. Character is important. The recent devastating effect that cheating and distorting the financial books has had on the corporate world and the US Wall Street should be ample evidence of the need for integrity. Satyam Computers fall is a case in point.

But beyond this, the non-technical society is at the mercy of the technical person. Careless design and lazy analysis can cause social, economic and environmental damage to society and technical embarrassment to you and your company. It can even cause people's injury and death. You, as an engineer, must exercise unyielding integrity to do your best to prevent these things from happening.

One measure you can use is called the ***"Newspaper Test"***. Can your action or conduct stand the Newspaper Test, i.e., appear on the front page of the newspaper without legal or moral embarrassment to you or your company?

4.1 To Succeed, You Must Make Your Boss Successful

Remember the boss recommends high potential people for promotion, determines salary actions, writes performance appraisals, assigns vital say in your future! Regarding your manager as your nemesis is a sure way to fail in your career. Don't do it. If you do not have respect for your manager or if you feel antagonistic towards him or her, transfer to another job.

Also, remember the fault may well be yours, examine your reactions and motives carefully. Perhaps introspective thinking or attitude adjustment on your part is necessary.

Learn to conduct your assignments so that you need little of the boss's attention. Be a "can do person".

4.2 Support Your University/Technical Society

Remember with gratitude and affection, the university and its professors who nurtured and taught you technical fundamentals of engineering. Support your university, visit it occasionally to give seminars, keep in touch with the faculty, talk to the students, share with them some of the wisdom you have gained, encourage them. Both you and the students will find this personally rewarding.

Active participation in the technical society for your chosen field is an excellent way for you to grow and network. You will have the opportunity to meet and learn from highly skilled engineers, researchers and educators from other organizations. You will have the opportunity to present your own work at international forums and have it published in respected, refereed technical journals. As you grow, you will then be able to give back by helping younger engineers.

But this may not be easy. You may be permitted to join the technical society, but attending major conferences, particularly overseas conferences, will likely be difficult. Travel and living budgets, time away from the job, limited number of persons permitted to go (i.e. slots allocated), etc. will be reasons for being denied permission to attend. But if you want to grow in this manner, you must persevere.

A suggestion is to ask a well-respected, well-known member of the technical society who works in a different company or agency to invite you to write a good technical paper or to organize a technical session at the confer

4.3 Enjoy Your Work

For goodness sake, HAVE FUN in your engineering career. Enjoy your work. If you aren't really having fun, move on or change careers. I can't think of too many things more dismal than someone coming to work and hating it. Surely there will be some things about your work that you dislike. But on the whole, love your work. There are many exciting and challenging opportunities in engineering, so having fun can be easy.

4.4 Manage Your Own Career

Control your destiny or someone else will! Whether you work in industry, academe, government or as an independent agent, the primary responsibility for managing your career rests with you. What do you want? Where are you going? How are you going to get there? Neither the company nor your manager will "take care of you".

You make your own destiny, ultimately.

4.5 Clearing Some Myths About Career Development

- ***Myth #1 - Do a good job and the company will "take care of you", or better yet, "take care of you for life".*** Nonsense. In reality no one will take care of you. You must take care of yourself. Do an outstanding job, better than anyone else. Even so, the days of companies providing lifelong employment are gone.

- ***Myth #2 - It's not what you know, but whom you know that counts.*** Rubbish. What you know counts a lot. Whom you know and what they know about you also counts, but what you accomplish counts even more.
- ***Myth #3 - Career planning is my manager's job.*** No! Your manager's job is to lead. He or she often doesn't have the time, skill, ability or inclination to manager your career. Your manager could be a mentor and role model (good or bad). Only you know what you want and what you are willing to sacrifice to get it.
- ***Myth #4 - Nobody reads performance appraisals anyway.*** Not true. Many people do read performance appraisals - very closely. It may be the only thing they know about you and could be the ticket to a job interview. It is a written record that follows you.
- ***Myth #5 - You only get ahead if you work in the current "high visibility" area.*** Actually, it might or might not help you to work in such an area. Diversity in business experience is important. If your skills are better matched to another area, you could have better success there.
- ***Myth #6 - I would rather be lucky than good.*** Be good. No, be excellent or outstanding. Luck and timing are important, but your performance is the best influence on both. Results matter - again and again and again.
- ***Myth #7 - Just tell me the career path I need to be on to reach my goal.*** Sorry! There is no explicit career path or magic formula. Career management is an art, although central tendencies do exist. Seek help through your network or your human resources representative.

5. TODAY'S REALITY

Many young engineers declared goal is to be a manager. "That's fine,...but", they need to realize that organizations are flat today with fewer managerial positions and pr promotion grades from bottom to top. This means that is a difficult goal to achieve.

Encouragingly, more and more companies are now making "dual career path" systems work. This will provide the opportunity for a non-manager (individual contributor) to achieve the same organizational level, salary and responsibility level of a manager. But whichever option you choose as a career path, you will have to be proactive in managing your career to succeed.

6. FINDING MENTORS AND CHAMPIONS

One needs a Mentor and a Champion. The two are different. A mentor is a wise person from whom one can learn the ropes. A champion is one who will promote one's career in management circles. One needs to find both. You will be helped substantially if you can find a champion who notices the Four E's about you and can pull you up through the organization. The fact is that pushing up from below is frustrating and often futile.

6.1 Diversify Yourself

Young engineers are hired, placed into a functional group, grow in the group and want to make a life-long career of this area. Or a Ph.D. graduate wants to make a career out of his or her narrow thesis topic. The reality is that today's engineering problems are multi-disciplinary.

While being a strong technologist in a narrow specialty can be fulfilling, provide significant value and be just right for you, it is usually wiser first to MCBMA (manage career by moving around). Seek diverse assignments. Broaden your experience and become more valuable. Stretch yourself and grow. Then, if you choose to specialize, you can do so. This can enhance your capacity for survival and for having more fun through diversity. You'll see the bigger picture.

6.2 Develop Lifetime Commitment to Learning

Sometimes it is useful to have an engineering license to do your job. In a small company, it is often necessary. If you want to work independently, it is vital to have one.

A big mistake is to think that college degree means education is over. Successful engineers adopt an attitude of life-long learning. There are so many opportunities available that there is no excuse for not continuing to learn.

These include company-paid education benefits, training programs, on-line web courses, technical conferences sponsored by professional societies, workshops etc. Technology continues to progress. Bright-eyed and keen new graduates will continue to nip at your heels, so learn you must

7. CONCLUSIONS

I have shared some ideas on how one can manage one's career in an engineering organization. The bottom line is that ultimately one makes or mars his or her career. Life time commitment to learning, enthusiasm, networking, developing will definitely strengthen one's growth prospects.

Allow me to wish you all a meaningful, rewarding and enjoyable engineering career.

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WHITETOPPING – A CASE STUDY FROM BANGALORE

V. RAMACHANDRA[1]

1. INTRODUCTION

Concrete Roads were first built by Romans (300 BC–476 AD). They were quite progressive in the construction with the use of innovative materials *viz.,* use of 'Pozzolana' cement from the village Pozzouli near Italy, horse hairs as fibres in concrete, admixtures in their primitive form (like animal fat, milk and blood). These roads, scientifically designed and constructed had a long life and thus lead to the adage '***all (concrete) roads lead to Rome***'.

Portland Cement Concrete (PCC) overlay on an existing bituminous pavement is commonly known as White topping. The principal purpose of an overlay is either to restore or to increase the load carrying capacity or both, of the existing pavement. In achieving this objective, overlays also restore the ride-ability of the existing pavements which have suffered rutting and deformations, in addition to rectifying other defects such as loss of texture. In our country, bituminous overlays have been popularly constructed in the past mainly due to abundant supply of bitumen, its amenability to stage construction and manageable traffic conditions, in terms of volume and axle loads in addition to the comfort levels of construction methods among engineers. It was also making economic sense to make bituminous pavements as it was relatively cheaper. In recent times all these advantages are reversed *viz.,* petroleum industry is using refined processing technology leading to reduction in the production of bitumen leading to increased imports, favourable cost economics of cement concrete and rapidly changing traffic scenario (in terms of volume as well as axle loads). In addition, rapid developments in concrete material technology and mechanization (both in concrete production and its laying) are favouring concrete overlays as a sustainable option. In recent times PPP (Public-Private Partnership) models are becoming popular in road construction shifting the focus on selection of overlays based on life cycle costs rather than initial costs. India is currently producing about 240 million tonnes of cement and cement industry is quite matured and equipped to meet the challenges in terms of various grades of cements as well as high quality blended cements suitable for making Pavement Quality Concrete (PQC).

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Concrete overlays have been used to rehabilitate bituminous pavements since 1918 in USA. There has been a renewed interest in whitetopping, particularly on Thin White Topping (TWT) and Ultra-Thin White Topping (UTWT) over Conventional White Topping. Based on the types of interface provided and the thickness of overlay, classification is as follows:

(i) *Conventional White topping:* which consists of PCC overlay of thickness 200 mm or more, which is designed & constructed without consideration of any bond between existing overlay and underlying bituminous layer (without assuming any composite action).

(ii) *Thin White topping (TWT):* which has PCC overlay between 100–200 mm. It is designed either considering bond between overlay and underlying bituminous layer or without consideration of bond. High strength concrete (M 40 or higher) is normally used to take care of flexure requirement. Joints are at shorter spacing of 0.6 to 1.25 m.

(iii) *Ultra-Thin White topping (UTWT):* which has PCC overlay of less than 100 mm. *Bonding between overlay and underlying bituminous layer is mandatory*. To ensure this, the existing layer of bitumen is either milled (to a depth of 25 mm) or surface scrapped (with a non-impact scrapper) or gently chiseled. Joints are provided at a spacing of 0.6 to 1.25 m.

2. ADVANTAGES OF WHITE TOPPING

- Reduced thickness–due to thickness of overlay remaining constant for over 2 decades.
- Fast-Track construction–making use of innovations in concrete technology and batch mixing, concretes can be designed to have 3 days' compressive (& flexural) strength, so as to open the road for traffic within 5 days of construction.
- Reduced maintenance – as the concrete overlays live for over 2 decades, with least maintenance.
- Cost-effective compared to asphalt overlays – when life cycle cost is taken into consideration.
- Improved service life – with better riding quality, improved fuel efficiency of vehicles.
- Little pre-overlay repairs
- Improvement in safety in view of the increased reflection of light – particularly on city roads, it would save 24% less electricity compared to flexible pavements.
- Reduction in operational costs and lower absorption of solar energy
- Improving the environmental benefits – as concrete roads are much greener and less polluting.

In this paper, the case history of a Thin White topping Technology Demonstration Project carried out on a stretch of road was carried out recently is presented.

3. DETAILS OF THE PROJECT

The trial stretch is located on Hosur Road in Bangalore. The details of the existing bituminous road and the other data are as follows:

1	CBR	8 to 10
2	Commercial vehicles per day	1000
3	Temp differential at Bangalore	17.3 deg C
4	Thickness of bituminous layer	4 to 7 inches
5	Base (40 mm metal) thickness	4 to 9 inches
6	Road width	100 feet
7	Length of road	350 m
8	Concrete grade	M 45
9	Axle load	16 T

4. DESIGN OF PAVEMENT AND CONCRETE MIX

Design of the overlay was carried out using Westergaard's Equation and warping stress as per IRC:58 -2002 and IRC: SP: 76 – 2008. Total stress (including temperature stress) was obtained as 30.83 kg/cm^2 and corresponding flexural strength requirement was 4.7 MPa. Design was done by M/s L.R. Kadiyali & Associates, New Delhi. Thickness of white topping was 150 mm.

Concrete mix design was arrived at by evaluating trial mixes and the design mix was arrived at with a cement content of 430 kgs, fly ash – 30 kgs, with a w/c ratio of 0.283, achieving a slump of 40–60 mm at site.

5. DETAILS OF CONSTRUCTION

In order to achieve the desired advantages of concrete roads, three essential conditions need to be satisfied.

(i) Production of concrete in a RMC plant or in a dedicated batching plant.

(ii) Using either fixed form or slip form mechanical pavers

(iii) Strict quality control at site including testing of fresh, hardened and extracted specimens of concrete and tests on pavement quality.

In this project design and production of concrete was carried out by UltraTech RMC; Fixed form paver provided by M/s Allen Buildwell Pvt. Ltd., was used. Quality control at site and testing were jointly done by the Technical Services team of UltraTech and M/s Civil Aid Technoclinic (P) Ltd., Bangalore.

6. SALIENT FEATURES OF CONSTRUCTION

(i) *Surface preparation*: In case of TWT, bond between PCC overlay and existing bituminous pavement is atleast partly desirable; in case of UTWT, effective bond is essential. To ensure this any of the following method can be adopted.

- *Milling* the existing bituminous surface to obtain a uniform surface. Milling can be used to remove surface distortion like cracks in the top portion and adjust cross slopes. Thickness of milling usually is in the range of 25 to 50 mm.

- *Surface scrapping* is carried out on bituminous surfaces which are quite hard. This can be for a depth of 10 mm and carried out with tools which have vertical impact control, so that the sub-grade is not damaged.
- *Chiselling* of the surface at regular intervals, if the existing surface is hard.

The minimum thickness of existing bituminous pavement (excluding the milled/scrapped thickness) shall be 75–100 mm to ensure a reliable and strong base.

(ii) *Profile correction* is carried out with the objective of filling existing potholes, ruts and wide cracks and also to ensure a level surface for resting the pavement. Profile correction and correction of camber can be carried out together with a thin bituminous levelling course or with dry lean concrete (DLC).

(a) If the existing road surface is good and only a few localized potholes/cracks exist, they can be repaired with a bituminous mix before concreting is done.

(b) If potholes/cracks are wider than 3 mm, they have to be treated with bituminous emulsion, slurry seal after trimming them to shape and cleaning out loose fragments with compressed air. Milling of the existing surface also addresses this problem.

(iii) *Laying of PQC* is quite similar to the construction of new concrete pavement. As mentioned earlier, concrete should be made either in an RMC or in a weigh batching plant. Use of either fixed form pavers or slip form paver machines is an essential ingredient for getting a good quality pavement. In the current project, a fixe form paver was used with a fixed side form work (steel channel box section) with 16 mm diameter steel rods of 1 m length as tie rods @ 500 mm c/c) and the paver had gang mounted vibrators equally spaced with variable rpm and three integral steel tubes with 8 tonnes vibratory rollers for screeding, levelling, compaction and finishing.

(iv) *Finishing of the surface* is mostly achieved by the paver itself. But to achieve uniform finish, a simple hand operated bull float is used when concrete is still in its fresh state. After the bull float operation, uniform surface texture is provided by using steel wire brush.

(v) To avoid evaporation of surface water from concrete surface (which leads to plastic shrinkage cracks), wax based curing compound is sprayed. As an additional measure, plastic sheets are spread over the pavement surface till normal curing process starts.

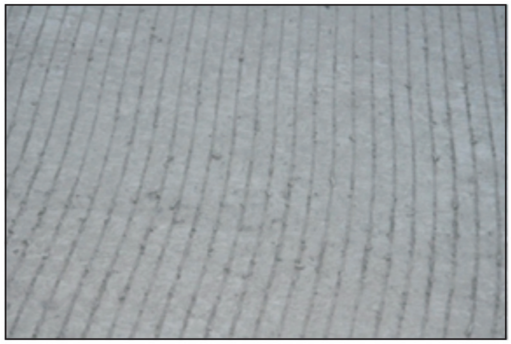
(vi) Contraction joints are provided by cutting groves (for a depth of one-third of the depth of white topping, 150 mm in this case) at a spacing of 1.2 m in longitudinal as well as transverse directions. The joints are cut using electrical grove machines within about 8 to 10 hours of pouring concrete. These joints are sealed with high quality sealant (either bitumen or poly sulphides) to prevent moisture and incompressible infiltration into the overlay system.

(vii) To ensure effective load transfer across the longitudinal segments as well as transverse construction joints, tie bars and dowel bars are provided.

Surface preparation and alignment of rails for paver

Paver machine in operation

Bull float operation to smoothen surface



Surface texturing with wire brush

7. TEST RESULTS

Strict quality control not only during mix design and production of concrete, but also testing for quality at regular intervals (for every 50 cum of concrete) was carried out. These tests included:

- Tests conducted on fresh concrete (slump test at site)
- Tests on hardened state (compressive strength of cube and cylinder specimens for 1, 3, 7 and 28 days), split tensile strength, flexural strength of concrete beams
- Fatigue and abrasion tests on pavement quality (results awaited).
- Test on extracted specimens of concrete (core tests) would be conducted to assess the long term performance of concrete.

All the above tests are conducted by Civil Aid Technoclinic (P) Ltd., Bangalore and the results obtained so far are tabulated. The road was opened for traffic after 5 days of curing.

Compressive Strength of Concrete Cubes (Total no. of samples 936)					
No.	Sample size	1 day strength (MPa)	3 day strength (MPa)	7 day strength (MPa)	28 day strength (MPa)
	60 cubes per test	Max: 24.1 Min: 21.1 Avg: 22.05	Max: 48.2 Min: 38.4 Avg: 43.2	Max: 55.2 Min: 48.4 Avg: 51.02	Max: 67.2 Min: 57.4 Avg: 61.8

Compressive Strength of Concrete Cylinders (Total no. of samples 60)		
No.	Sample size	28 day strength (MPa)
	60 per test	Max: 61.4 Min: 43.7 Avg: 52.45

Flexural strength of Concrete (Total no. of samples 60)		
No.	Sample size	28 day strength (MPa)
	60 per test	Max: 7.35 Min: 6.2 Avg: 6.3

Split Tensile strength of Concrete (Total no. of samples 60)		
No.	Sample size	28 day strength (MPa)
	60 per test	Max: 4.01 Min: 2.92 Avg: 3.36

8. CONCLUSIONS

Due to advances in the area of mechanization and fast track construction, concrete roads and white topping provide a sustainable as well as cost effective option for pavement construction. This technology demonstration project in Bangalore has evoked positive response from people across the spectrum *viz.,* technical consultants, construction industry, academic & research institutions. The Government of Karnataka, BBMP and other civic agencies have come forward to adopt this technology. On behalf of the cement industry, CMA (Cement Manufacturers' Association) has come forward to assist all those involved in the construction on concrete roads/ white topping by way of several useful publications, user-friendly software for analysis, design and estimation of quantities (and comparative cost), conducting training programs for engineers and providing the necessary technical assistance.

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CONSTRUCTION OF A DEEP UNDERGROUND CAVERN FOR STORAGE OF LPG

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1. INTRODUCTION

Petroleum products such as crude or Liquefied Petroleum Gas (LPG) are usually stored in tanks located on the ground surface. However, a tank farm with large overall capacity will be spread over a large area, involve a lot of connecting pipes and valves and be exposed to many hazards such as fire, sabotage, accidents, etc. If the same material can be stored in an underground rock cavern in bulk, it would be a simpler arrangement having many advantages compared to a surface level tank farm. Caverns are underground structuresof large size used for a variety of purposes, including storage of bulk materials. However, normally such a cavern in rock, which usually has many natural fissures and cracks, will have to be lined using appropriate materials such as concrete or steel. To minimize the costs involved in such lining, a special technique is used to contain the evaporating liquid within a rock cavern without lining. This article describes the process involved for such storage as well as the engineering, construction and project management aspects involved in constructing one such cavern. This project was notable for the large depth of the cavern below ground level, the innovative techniques used to overcome the difficulties posed in using only the minimal size access shafts permitted to access the cavern during construction on account of various constraints, the construction methods and project management techniques used and the excellent safety record achieved during construction.

2. DESCRIPTION OF THE PROJECT

2.1 Basic Details

One of the world's deepest underground Storage Caverns for storage of LPG has been constructed in the city of Visakhapatnam (Vizag for short). The cavern with a capacity of 125,000 cu.m. is located at 186 m below ground level. See Fig. 1. The cavern is unlined and the petroleum product is retained in by the water containment principle, whereby the cavern is located at such a depth

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that the static pressure of the water naturally present in the surrounding rock flows all around and towards the cavern, preventing the LPG from escaping. The rock mass surrounding the cavern is also further saturated by water percolating from a number of horizontal holes drilled from a (water curtain) gallery or tunnel located above the cavern. The depth of such a facility below ground level is governed by the vapour pressure of the stored material. The large cavern is accessed only by two vertical shafts of small diameters - a 6.5 m dia Access Shaft (AS) and a 4.0 m dia Operation Shaft (OS) of depths 186 m and 201m respectively. (See Fig. 2). The shaft sizes were constrained by the cost of excavation and the requirement to minimize disturbance to the existing strata.

FIG. 1 VIEW OF FINISHED CAVERN

The Project is located in a 13 acres site at the foot of the famous Dolphin's Nose hillock in Vizag. The Owner is South Asia LPG Company Private Limited (SALPG), a 50:50 Joint Venture between Hindustan Petroleum Corporation Ltd. (HPCL) and Total Gas and Power India (TGPI), a subsidiary of the French oil major, TOTAL. Geostock of France provided consultancy to the Owner for aspects covering conceptual, geological, hydro-geological and geo-mechanical designs. Larsen & Toubro Limited (L&T) – ECC Construction Division was the contractor for engineering and construction of both Underground and Above-ground works.

2.2 The Facility and its Importance

The Project envisaged the underground storage of LPG, the first project of its kind in South Asia. Bulk storage of LPG in rock-mined caverns, in preference to surface tankage installations, offers many advantages such as:

- safety from natural calamities and various forms of sabotage.
- safety from the hazards of leakage of the inflammable gas.
- spatial economy (economy in usage of surface land area), lower capital cost (also due to savings in piping, instrumentation, etc) and lower operating costs compared to conventional pressurised spheres and refrigerated tanks used for surface storage of the gas

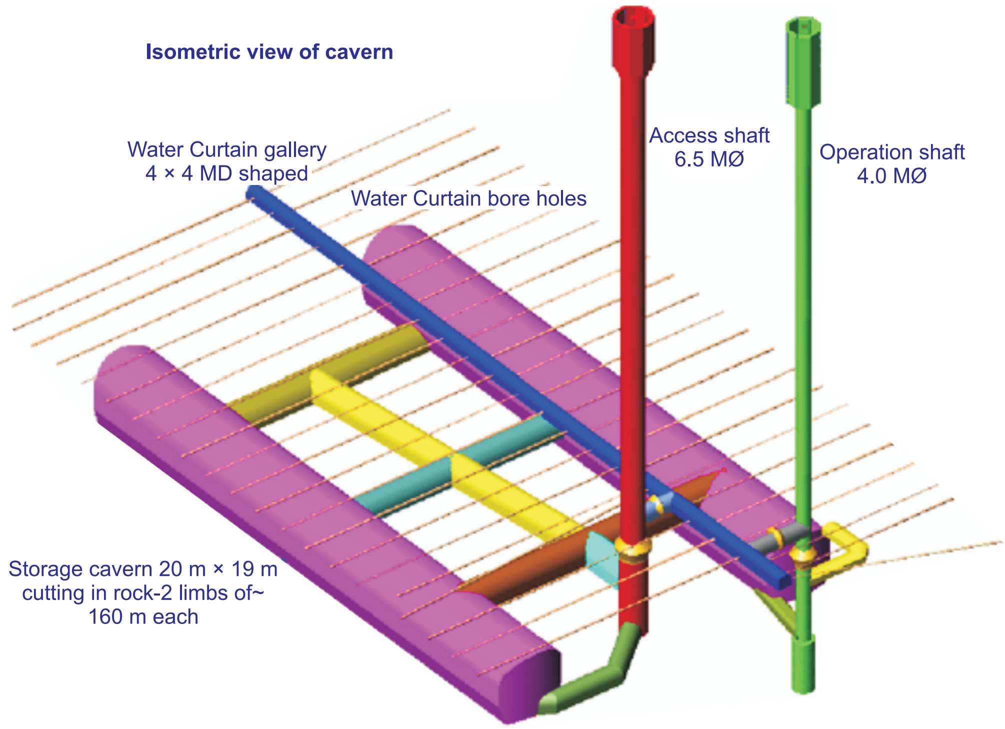

FIG. 2 AN ISOMETRIC VIEW OF THE CAVERN

- underground storage needing little maintenance
- inherent safety over the above-ground storage systems
- preservation of the natural landscape and scenic beauty of the project area as the major installations are located underground as compared to above-ground storage facilities
- possibility of usage as buffer/strategic storage for the country
- longer life for underground storage as compared to surface tanks

This mined cavern will be one of the world's deepest LPG caverns. While for caverns at shallower depths an inclined approach through tunnels/drifts/ramps would be feasible given adequate land space, for deeper caverns a vertical approach through vertical shafts would only be feasible. Though generally conventional civil engineering principles are used, efficient operations are required to ensure speedy construction and overall economy. The selected site should have suitable geological conditions and the rock must be strong enough for the cavern to be stable. The geometry and arrangement of the caverns are selected on the basis of the geotechnical properties of the rock. Stability of the rock is also improved by installing appropriate strengthening measures, such as rock bolts, shotcreting with wire mesh or with integral steel fibres and structural steel ribs.

Vizag was ideal for such a project because of suitable ground conditions covering rock quality (hard silimanite garnet gneiss bedrock), lesser fragmentation and high water table. Vizag has a Major Port, handling considerable shipping volumes of various goods. The site has advantages of having an existing LPG-handling infrastructure, high demand for LPG in the region along the east coast of India and potential for re-exporting LPG to South-East Asia. The storage facility is linked to the nearby Visakhapatnam Port Trust (VPT) jetty where large refrigerated shipment parcels will deliver the LPG to the Cavern. LPG will be sent from the Cavern to the nearby HPCL refinery through an existing pipeline or to smaller pressurized vessels at the VPT jetty for re-exporting.

3. DESCRIPTION OF THE FACILITY

3.1 Basic Principle

The cavern walls are not lined with concrete or steel and the rock is left exposed. The LPG is prevented from escaping using the principle of hydraulic containment, as explained earlier. See Fig. 2 for the overall configuration of the system.

3.2 Electro-Mechanical Systems

The storage and retrieval facilities are operated using a system of tubes placed within outer casings installed in the shafts to inject and withdraw the LPG, and to carry out necessary monitoring and measurements. The pipes are also equipped with special down-the-hole safety devices. The steel casings are vertically supported on concrete sealing plugs located in the shafts just above the cavern and laterally restrained through a number of steel brackets provided in the shafts. Steel tubes used for transporting LPG or water, or for housing instrumentation, etc., are located inside these casings to permit future raising and lowering.

The surface installations include product injection and withdrawal systems and the specific units needed for product metering and treatment.

3.3 General Arrangement of the Components

The layout and general arrangement of the underground cavern are shown in an isometric view in Fig. 3. The cavern has two limbs, each 19 m high, 20 m wide, 160 m long and 64 m apart from each other. Each shaft had a concrete-lined fore-shaft in the upper overburden layer and a rock-shaft below, covering weathered rock in upper reaches and hard rock in the lower reaches.

The Water Curtain Gallery is an invert-D shaped tunnel located 15 m above the main cavern. From this tunnel horizontal boreholes are drilled laterally on both sides, with a maximum length of about 82.5 m.

3.4 Contract Packages

The construction of the Facility was contracted out in two packages—Underground and Above-ground and included all construction engineering. The Above-ground package comprised the electromechanical installations required for injection and withdrawal of the product and for the monitoring systems. Operation of the Facility is carried out through casings and tubings installed in the Operating Shaft and Access Shaft, submerged pumps for LPG and for seepage water, injection line, instrumentation casings and vent lines.

The Underground contract package comprised the construction of the cavern, the water curtain gallery and the connecting shafts. The civil work quantities included 137,000 cu.m of rock excavation, 34,000 sq.m of shotcreting, 115t of rock bolting and 175t of grouting. The holes drilled horizontally from the water curtain gallery are charged with bacteria-free water from the surface and the water seeping down from these boreholes ensures that the cavern has a curtain of water which saturates the surrounding rock, preventing the escape of the contained LPG.

4. ENGINEERING OF THE FACILITY

4.1 Site Investigation Works

After a pre-feasibility study which concluded that the geology at this location would be favourable, the initial exploration programme covered cored boreholes, hydro-geological tests (water loss, injection/relaxation and interference tests) and wireline logging as well as comprehensive laboratory tests on the samples selected from the cores. Later, prior to carrying out the basic engineering design additional investigations were carried out, covering cored boreholes to investigate the area of the two shafts and to further narrow down the location of the cavern in order to detect any major faults or jointed zones. No major rock problems were encountered in the site. In-situ rock stress measurements were conducted at various locations as the construction progressed.

4.2 Original Engineering Design

The design of the underground works focused on the stability of the rock and the hydro-geological aspects and involved the setting up and studying of numerical models for the behaviour of the cavern both during the excavation phase and during the operating life of the cavern when it is exposed to LPG.

The basic design by the project consultant covered aspects such as:

- layout and cross-sections for the main cavern and water curtain
- rock support systems for various types of rock mass classification
- rock instrumentation to check the stability and in-situ stress measurements
- hydro-geological monitoring networks
- a set of specifications for all the site works: Surveys, instrumentation, drilling and blasting techniques, installation of rock bolts and shotcrete, grouting, cavern tests, etc.

Based on the above, detailed engineering was developed by the contractor for rock supports, monitoring piezometer status, appropriate construction methods, etc.

4.3 Design Change during Construction

In order to validate the initial designs the in-situ stresses were measured more precisely during earlier stages of construction by hydraulic fracturing. The results showed a ratio of horizontal-to-vertical stresses reaching a factor of 4. Taking this into account and the existence of sub-horizontal joints, it was decided to modify the initial design, especially the cross-sectional shape of the main storage cavern. The plan of the cavern was changed from a single continuous horse-shoe shape to two individual cavern limbs with rectilinear layout. (See Fig. 3). This change, however, had an impact on the construction methodology originally planned.

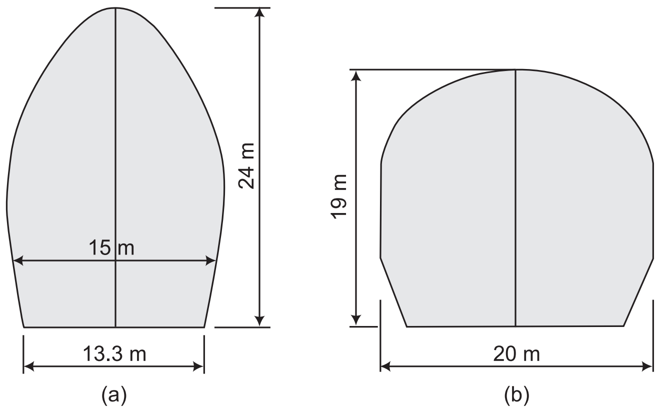

FIG. 3 CAVERN SHAPE CHANGE (a) BEFORE (b) AFTER

5. METHODOLOGIES ADOPTED-UNDERGROUND WORKS

5.1 Fore-Shaft: Diaphragm Wall and Excavation

Initially the fore-shaft was constructed using a polygonal diaphragm wall enclosure in the overburden above the rock level as the first stage for the shafts. The reinforced concrete diaphragm wall panels extended into weathered rock strata for adequate keying in. The diaphragm wall was constructed with 8 panels for the Operation Shaft and 10 panels for the Access Shaft. Trenching of the panels in the overburden soil and within the depth of anchoring into the rock below was carried out by reverse mud circulation method.

The depth of the fore-shaft was 20 m in Operation Shaft and 16 m in Access shaft. After completing all the panels of the diaphragm wall a capping beam was cast at the top to integrate all the panels. Then a grout curtain was formed all around below the diaphragm wall (in hard rock) in order to reduce the seepage into the shafts while excavating the deeper reaches. While excavating the fore-shaft, intermediate RCC ring beams and a bottom ring beam were also cast to stabilize the diaphragm wall panels. The beams were anchored to the rock using rock bolts.

The excavation was carried out using a combination of a small excavator inside the shaft and a crane lifting a suitable bucket for bringing the muck to surface level where it was dropped into dumpers for disposal. The excavation was carried out in stages of 2-3 m depth, to avoid possible collapse or dislocation of diaphragm panels due to existing hydrostatic pressure on the outside. Some part of the excavation in the fore-shaft was carried out by controlled blasting. The fore-shaft was provided with a suitable ventilation system. (See Fig. 4.)

FIG. 4 VIEW OF FORE SHAFT

Below the fore-shaft, the rock-shaft was excavated first in weathered rock and then in hard rock. Drilling, charging and controlled blasting were initially carried out in the rock-shaft for about 20 m depth below the ring beam. The muck generated was manually loaded into a bucket and the bucket lifted up using a crane with a clamshell arrangement for muck removal. After reaching about 20 m depth below the ring beam, a moving scaffold with two decks operated by two winches and a winder arrangement (a high speed hoisting system usually employed in deep mines) for bucket hoisting was established.

The moving platform served as a protective roof to the workforce working at the bottom as well as housing the various equipment/services required.

A suitable structural steel head frame was provided to support the sheave pulleys which carried the wire ropes of the winder and the winches. The winder was operated with high speeds ranging from 1.2 m/sec to 6.8 m/sec. It had a double drum arrangement which supported double bucket operation and enabled slow banking system which provided access to any level inside the shafts. Muck in the bucket was dumped into a launder/chute at the top which discharged it into dumpers for disposal. (See Fig. 5 and Fig. 6.) At collar level platform an openable door, suitably triggered by the traveling bucket, ensured safe operations for the bucket to go up and down.

Drilling was carried out with jack hammers and charging with cartridge explosives. Muck loading into the bucket had to be done manually in the smaller Operation Shaft, and by using a small excavator in the larger Access Shaft. Rock bolting was carried out by manual drilling, inserting cement capsules and pushing the rock bolts in by using a hand held machine. Shotcreting in the small shaft was a real challenge and was carried out using a small shotcrete machine.

A suitable drilling pattern was designed to ensure the required smooth blast pattern. Detonation was with non-electric detonators. A blasting mat was placed over the charge to avoid damage to permanent structures/equipment due to flying fragments. Safety was totally ensured by the HSE team by systematic working-evacuation of men and materials from shaft bottom before blasting and using a work permit system, confirmed by signature in approved checklist.

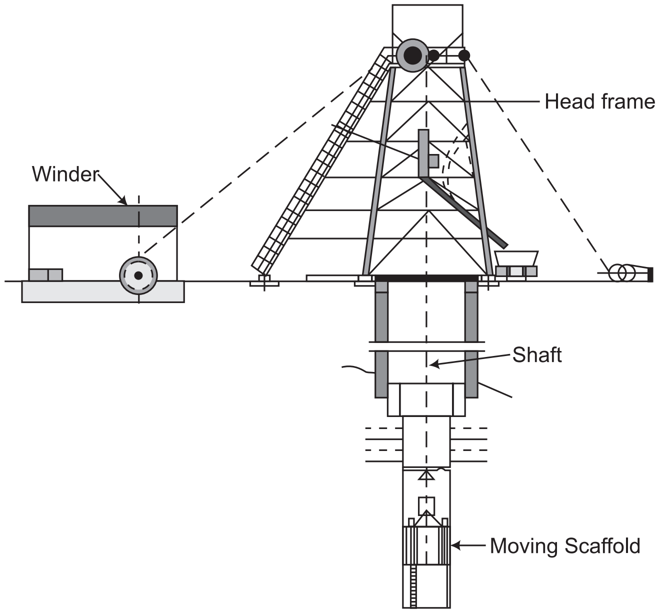

FIG. 5 HEAD FRAME AND MOVING SCAFFOLD

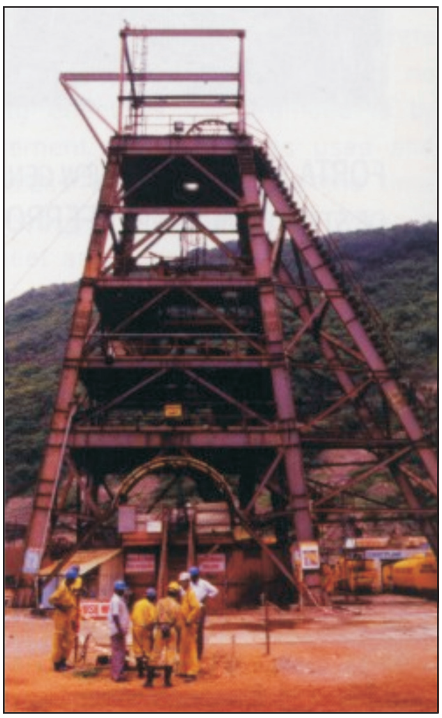

FIG. 6 VIEW OF HEAD FRAME

A system of probe holes of 10 m length (drilled ahead of the face to detect possible water seepage conditions) in the larger shaft and 3 m length in the smaller shaft was adopted. Each probe hole was inspected and checked for water seepage by fixing a packer and measuring the water loss or gain.

5.2 Water Curtain Gallery

The Water Curtain Gallery had a size of 4 m height and 4.5 m width. (See Fig. 7.) Since the size was small, drilling was carried out using jack hammers and charging was with cartridge explosives. A skid steer loader (Bobcat) and a bi-directional dumper were used for muck transportation from the face on to the bucket being operated by the winder.

FIG. 7 VIEW OF WATER CURTAIN GALLERY

The rock bolting and shotcreting methodologies were the same as those for shaft sinking. Horizontal bore holes having a maximum length of 82.5 m were drilled on either side of the main gallery. The rock bolting and shotcreting methodology were the same as that for shaft sinking phase. Each hole was measured for its deviation which was restricted. All the holes were individually checked for pressure loss when injecting water under sealed packers.

5.3 Storage Cavern

The start of cavern work marked a major change from vertical excavation to horizontal excavation. The initial part of the storage cavern was excavated by manual drilling for creating enough space for parking, maneuvering and protecting the equipment. Then the drilling, mucking and shotcrete equipment were dismantled, lowered through the shafts and re-assembled below. (See Fig. 10). The cavern was excavated in three main stages: a top heading and two benches. (See Fig. 8.) For the cavern excavation, drilling was carried out with drilling jumbos having two drilling booms and a basket. Charging was done with Power bulk, a bulk explosive by pumping explosives using a pumping unit into the drilled holes, after loading the priming cartridge. Shotcreting was carried out using a Robojet machine. Rockbolts were installed by drilling and pushing in the rockbolts with a Jumbo and grouting with a grouting pump. A view during excavation is shown in Fig. 9 and a view of the finished cavern is shown in Fig. 1.

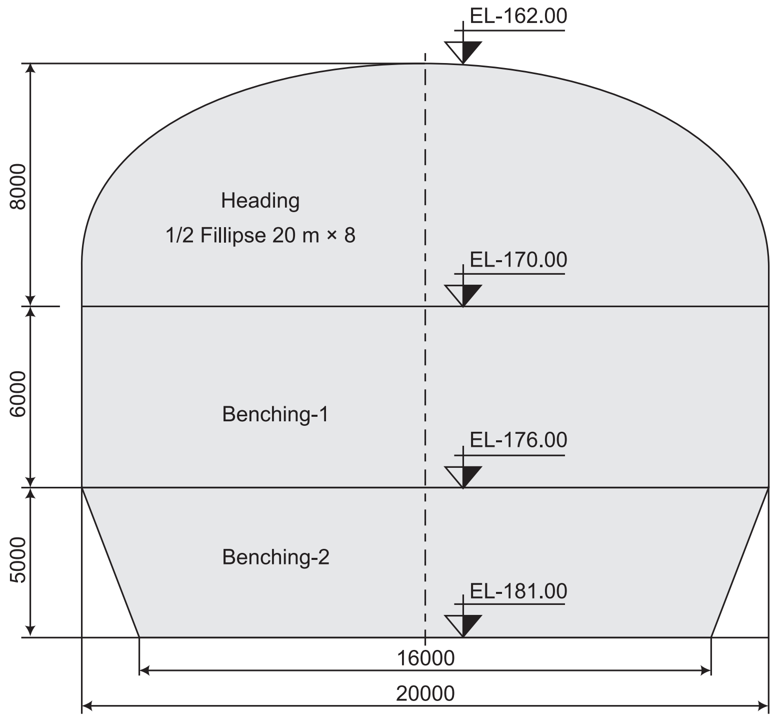

FIG. 8 SCHEME OF CAVERN EXCAVATION

Muck was hauled from the face by two Load Haul Dumpers (LHD) to discharge into an under ground hopper. The hopper was covered with a grizzly to filter out the bigger fragments. The hopper door opened down to discharge the muck into measuring bins. The bins then unloaded the muck into skips, which were lifted up using a winder to discharge into a surface hopper and then to disposal tippers. A crusher was installed underground to crush the rock into smaller sizes to improve handleability. With optimized mechanised handling, the muck hoisting rate went upto a high of about 2550 tonnes per day.

6. HEALTH, SAFETY AND ENVIRONMENT AND QUALITY ASPECTS

6.1 Health, Safety and Environment Aspects

Health, Safety and Environment aspects are critical during execution of such projects in view of the limitations of access, blasting method used and the working environment. Various Health,

FIG. 9 VIEW DURING CONSTRUCTION

FIG. 10 DISMANTLED EQUIPMENT BEING LOWERED THROUGH SHAFT

Safety and Environment aspects implemented covered workmen management, hazard analysis, incidence analysis, emergency response, medical services, mechanical integrity checks, motor vehicle safety, industrial hygiene, personnel training, personnel protection equipment, management of chemicals, air, water and wastes, etc. Job safety analysis and job hazard analysis studies were developed along with the required mitigation plans for each sequence of activities and these were then implemented at site. A work permit procedure was put in place to ensure the safety of ongoing works during the usage of the existing adjacent Process Facility. As a result of stringent safety monitoring there was no fatal accident during the execution of the underground works. Particular care was taken during dismantling and lowering the heavy and bulky equipment required for the excavation of the cavern and bringing them back to the surface again in a dismantled condition.

6.2 Quality Aspects

The quality parameters governing the drilling and blasting works for rock excavation were smooth blasting, ensuring required tolerances for the profile, vibration limits as per national standards for each existing structure and rock fragmentation. National Institute of Rock Mechanics (NIRM), was involved in the blast design for various sections. Blast design and mapping were carried out by expert blasting engineers and geologists at the site, who performed geological mapping to classify the encountered rock and suggesting the rock support systems to be implemented. The parameters for shotcreting were strength, sprayability and thickness of application. Accordingly the mix design was developed for the shotcrete and established with trial tests for implementing at site. The applied thickness varied from 50 mm to 100 mm based on the rock mass classification. The parameters for rock bolting were strength and elongation. Trial tests were conducted for initial and routine pull out tests for different lengths of rock bolts. For the drilling of the Water Curtain boreholes, stringent deviation limits were specified to ensure that they do not approach the storage locations. Quality Assurance Plans and Inspection Test Plans were developed for the above parameters and successfully implemented at site.

7. SIGNIFICANT ACHIEVEMENTS

The shaft sinking progress was good, and a national record was set. Cavern excavation rate was also high, and over 16, 500 cu.m of muck was removed in one month. The liquid explosive method was used for the first time in the country for such large scale underground construction. This resulted in reduction in cycle times and increased safety. Health, Safety and Environment practices in many areas were audited by many parties including independent third party checks for quality by NIRM, SGS India Private Limited and Lloyds Register Asia. Special interaction sessions were held by L&T with the clients to optimize the work permit system. Five million safe man-hours were recorded without any lost time incident. Excellent systems of documentation, methodology development and project management were implemented with innovative working which secured the prestigious CII-EXIM Excellence award to L&T-ECC, apart from the International Safety Award from British Safety Council and the ACCE Sarvamangala Award for Excellence in Construction in the field of Civil Engineering.

8. CONCLUSION

Underground Cavern construction is an elegant solution – technically feasible and commercially viable – for storage of large volumes of LPG or crude oil. At present many such caverns are being planned for strategic storage of crude oil. The construction of the underground facility through deep vertical shafts is a technically challenging job. The successful completion of such a project depends on the deployment of the right kind of equipment, preparedness to face various eventualities, and great teamwork. While a project with access from shafts alone involves many complexities, some of the problems of construction can be mitigated by providing an inclined access, provided the Cavern is located at shallower depths below the ground level. However, providing an inclined access depends on the availability of required space as large horizontal distances have to be traveled with an easy slope for the ramp.

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LEAN CONSTRUCTION – THE NEW PROJECT MANAGEMENT PARADIGM

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1. INTRODUCTION

In the recent past the Indian economy has been facing many difficulties and the growth rate of the country has also come down. Resources are becoming more expensive and scarce and profitabilities of the construction industry are under pressure. Constructors and Developers in India already have a challenging profession on account of the numerous uncertainties associated with construction in India, which are now getting compounded by the current difficult situation. Construction is well known for its many uncertainties, so much so that uncertainty seems to be the only certainty in this field! Even in earlier times the project implementation track records in India – as for instance evidenced by the statistics quoted in the website of the Ministry of Programme Implementation- have not been so good and realistic planning and systematic implementation are not being practiced by many of the players in the industry. Time and cost overruns are quite common. The myriad factors impacting construction are quite complex and a construction manager probably requires more skills than a manager in the business world!

Progressing from the simple bar charts of yesteryears, Critical Path diagrams, PERT networks and GANTT charts have had their sway. Software packages such as MS Project and Prima Vera have been used, mostly without utilizing their full potential. Some newer principles such as Earned Value Management have also been tried out. However, the percentage success in project implementation in terms of time and cost control is still quite low. In such a context, one major process which promises to reduce the uncertainty and make the construction process more efficient and cost-effective has made its advent in India in the recent past. That is Lean construction. Over the last decade, Lean construction practices have been adopted in many countries around the world. In the last couple of years, a few Indian organizations have also gone in for adoption of Lean principles and are reaping the benefits. The Lean construction concept is a solution waiting for adoption to improve efficiency, cut down wastage and improve the margins in the Indian construction industry.

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2. ORIGIN OF LEAN CONSTRUCTION CONCEPT

As part of the many success stories arising from post-war Japan, Toyota Motors had successfully implemented their Toyota Production System (TPS), which was based on Lean manufacturing principles. This system was also subsequently adopted extensively in the western countries for use in the manufacturing industries to considerable benefit. Even though construction is quite unlike manufacturing, many of the principles of Lean Manufacturing can still be applied to construction, as has been demonstrated quite well. The International Group for Lean Construction (IGLC) founded in 1993, The Lean Construction Institute (LCI)- USA founded in 1997, Lean Construction Institute-UK founded in 2005 and others have contributed substantially to the development and propagation of Lean construction concepts. The Latham Report and Egan Report released in UK in the last decade looked at the ailments of the British construction industry and recommended the Lean construction concept as a positive cure. Apart from USA and UK, some of the Nordic countries and South American countries have implemented Lean construction concepts. Some of the famous international proponents in this field include Laury Koskela, Glen Ballard, Greg Howell, James Womack, Tariq Abdelhamid,….In India, the Institute for Lean Construction Excellence (ILCE) founded in 2008 has been steering the propagation of Lean practices, along with IIT Madras and IIT Delhi.

3. LEAN-BASIC CONCEPTS AND PROCESSES

Lean is a production management-based method of project delivery. Though it has taken off from Toyota's Lean manufacturing techniques, Lean Construction has already been well adapted for construction. Womack's 2003 definition would still stand: Lean construction is a way of thinking that focuses on making the product flow through value-adding processes without interruption, a "pull" system that cascades back from customer demand by replenishing only what the next operation takes away at short intervals and a culture in which everyone is striving continuously to improve.

It is essentially based on a continuous improvement strategy, covering avoidance of all types of waste, optimising and improving processes, smoothening workflow, synergising and integrating efforts of all stakeholders to improve certainty at various stages and to get the best overall results for the project. Lean is a long-term transformational process which is inclusive and multi-dimensional, encompassing all stakeholders.

Lean construction is essentially a concept and is based on developing and applying a culture of continuous improvement, towards increasing Certainty in all respects—time, cost, quality, and so on. In the world of construction notorious for its uncertainties, this is a welcome breath of fresh air! Like any cultural change, it has to be driven from the top, but encouraged to develop from the bottom. The Lean process identifies waste in all forms and strives to eliminate waste and hence add considerable value. The emphasis is more on the overall flow of work rather than on point speed for completing specific activities.

4. ADVANTAGES OF LEAN CONSTRUCTION

Based on an underlying concept of superior value generation through optimized and continuously improved processes, Lean reduces waste and cost, creates more stable schedules and reliable material deliveries. It promotes employee participation, leading to satisfaction all round and hence better quality, all ending up in improved customer satisfaction. The improvements in the various stages of project realization have a substantially beneficial impact on the constructor's bottom line. Other cascading advantages such as higher employee morale and staff retention, more systematic working at the sites, improved brand image for the stakeholders are also seen.

Reduction of waste would be one of the most significant advantages of practicing Lean construction. Thus, Lean construction practices have a beneficial impact on all aspects of construction and the quality of work and the level of satisfaction in the entire construction industry may improve as a result of implementing Lean construction practices extensively.

5. ELIMINATION OF WASTE

Wastage pertains not only to waste of materials but also to precious time lost in waiting for decisions, fronts, materials, resources, etc., using wasteful processes and practices, double handling of materials, using wrong equipment as the right one was not available when required, and so on. Some of the other common wastages at construction sites which get eliminated by Lean methods are: Waiting for materials or resources or inputs, unnecessary transportation, using wrong methods, unnecessary inventory, rework as a result of poor quality or misunderstanding of work content or methods, defects and reworking, inefficient teamwork/communication, buffering, "Making Do", i.e. starting work without all inputs and somehow managing.

It has been estimated that construction anywhere in the world involves about 30 to 40% wastage and in the Indian context the total amount may be quite staggering. Hence elimination of waste to whatever degree would be a very significant benefit.

6. LEAN PROJECT DELIVERY

6.1 Lean Operating System

While delivering project execution with Lean principles, the Lean operating System uses three inter-connected major opportunities:

- Impeccable coordination by involving all the actual people responsible for frontline working and going into details.
- Project as a production system by using systematic planning.
- Project as a collective enterprise, by involving all stakeholders in the planning and monitoring activities.

Production planning is carried out using Lean Work Structuring and Production control using Last Planner™ System.

The main objective is to improve Work Flow Reliability, which is governed by variability of performance (ex. Cycle time) of operations. Predecessor activity releasing work to successor activity erratically is a common reason for variability and such variability hampers Reliability. Some examples are: Waiting for formwork/rebar cage/conduiting to be ready when mixed concrete is waiting to be poured, Rebar crews idle as concreting has not caught up with backlog, Concreting time getting protracted as the elements to be concreted are inaccessible and too intricate, Client hold-up, Use of inappropriate method, etc. All these aspects are adequately addressed by the Lean method.

6.2 Lean Work Structuring

Work structuring is production system design all the way through. It develops and aligns the Project's process design with the engineering design, supply chain capability, resource allocation strategies and assembly efforts. Each component of work is designed so that it can be produced rapidly and for low cost, supports optimizing at the project level and delivers value to the customer and the constructor. It ensures thorough thinking through of production (flow) during design and project planning stages.

Some of the tools used for work Structuring are Value Steam Mapping and First Run Studies, which are dealt with in a later section.

The Work structuring will yield the following information:

- Global sequencing of activities.
- Master schedules and Phase schedules.
- Project organizational structure.
- Supply chain details.
- Operations designs, for instance using Precasting Vs in-situ working, using a gantry Vs tower crane, etc.
- Detailed methods including Work Method Statements.

6.3 Lean Execution

6.3.1 Basic concepts

In line with the main philosophy of Lean operating system as stated above, for production control the Last Planner™ system can be adopted. This ensures the involvement in the planning and control process of all the stakeholders, particularly the front line supervisors (the "Last Planners"). The main difference between this approach and another, such as Earned Value Method, is that instead of waiting for the work to proceed and then measure the variance between planned and actual, Lean attempts, in a proactive manner, to control the work to cause a desired future.

The main process starts from establishing a Master Schedule for the Project, going on to develop Phase Schedules and Look-ahead schedules and from then on go into detailed Weekly and Daily Schedules, measure the success achieved and work out corrective measures. (See Fig. 1). The main difference is that while developing the detailed schedules, the frontline people as well as the other stakeholders are involved to make the planning more realistic and letting the planning be developed by those who are responsible on the ground. Work Flow Control is by the Look-ahead process and Production Unit Control is by Weekly work planning.

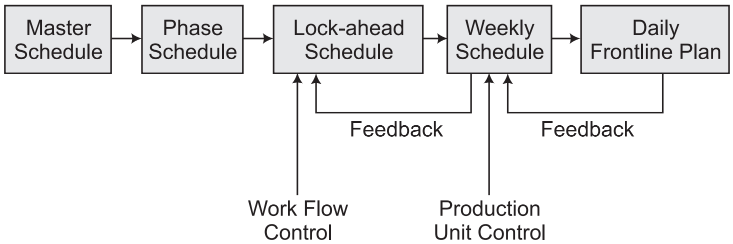

FIG. 1 FLOW OF SCHEDULES

6.3.2 The various schedules

(a) **Master Schedule:** The Master schedule covers delineating the contractual milestones and various phases, setting forth the project completion date, helping develop the overall execution strategy and planning for long-lead items. It will be inappropriate at this early overall stage to try to incorporate too much of schedule detailing as well as for any accurate long term predictions.

(b) **Phase Schedules:** The Phase schedules pertain to the major phases which comprise the overall project and are taken up one by one as and when a particular one is impending for execution. They are better developed by cross-functional teams, using "pull" techniques as close to the date of commencement of the phase as possible. This process helps in overall synergy with deployment of cross-functional teams and closeness to actual time of start of the phase will improve the accuracies for forward planning.

Conventional planning is based on a "push" process, i.e. finishing off an activity as quickly as possible without thinking about the successor activity being ready for execution. The "pull" technique concept is different in that each person pulls in only that much work which he can handle in the given time and only when it is totally ready for execution without any constraints.

(c) **Look-ahead schedules:** Look-ahead schedules are generally for 3 to 12 weeks duration, depending on the complexities and the overall duration of the project. They will consider only those activities which have been screened by the planners so as to be totally ready for execution. The process screens out unrealistic options and readies scheduled tasks for assignment by ensuring that there are no constraints. The idea is to create a workable backlog, a basket of constraint-free tasks by analysis of the various constraints and resolving them well in time. This process also enables early warning of potential problems when sufficient time is available to solve them. (See Fig. 2).

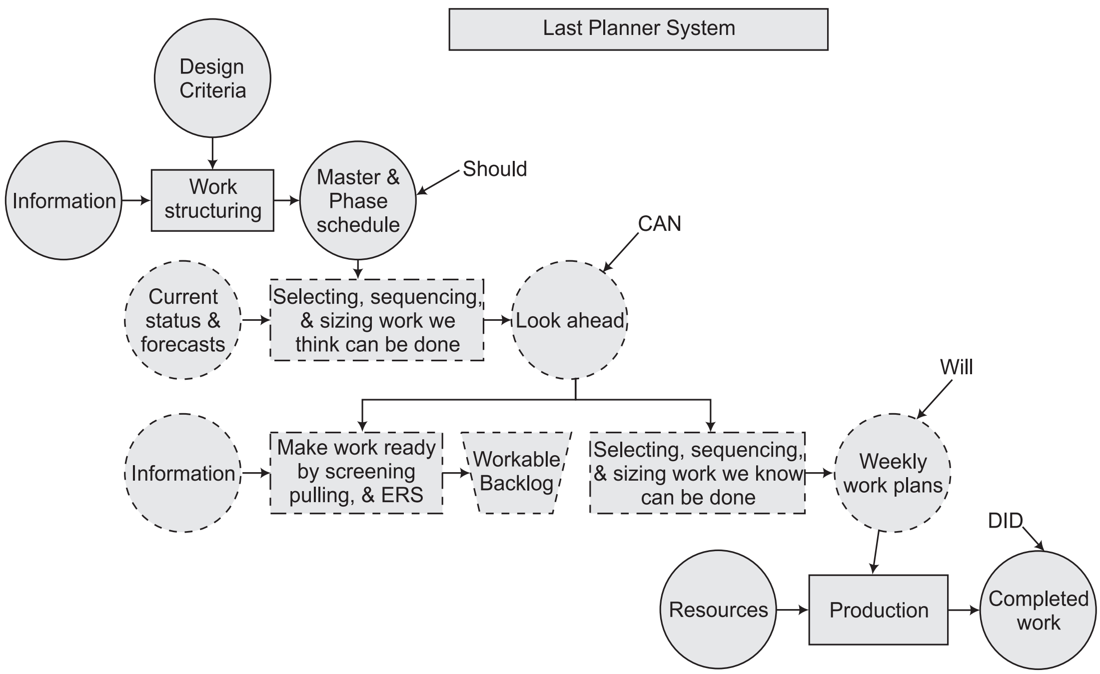

FIG. 2 PROCESS OF LAST PLANNER SYSTEM ™

(d) **Weekly Plans:** Narrowing down further, Weekly plans are prepared by frontline supervisors, collaboratively, by Pull process considering only the activities which are totally constraint-free. (See Fig. 3). Hence frontline supervisors have greater confidence in the success of their plans. These plans are Weekly Production Assignments, based solely on ability to perform them and not on what "should" be done. This Last Planner™ Concept was developed by Glenn Ballard and Greg Howell and is a trade mark of Lean Construction Institute (LCI), USA. In the Indian context a similar Collaborative Planning System (CPS) of production control is sometimes recommended.

6.3.3 Monitoring

The variability of the process is tracked by a factor called PPC (Percentage of Plan Completed). It is a measure of effectiveness of the Production System, to complete the commitments made.

$$\text{PPC} = \frac{\text{Number of completed assignments}}{\text{Total number of assignments committed}} \times 100$$

PPC ranges from 0 to 100%, higher being the better. High PPC indicates well-planned production process with high workflow reliability and good collaboration between production units, and a lower PPC indicates some failure of the production planning process.

FIG. 3 TYPICAL COLLABORATIVE PLANNING MEETINGS

6.3.4 The collaborative planning process

This process improves work flow and eliminates constraints in advance. It improves reliability of commitments and predictability (by eliminating variability) of work flow. The emphasis is not on spot progress of isolated activities but on a smooth flow of all work items to get better overall progress.

The front line supervisors are empowered to plan, commit, review and improve their own delivery performance week after week to reduce variability. They "pull" work to the extent they can manage, rather than "push" not-needed work to another. Workflow is improved by ensuring that future work is ready, through the look-ahead process, which is a pull process. In the Indian context, CPS requires good involvement of the Site Planning Manager and Project manager at various steps of the process. The process is further improved by including all the stakeholders-Subcontractors, Vendors, resource allocation teams, Supply Chain teams, etc. See Fig. 3 and Table 1.

Table 1. *Shift in Emphasis at Various Stages*

Stage	*Emphasis on*
Milestone Planning – Master Schedule	
Phase Schedule/Pull Scheduling	Should
Look Ahead Planning/Constraints Management	Can
Weekly Work Planning – by Frontline Supervisors	Will
Daily Reports - PPC (Per cent Plan Complete)	Did

To improve reliability, apart from CPS Work Structuring improvements are also necessary, by resorting to one or more of: Value Stream Mapping, First Run Studies, Productivity improvements, Constraint Analysis, Integrated Project Delivery, etc.

6.3.5 Benefits

Lean is Continuous Improvement all the time! With all stakeholders being involved, the best possible plan results with minimized operational conflicts. With the understanding of all getting properly aligned, better relationships are built up. Only value adding tasks are selected, as we work backwards from the results required. Development of planning skills in frontline supervisors increases PPC and productivity as well as savings in cost and time over a period of time, resulting in substantial rise in confidence levels of the site team to meet the Project's challenges.

6.3.6 Implementation concerns

If PPC results do not show consistent improvement, it is essential to understand the reasons for the same to avoid future failures and to improve the system. See Fig. 4 and Fig. 5 for typical methods of analysis. It may be necessary to forge significant change in the mindset of site people, to have more collaborativeness, more openness, more supportiveness, more sharing, readiness to appreciate and understand others' problems, ability to solve problems collectively, etc. Some of the other common problems are: Reluctance from frontline supervisors to "plan" (being more used to "action", due to lack of knowledge and being not used to think beyond a couple of days); reluctance to take time off from frontline to sit and plan; suspicion from management about frontline people wasting time to sit down and "Plan"; lack of formalised approach in planning process in frontline people; reluctance from Planning Dept to let go of the planning functions to frontline people; reluctance to involve subcontractors and vendors in the overall planning; distrust to share information with other Departments, etc.

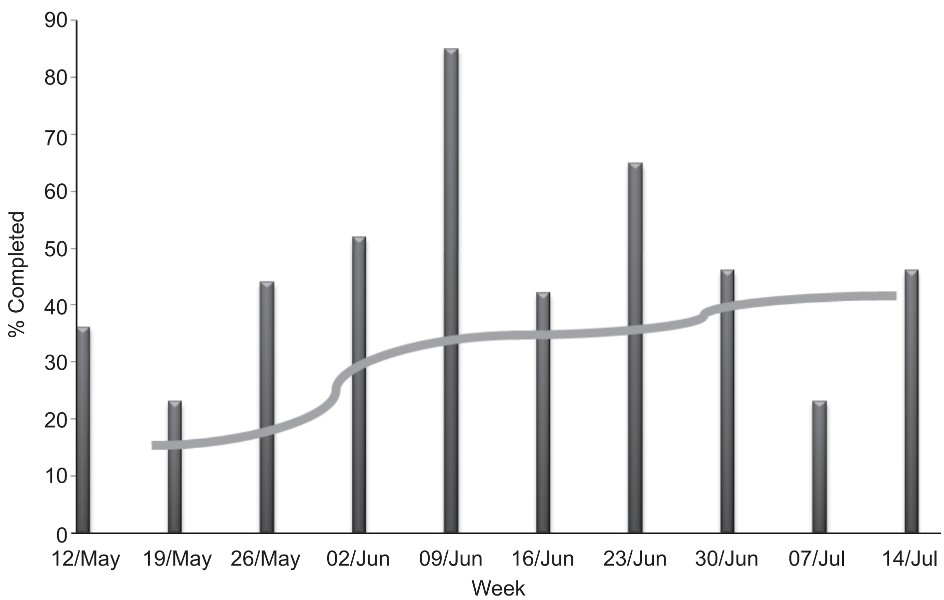

FIG. 4 TRACKING PPC OVER TIME

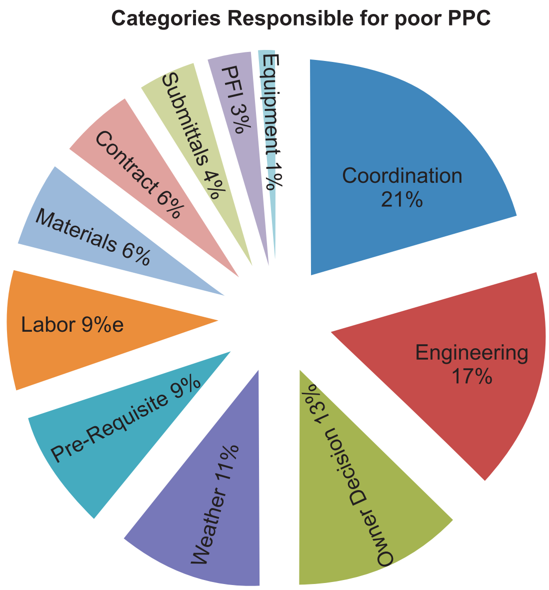

FIG. 5 ANALYSIS OF PPC

7. SOME INTERESTING LEAN CONSTRUCTION TOOLS

Some interesting tools are commonly used in Lean construction processes, as described below.

7.1 Value Stream Mapping(VSM)

VSM is a technique used to analyze and design the flow of materials and information required to bring a product or service to a consumer. VSM is a technique for identifying value-adding activities and eliminating non-value adding activities to optimise processes. Activities are generally divided into three categories: (1) non-value adding (NVA); (2) necessary but non-value adding (NNVA); and (3) value-adding (VA). In a formal sense, two depictions of the status are made: Current state of VSM (CVSM) and Future state of VSM (FVSM). Each scenario is depicted pictorially using standard symbols. We have to work on moving from CVSM to FVSM**.** For making the improvements, some of the methods used are: Work (Time, Motion) studies to identify NVAs and eliminating them; Modularisation/Standardisation; design changes to improve Constructability; off-site fabrication and assembly; reducing Batch size (ex. going in for multiple smaller batching plants in the site to enhance flexibility in delivery of concrete mix); bringing closely interconnected operations (ex. formwork, reinforcement and concreting) under supervision of one agency, etc.

7.2 First Run Studies

This process is essentially trial execution of a process in order to determine the best means, methods, sequencing, etc., to perform it. First-run studies are generally done a few weeks ahead of the scheduled execution of the project, while there is still time to mobilise different or additional prerequisites and resources. They can also be used during construction, but before the relevant activity starts. Casting concrete “mock-ups’ of difficult elements before the start of production of a large number of such elements is an example.

7.3 Building Information Modeling (BIM)

BIM is a graphical process of generating and managing building data during its life cycle. BIM is an evolving term generally referring to the broad use of 2D or 3D digital building models with linked parametric information to achieve the goal of integrated project data, enhanced visualisation and data sharing and reuse by various members of the project team. BIM is the enabler for integration and open information sharing. BIM is much more than mere three-dimensional visualization in that the various graphic elements also hold complete information pertaining to them. BIM seamlessly integrates design, drawing and specifications as well as construction sequence and methods. When the scheduling aspects are also integrated, the resulting 4D format can display time-based construction stages. BIM facilitates better understanding of the structures for the site people, eliminates clashing of various components of the project including services and brings all the stakeholders on a common platform, thus saving time and cost. It helps in minimising re-work, planning of construction methods, dovetailing of all required information in a most efficient manner, motivation of construction crews through visualization, first run tests of construction sequences, product walk-through, etc. (See Fig. 6).

FIG. 6 BUILDING INFORMATION MODELING

8. LEAN APPLICATIONS FOR OTHER ASPECTS OF CONSTRUCTION

Lean applications in Architecture and Design aim at sharper focus on client requirements, cutting down on extra margins and non-value adding aspects, ensuring better constructability and hence reducing costs and time. Target Value Design is a method to develop a design to suit the client-stipulated target cost rather than ending up with whatever cost which arises from a design and then cutting corners to reduce costs. Lean applications in Supply Chain Management focus on Just In-Time techniques to reduce inventories and material deliveries based on "pulls" from the site, thus cutting down on costs for stocks as well as needless storage.

Integrated Project Delivery concept brings together the Customer, Designer and Constructor to join hands seamlessly right from the conceptual stage, to increase overall Value and share the benefits. Forming Alliance Teams where all stakeholders work as a single team in an all-encompassing contract format for the overall good, can synergise all the stakeholders to focus on overall value for the Customer in a holistic manner and share the accruing benefits.

9. IMPLEMENTING LEAN IN CONSTRUCTION

A major step required for achieving success with Lean is to ensure a Lean Culture to permeate throughout the organization. The Toyota success came after a definite organisational culture was established. People engagement came after a rigorous selection procedure. A high performance environment was provided there with framework and coaching to successful problem solving, being inspired, two-way communication, empowering even the lowest level employee, respect, continuous improvement, etc. Strong Top Management commitment is necessary to implement Lean. Once implemented, continuous follow-up is also necessary to see that Lean becomes a way of life till it is firmly entrenched in the organisational culture. Then it will deliver its full potential with substantial results.

10. WAY FORWARD FOR LEAN CONSTRUCTION IN INDIA

The various agencies engaged in construction or project development in India have grown to realize the benefits of Lean construction concepts in the recent periods. Everyone involved in the construction industry accepts that there is a significant amount of wastage in the system, though the quantum of waste could be debatable. Adopting Lean methods in construction would solve many of the persisting problems in the industry.

Institute for Lean Construction Excellence (ILCE – www.ilce.in) is a non-profit body headquartered in Mumbai, founded in 2008 along the lines of the Lean Construction Institute of USA to develop Lean practices in the Indian construction industry. Today it boasts in its list of Chartered Members many famous names from the construction industry. IIT Madras and IIT Delhi provide academic and research support for the Lean concepts. Many seminars and workshops have been organized with faculty comprising leading international proponents such as Laury Koskela, Greg Howell, Carlos Formoso and various Indian experts from the industry and academia. BIM has caught the fancy of many users to improve understanding of structures, avoid costly construction-time problems and improve efficiency. Many consultants have also come up on the scene to provide hand-holding assistance to new users of Lean principles.

11. CONCLUSION

Lean looks at delivering value to the customer as a holistic process, instead of going in only for narrow focuses on work items or activities. It has an emphasis on elimination of wastages by looking at the processes closely. Planning is a more realistic process with a closer look at the current window, engaging the grassroots level people actually involved in the implementation. Constraints are resolved well in time, increasing predictability. Pull-based systems are used instead of pushing work into hands where it piles up inefficiently as “work in progress”. The emphasis is on constantly creating value for the project and for the ultimate customer.

In the current national plan it is expected that over ₹5,000 crores will be invested for infrastructure development. Such large investments would definitely call for the use of advanced project management techniques to ensure timely and economical implementations. Going for the Lean construction way would be in National interests to minimize wastage and improve productivity in a sustainable manner. It is a transformational process with a longer journey but one certain to deliver results.

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Current Trends in Engineering Practice Vol. III
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SUSTAINABILITY ASPECTS IN CONSTRUCTION

N. RAGHAVAN[1]

1. INTRODUCTION

Almost all activities for development and sustenance of human life depend on construction to some degree or other. Construction touches practically all areas of human endeavour - habitats, work areas, pleasure spots, sports arenas, transportation, infrastructure, …. In the process construction also impacts the environment we live in. There is a symbiotic relationship between the Environment and Construction: both impact each other. As human population has been increasing, almost exponentially in the recent past, and with increasing human activities in many spheres, the ability of the environment to sustain the large demands imposed by the populace is getting severely strained. So much so that the drastic deterioration in the quality of the environment is bound to severely and adversely impact the quality of life of the future generations. Numerous studies have been conducted on sustainability and considerable amount of data is also available. In the present context we will take a look at the possible ways in which construction affects sustainability and what can be done to avoid any negative impacts on sustainability from construction point of view.

2. BASIC CONCEPTS

Sustainability, in general, is the capacity to endure. In terms of its modern definition: Sustainability is the long-term maintenance of responsibility, which has environmental, economic, and social dimensions, and encompasses the concept of stewardship, the responsible management of usage of resources. Sustainability is improving the quality of human life while living within the carrying capacity of supporting eco-systems. Thus sustainability is not only limiting the exploitation of the environmental resources within acceptable limits, but also taking on Responsibility to ensure that the environment continues in undiminished form in the future also. While earlier definitions of sustainability were limited to the environment, growing realisation has lead to enlarging the scope to include the economic and social dimensions also (See Fig. 1).

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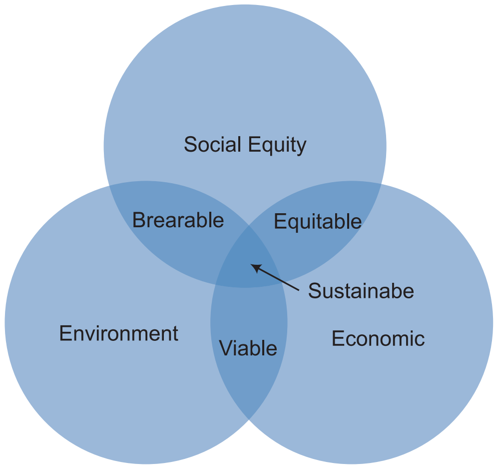

FIG. 1 THE 3 E'S OF SUSTAINABILITY

As far as construction goes, sustainability can be applied either to the constructed elements such as buildings or to the construction process itself.

As far as the former is concerned, the sustainability aspects pertaining to the entire lifecycle have to be looked at. Right from the conception stage, through planning and design stages the constructed facility has to be configured to have the least impact on the environment. "Green" buildings which satisfy this criterion get various grades (basic Certified to Platinum levels) of LEED (Leadership in Energy and Environmental Design) ratings. The green buildings use less water, optimize energy efficiency, conserve natural resources, generate less waste and provide healthier space for the occupants, as compared to conventional buildings. However, in this study the focus will be on the latter aspect, pertaining to the construction process itself.

3. SPECIAL ASPECTS OF CONSTRUCTION TO BE CONSIDERED

Unlike manufacturing, construction has many peculiarities and special aspects. Construction sites are multi-locational, diverse in nature, seasonal and mostly pose challenging conditions for implementation. For instance, construction of a residential building is quite different from that of a thermal power plant or a hydro power plant or an industrial building. The climatic conditions, the soil conditions, the loads applicable for the site in terms of seismicity or wind, ambient conditions, etc., all vary from site to site. The skills required for constructing the various types of projects are again quite diverse. In India labour is largely casual, ill-motivated and untrained. Work is highly risk-prone and highly variable in terms of predictability for execution. On the commercial side the industry generally has low margins and high competition. With all these negative factors, usually Sustainability is the last concern for the construction agencies!

In view of the above, ensuring sustainability during construction is quite challenging and calls for special steps to be taken.

4. IMPACT ON SUSTAINABILITY FROM GENERAL CONSTRUCTION/ "DEVELOPMENT"

In general, all "development" of land or construction activities will have some impact on the environment. The exact nature and extent of the impact will depend on many factors such as the nature of construction, nature of the ambience at the site, etc. However, broadly the following areas of concern can be identified:

(a) Land pollution: Modification of the site by the construction process—excavations, fills, shallow/deep foundations, solid wastes, Injections into the ground, changes in the skylines (the "view" goes!)

(b) Water pollution: Effluents from the site, rain run-off, cleaning/wash water, waste washing out (residual/blocked concrete), wastes from stockpiles; seepage into the ground; liquid wastes, oil spills, dispersion of toxic substances/hazardous wastes

(c) Air pollution: Dust creation, smoke from equipment

(d) Pollution of external areas: spill-outs from site, damage caused by transport access corridors (ex. hydro project supplies!), dirt tracked out onto roads from transport emanating from the site

(e) Noise pollution-due to construction equipment and activities

(f) Soil erosion

(g) Deforestation, loss of bio-diversity, depletion of fisheries

(h) Climate change due to CO_2 emission

(i) Ozone depletion-due to chemicals used in construction/operations

(j) Desertification-due to loss of water bodies in the process of development

(k) Eutrophication-water contamination

(l) Acidification-due to gas generation

(m) Depletion of mineral Resources.

FIG. 2 EXAMPLES OF CONSTRUCTION WASTE

All these potential damages have their own ameliorative measures which can be implemented before/during/after construction or development as the case may be, to restore the environment, societal status and economic status in a sustaining mode. The term "Land Development" is often a misnomer, as the effect of such a process is often detrimental rather than developing any of the land, or the habitants or the environment/ habitat! It is actually supposed to improve the usage of existing land from that which was prevailing earlier,; ex. Modifying a desert into cultivated land, using drip irrigation, etc. However, recent lessons learnt in ecology show that ecology is complex and any tinkering with the existing environment has adverse fall-outs in some way or other unless it is very well thought out.

FIG. 3 EXAMPLES OF QUARRYING

5. MAIN SUSTAINABILITY INTERFACES IN CONSTRUCTION

The major interfaces on which construction impacts the sustainability aspects are generally as follows:

- General impact of any "development" or construction.
- The very construction process—land grading, foundations, building up, etc.
- Construction materials—ex. Coarse aggregate has to come from quarries which degrade hills; sand for concrete has to come from rivers whose water course gets affected adversely; timber from felled trees destroys forests, etc. For instance for a large size hydro power project, aggregate quantity required would be about 50 lakh cum and for this a hill of 30 m height, 60 m width and 5 km length will have to be cut!
- Enabling works—formwork, excavation, dewatering.
- Construction Infrastructure—offices, Stores, Godowns, Colony, etc.
- Construction waste disposal: for instance, for the above-mentioned hydro project, disposal of excavated materials of 100 lakh CuM volume, a mountain will be created, 20 km long, 50 m wide, 10 m high!

The above should not be taken as detracting from the necessity for construction but only as raising a cautionary note on some of the prevailing practices and creating an awareness. Most of the ill effects discussed here can esaily be offset by taking appropriate corrective measures.

6. SOME MEASURES TO PROMOTE SUSTAINABILITY IN CONSTRUCTION PROJECTS

While there seem to be many negative impacts on sustainability on account of construction, many measures can be taken to remedy the situation. Some useful measures which are to be taken in the various stages are discussed below.

6.1 Project Preparation Stage

It is necessary to carry out a full-fledged Sustainability Impact Study, covering the impacts on the Environment, Economic scenario and Social Equity aspects well before the Project is to start. Once the various impact scenario are identified, corrective measures for each should be drawn up and implemented, before the commencement of the project to the extent possible. The onus is mainly on the client/owner for planning and implementing these measures, as the Constructor occupying the site only for a short period cannot be expected to address such issues, particularly when the cost of doing so may not be quantifiable in advance. Some of the measures which will need to be taken before commencement of the project are:

Identifying appropriate sources for the various construction materials required in adequate quantity and quality and the mode of exploitation of the same, whereby the negative impact on sustainability is avoided. Similarly waste disposal areas have to be identified in advance and prepared properly.

Planning of the development of the Site in such a way that there is minimal impact on the land, covering preservation of greenery, minimal excavation and filling, etc.

Planning for treatment of all effluents and waste/drainage water from the site before the water is let out of the site.

In all planning the life cycle costs should be considered and not merely capital costs.

Sustainability efforts have to start right from the Conceptual planning stage. Tenders and Contracts have to specify the required measures, extra cost has to be budgeted for and implementation standards should be strict.

6.2 Project Execution Stage

- Instituting procedures for recycling of aggregates from all waste or dismantled concrete and recycling of bitumen from all bituminous roads being re-laid.
- All wastage should be avoided. Here practicing the Lean philosophy will be of great help in tackling the seven types of common wastes.
- Local materials should be used to the maximum extent possible.
- Energy efficient lighting and equipment should only be used.
- Appropriate tools/equipment should be used for all construction operations.
- All vehicles leaving the site should have their tyres washed before leaving, to avoid the access roads from being spoilt by mud tracks. DMRC had set-up an excellent example in this respect in the country, worth serious emulation.

- Installing proper drainage to trap all effluents for proper treatment before being let out.
- Where appropriate, waste/discarded materials should be stored and recycled.
- Wherever possible for construction infrastructure the permanent facility should be used. For instance when many buildings are required for the facility, some of them could be constructed early to serve as construction office/stores, etc. Otherwise the temporary structures should be of reusable/recyclable type.

FIG. 4 EXAMPLES OF GOOD TEMPORARY STRUCTURES

6.3 Post-Project Execution Stage

- The site clean up and restoration of the site to the pre-existing state to the maximum extent possible is important. This is one activity normally not carried out by many constructors.
- Where it is not possible to avoid material dumps, they should be "greened" by turfing, etc and dressed up in other possible ways also to minimize the negative impacts. Particularly rain water run-offs from such dumps should be addressed.

6.4 Sustainability Measures

Measures of sustainability are sometimes classified into two categories:

(a) Simple Measures:
  - Those which minimize Embodied Energy – Initial stage (production, construction, transportation,..), Recurring stages (maintenance, repairs & rehabilitation,..)
  - Operating Energy – during service (LEED,..)
  - Exergy (Absolute energy efficiency) (=Energy Quantity X Quality)
  - Durability
  - Externalities (pollution, etc.)

(b) Complex Measures (multi-dimensional):
  - Ecological Footprint
  - Eco-labelling (ISO 14000,..)
  - Life cycle assessment

LEED is the standard for sustainable design worldwide. LEED showcases design and construction practices that significantly reduce or eliminate the negative impact of buildings on the environment during service. It is a point based system that ranks the sustainability of a building's design by grades ranging from "Certified' to "Platinum".

7. LEAN AND SUSTAINABILITY

*Lean concepts originated in manufacturing, owing their origin to the highly successful Toyota Production System. Later the principles got transformed to apply to construction and Lean Construction is growing in popularity in many countries around the world. In India also Lean has found some application in many projects. Lean is essentially based on a continuous improvement strategy, covering avoidance of all types of waste, optimising and improving processes, smoothening workflow, synergising and integrating efforts of all stakeholders to improve certainty at various stages and to get the best overall results for the project. (See Table 1).

Table 1. *Connection Between Lean and Sustainability*

Lean	*Sustainability*
Long term philosophy-create value for people, community (including environment), economy	Invest in long term-consider people, community, financials, environment
Create the right process to produce the right results	Ensure the ecosystem is in balance; if necessary, intervence in the system
Add value by developing people and partners	Invest in people-Consider stakeholders including your staff and partners (e.g. suppliers)
Continuously making problems visible and solving root causes driving organizational learning	Be transparent and consider the whole system Vs. treating symptoms
Minimize or eliminate waste of any kind	Creating waste harms something else in the system

Lean has synergy with Sustainability in many ways:

- Modern Lean principles are well suited to Sustainable construction.
- Lean is a way of thinking and acting that focuses on delivering pure Value; and Lean seeks creation of that value with fewer resources (ex. Money, time, materials,..).
- Both have common objectives- better efficiency, less wastage, better value for money, workable in the long run, better utilisation of human capital, etc.
- This combination can tremendously add to reduction of carbon footprint.
- Lean talks of seven deadly wastes: Transportation, Inventory, Motion, Waiting, Over-processing, Overproduction, Defects. Avoiding these also promotes sustainability.

The one area of divergence between the two could be cost. While Lean strives to minimize costs, sustainability may result in higher costs, for instance for ecological protection and enhancement,

* Lean construction concept is a recent development in the field of construction project management.

etc. However, both may converge when overall life-cycle cost is considered. Lean emphasizes value to the client while sustainability emphasizes value to enviornment, society and economy.

8. CONCLUSION

Sustainability has been recognized the world over as a tool for taking responsibility for the deterioration of the “3 E’s” as part of current lifestyles and taking measures to leave the world a better place for posterity. The measures being taken are still in an early stage and may not bear fruits as quickly as they are (badly) needed.

However, in India the realization is still not felt seriously and we have to go a long way before sustainability can have any real meaning in the Indian context! Particularly in construction, which is an all—pervading industry which touches practically all walks of our modern life, it is still not an acceptable philosophy. Some of the reasons are: there are too many small contractors/ constructors and construction is still an unorganized industry here; there is not much awareness or education/training regarding sustainability aspects. Clients/Owners have a major part to play and should demand (and pay for the same!) due standards in Quality, Safety and Sustainability. We need to do more, and very quickly at that, to rectify our standards and processes to pay due homage to sustainability. Fortunately India’s eco-footprint is still much smaller than that of many western countries!

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AN OVERVIEW OF APPLICATION OF NANOTECHNOLOGY IN CONSTRUCTION MATERIALS

A. K. TIWARI[1]

1. INTRODUCTION

Nanotechnology has change the way, material and process are being today, in a number of applications. For Civil Engineering applications, however the effect is not so visible, though a couple of applications are available. One of the biggest issues of concern for civil engineers is the amount of materials being used for various developmental projects around the world. This large consumption, is mostly exhausting the natural materials, which are non-reclaimable and hence the present use is unsustainable. Nanotechnology can help reduced uses of these natural materials without losing their optimum applications. Construction being the single largest industry today in the world would certainly benefit with this application. Nanotechnology has the potential to make construction faster, cheaper, safer, and more varied. Automation of nanotechnology construction can allow for the creation of structures from advanced homes to massive skyscrapers much more quickly and at much lower cost.

Nanotechnology is one of the most active research areas that encompass a number of disciplines such as electronics, bio-mechanics and coatings including civil engineering and construction materials. The use of nanotechnology in construction involves the development of new concept and understanding of the hydration of cement particles and the use of nano-size ingredients such as alumina and silica and other nanoparticles. The manufacturers are also investigating the methods of manufacturing of nano cement. If cement with nano-size particles can be manufactured and processed, it will open up a large number of opportunities in the fields of ceramics, high strength composites and electronic applications. At the nanoscale the properties of the material are different from that of their bulk counter parts. When materials become nano-sized, the proportion of atoms on the surface increases relative to those inside and this leads to novel properties.

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Use of nanomaterials can improve fluidity, strength and durability of the concrete. Nano-materials also have the potential to be used to improve the reinforcement qualities like anti-corrosion. Nano enabled coating of construction materials is going to constitute the largest application of nanotechnology in construction. Nanoproducts like architectural paints, water sealers and deck treatments; treatments applied during fabrication, such as scratch-resistant coatings on vinyl or wood flooring, insulation coatings etc., offer immense market opportunities for nanomaterials. Nanotech products and applications, among other benefits, may enhance the performance with regard to blocking of the ultra violet rays, transparency of the structures, photo reactivity, and resistance to stain and odor. Moreover, nanotechnology based coatings can enable creating self-cleaning surfaces. Many of these are already being embedded into window glasses and plumbing fixtures. Nanomaterials and nanotechnology based applications will thus take the construction industry much beyond bricks and mortar.

2. OPPORTUNITIES IN THE FIELDS OF CEMENT-BASED COMPOSITES

Nanotechnology is being used for the creation of new materials, devices and systems at molecular, nano- and micro-level [4-9]. Interest in nanotechnology concept for portland cement composites is steadily growing. The most reported research work regarding application of nanotechnology in cement-based materials is either related to coating or enhancement of mechanical and electrical properties. Some of the widely reported nanoparticles in cement concrete industries are Titanium dioxide (TiO_2), Nano silica (SiO_2), Alumina (Al_2O_3), Carbon nanotube (CNT) etc. Currently, the most active research areas dealing with cement and concrete are: understanding of the hydration of cement particles and the use of nano-size ingredients such as alumina and silica particles [4-7]. A typical scale of various constituent of a normal concrete is given in Fig. 1.

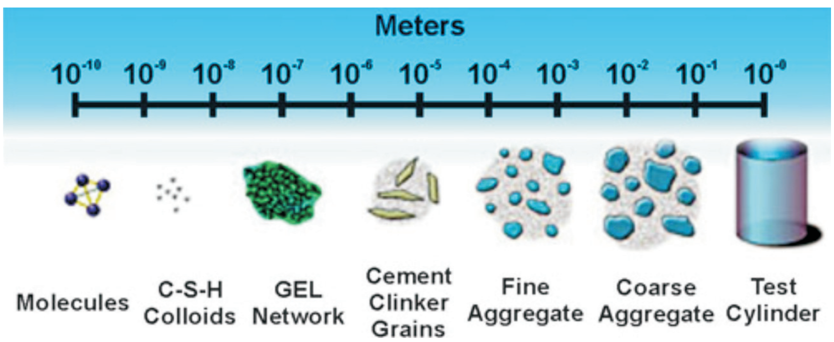

FIG. 1 SCALES OF VARIOUS CONSTITUENTS OF CONCRETE (REF 1)

Average size of Portland cement particle is about 50 microns. In applications that require thinner final products and faster setting time, micro cement with a maximum particle size of about 5 microns is being used. Knowledge at the nanoscale of the structure and characteristics of materials will promote the development of new applications and new products to repair or improve the properties of construction materials. For example, the structure of the fundamental calcium-silicate-hydrate (C-S-H) gel which is responsible for the mechanical and physical properties of cement pastes, including shrinkage, creep, porosity, permeability and elasticity. C-S-H gel can be modified to obtain better durability. Cement-based materials containing carbon nanotubes can be used for both strengthening and enhancing electrical and electronic properties of the concrete besides their mechanical properties. Development of smart concrete using carbon nanotubes would be easier. If nanocement particles can be processed with nanotubes and nano-size silica particles; conductive, strong, tough, more flexible, cement-based composites can be developed with enhanced properties, for electronic applications and coatings.

3. NANO CONCRETE AND NANO INGREDIENTS

Nano concrete is defined as a concrete made with portland cement particles with sizes ranging from a few nanometer to a maximum of about 100 micrometers. Nano ingredients are ingredients with at least one dimension of nano meter size. Therefore the particle size has to be reduced in order to obtain nano-portland cement. If these nanocement particles can be processed with nanotubes and reactive nano-size silica particles; conductive, strong, tough, more flexible, cement-based composites can be developed with enhanced properties, for electronic applications and coatings. There is also limited information dealing with the manufacture of nanocement. If cement with nano-size particles can be manufactured and processed, it will open up a large number of opportunities in the fields of cement-based composites. Current research activity in concrete using nano cement and nano silica includes:

3.1 Carbon Nanotubes (CNTs)

Carbon nanotubes are among the most extensively researched nanomaterials today. CNTs are tubular structures of nano meter diameter with large aspect ratio. These tubes have attracted much attention in recent years not only for their small dimensions but also for their potential applications in various fields. A single sheet of graphite is called grapheme. A CNT can be produced by curling a graphite sheet. Carbon sheets can also curl in number of ways. CNT can be considered as the most superior carbon fiber ever made. Addition of small amount (1% by wt.) of CNT can improve the mechanical properties consisting of the main Portland cement phase and water. A CNT can be singled or multi walled. CNTs are the strongest and most flexible molecular material with Young's modulus of over 1 TPa. The approximate diameter is 1 nm with length to micron order. CNTs have excellent flexibility. These are essentially free from defects. Nanotubes are highly resistant to chemical attack and have a high strength to weight ratio (1.8 g/cm^3 for MWNTs & 0.8 g/cm^3 for SWNTs). CNT has maximum strain of about 10% which is higher than any other material. Figure 2 shows the flexible behaviour of CNTs. Electrical conductivity of CNTs are six orders of magnitude higher than copper, hence, have very high current carrying capacity. Hence, carbon nanotubes have excellent potential for use in the cement composites.

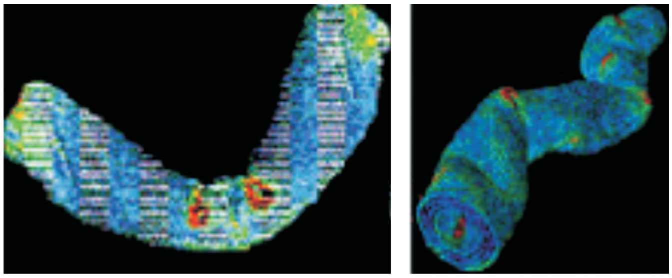

FIG. 2 FLEXIBLE BEHAVIOR OF CNTS (REF 3)

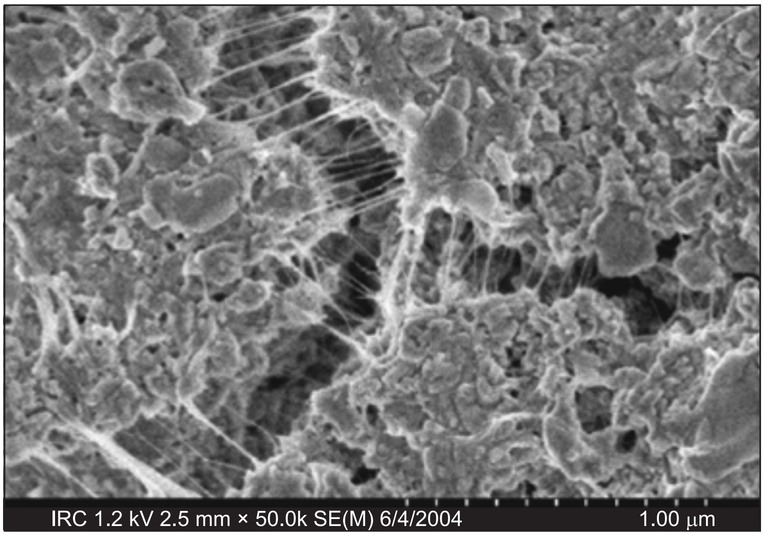

FIG. 3 CRACK BRIDGING BY CNT BUNDLES WITH CEMENT MATRIX(REF 3)

3.2 Nano Silica Fume for Improving Concrete Performance

Nano silica is most common nano additive to concrete. It is reported that nano silica was found to be much effective than micron sized silica for improving the performance such as permeability, and subsequently, durability. In addition, reduced amount of about 15 to 20 kg of nano silica was found to provide same strength as 60 kg of regular or micro silica.

Nano silica is effective additives to polymers and concrete, a development realized in high-performance and self compacting concrete with improved workability and strength. Nano-silica addition to cement based materials control the degradation of the fundamental C-S-H (Calcium-silicate-hydrate) reaction in water as well as block water penetration and leads to improvement in durability. The addition of nano SiO_2 particles enhances the density and strength of concrete. The results indicate that nano silica behaves not only as a filler to improve microstructure, but also as an activator to promote pozzolanic reaction for fly ash concrete as a result strength of the fly ash concrete improves particularly in the early stages.

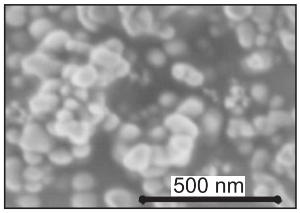

FIG. 4 A TYPICAL SEM OF NANO-SILICA PARTICLES (REF 2)

3.3 Coatings for Concrete

Another major large volume application of nano powder in cement-based materials is the area of coatings. The attractive colouring on ancient Czech glasses is found to contain nanoparticles. This shows that nanotechnology was used for coating surfaces i.e., spraying and making a product look attractive from ancient time. Nano-powders have a remarkable surface area. The surface area imparts a serious change of surface energy and surface morphology. The change in properties causes improved catalytic ability, tunable wavelength-sensing ability and better designed pigments and paints with self-cleaning and self-healing feature. One promising area of application of nanoparticle for cement based materials is development of self-cleaning coating. Titanium oxide is commonly used for this purpose. It is incorporated, as nano particles to block UV light. It is added to paints, cements and windows for its sterilizing properties as TiO_2 breaks down organic pollutants, volatile organic compounds, and bacterial membrane through powerful catalyst reactions and can reduce airborne pollutants applying to outer surfaces. Additionally it is hydrophilic and therefore gives self-cleaning properties to surface to which it is applied.

4. CONTROLLED RELEASE OF ADMIXTURES

Currently, there is an extensive use of chemical admixtures mainly to control/modify the fresh and hardened properties of concrete. The most common admixtures for cement and concrete include accelerators, set retarders, air entraining agents, and superplasticizers. Their successful use requires a basic knowledge of concrete technology, standard construction procedures, and familiarity with cement-admixture interactions. A particular challenge of interest to the authors is to optimize the use of dispersing agents such as superplasticizers in high performance concretes containing high volumes of supplementary cementing materials (SCMs). Dispersing agents such as superplasticizers are commonly used in these concretes. There are, however, practical problems such as loss of workability with time that are controlled by interactions with cement components. Controlling the timing of the availability of an admixture in cement systems is essential for its optimal performance. Control release technology provides a route to prolonged delivery of chemicals while maintaining their concentration over a specific time period. Here, a nanotechnology-based approach for controlled release of admixtures in cement systems using layered double hydroxides can be used.

There have been a number of applications in cement and concrete where different means of controlling the effect of admixtures via a controlled release technique were used. A number of patents and research articles describe "encapsulation" procedures for delivery of liquids and solids. A corrosion inhibitor, such as calcium nitrite, was dispersed by encapsulation in coated hollow polypropylene fibers. This anti-corrosion system was activated automatically when conditions would allow corrosion to initiate in a steel reinforced concrete. Porous aggregates were also used to encapsulate anti-freezing agents. Porous solid materials (e.g., metal oxides) have also been used as absorbing matrices to encapsulate chemical additives (e.g., accelerators, retarders, and dispersants) and to release them at a slower rate when combined with oil well treating fluids.

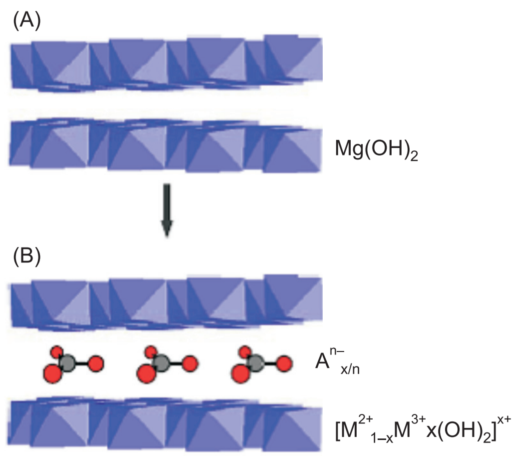

FIG. 5 CRYSTL STRUCUTRE OF BRUCITE (A) AND LDH(B) (REF 6)

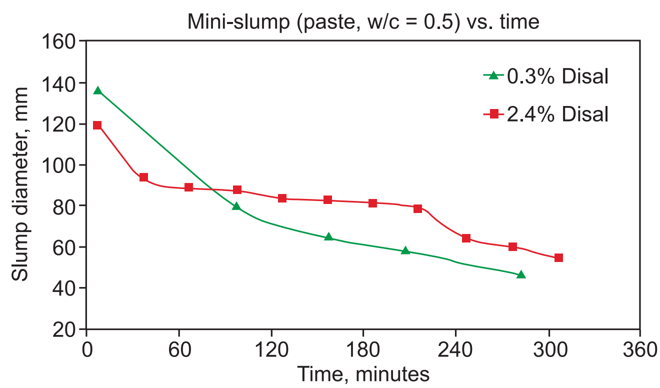

FIG. 6 SLUMP RETENTION WITH LDH TECHNOLOGY (REF 6)

Another method to control the release of chemicals in cement-based materials is by "intercalation de-intercalation". A cement additive for inhibiting concrete deterioration was developed with a mixture of an inorganic cationic exchanger: a calcium zeolite capable of absorbing alkali ions (sodium, potassium, *etc.*) and an inorganic anionic exchanger: hydrocalumite capable of exchanging anions (chlorides, nitrates, sulfates, *etc.*). The results of their tests showed the potential of increasing concrete durability by exchange of alkali and chloride ions to inhibit alkali-aggregate reaction and corrosion of rebar.

More recently, work examined means to control the timing of the release of chemical admixtures through their incorporation in nanoscale composite materials. More specifically, the technique consisted of intercalating an admixture into a hydrocalumite-like material, a calcium-based LDH derivative, and adding this composite to a cement-based mix. De-intercalation of the admixture can be actively programmed through controlled chemistry involving, for example, type of layered inorganic material, charge density, concentration, and/or pH. A sulphonated naphthalene formaldehyde-based superplasticizer, called Disal™ was used to produce the controlled release formulation (CaDisal).

The effectiveness of Disal™ alone in controlling the slump-loss *versus* time characteristic wascompared to that of the controlled release formulation CaDisal.

5. NANOPARTICLES AND STEEL

Steel has been widely available material and has a major role in the construction industry. The use of nanotechnology in steel helps to improve the properties of steel. The fatigue, which led to the structural failure of steel due to cyclic loading, such as in bridges or towers.The current steel designs are based on the reduction in the allowable stress, service life or regular inspection regime. This has a significant impact on the life-cycle costs of structures and limits the effective use of resources.The Stress risers are responsible for initiating cracks from which fatigue failure results. The addition of copper nanoparticles reduces the surface un-evenness of steel which then limits the number of stress risers and hence fatigue cracking. Advancements in this technology using nanoparticles would lead to increased safety, less need for regular inspection regime and more efficient materials free from fatigue issues for construction.

The nano-size steel produce stronger steel cables which can be in bridge construction. Also these stronger cable materials would reduce the costs and period of construction, especially in suspension bridges as the cables are run from end to end of the span. This would require high strength joints which lead to the need for high strength bolts. The capacity of high strength bolts is obtained through quenching and tempering. The microstructures of such products consist of tempered martensite. When the tensile strength of tempered martensite steel exceeds 1,200 MPa even a very small amount of hydrogen embrittles the grain boundaries and the steel material may fail during use. This phenomenon, which is known as delayed fracture, which hindered the strengthening of steel bolts and their highest strength is limited to only around 1,000 to 1,200 MPa.

The use of vanadium and molybdenum nanoparticles improves the delayed fracture problems associated with high strength bolts reducing the effects of hydrogen embrittlement and improving the steel microstructure through reducing the effects of the inter-granular cementite phase.

Welds and the Heat Affected Zone (HAZ) adjacent to welds can be brittle and fail without warning when subjected to sudden dynamic loading. The addition of nanoparticles of magnesium and calcium makes the HAZ grains finer in plate steel and this leads to an increase in weld toughness. The increase in toughness would result in a smaller resource requirement because less material is required in order to keep stresses within allowable limits. The carbon nanotubes are exciting material with tremendous properties of strength and stiffness, they have found little application as compared to steel, because it is difficult to bind them with bulk material and they pull out easily, which make them ineffective in construction materials.

6. NANOPARTICLES IN GLASS

The glass is also an important material in construction. There is a lot of research being carried out on the application of nanotechnology to glass. Titanium dioxide (TiO_2) nanoparticles are used to coat glazing since it has sterilizing and anti-fouling properties. The particles catalyze powerful reactions which breakdown organic pollutants, volatile organic compounds and bacterial membranes.

The TiO_2 is hydrophilic (attraction to water) which can attract rain drops which then wash off the dirt particles. Thus the introduction of nanotechnology in the Glass industry incorporates the self-cleaning property of glass. Fire-protective glass is another application of nanotechnology. This is achieved by using a clear intumescent layer sandwiched between glass panels (an interlayer) formed of silica nanoparticles (SiO_2) which turns into a rigid and opaque fire shield when heated. Most of glass in construction is on the exterior surface of buildings. So the light and heat entering the building through glass has to be prevented. The nanotechnology can provide a better solution to block light and heat coming through windows.

7. NANOPARTICLES IN COATINGS

Coatings are important area in construction. Coatings are extensively used to paint the walls, doors, and windows. Coatings should provide a protective layer which is bound to the base material to produce a surface of the desired protective or functional properties. The coatings should have self-healing capabilities through a process of "self-assembly." Nanotechnology is being applied to paints to obtain the coatings having self-healing capabilities and corrosion protection under insulation. Since these coatings are hydrophobic and repel water from the metal pipe and can also protect metal from salt water attack. Nanoparticle based systems can provide better adhesion and transparency. The TiO_2 coating captures and breaks down organic and inorganic air pollutants by a photo catalytic process, which leads to putting roads to good environmental use.

8. CONCLUSION

Nanotechnology can change the way we construct our structure today. It can help us to utilize the natural resources to optimum level and make them sustainable. This will also allow use of resources for present development and leave the same for the use of future generations also.

Though presently at research level, scope is enormous and engineers and scientist need to increase their effort on the directions to overcome challenges.

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ENVIRONMENTAL ISSUES RELATING TO PORT AND HARBOUR DEVELOPMENTS

M. M. KAMATH[1]

ABSTRACT

Ports are the principal conduits through which the economic life of a maritime nation flows. As maritime gateways, ports serve as interface between sea and land links and have to handle enormous flow of goods, which are broken down into smaller flows for distribution to the hinterland by road, rail and inland water ways. Thus the port is a crucial sub-system of the total transport chain. Ports handle 82% of the world's trade and hence its capacity and efficiency will determines the growth and economic potential of the region or the country. The planning, construction and operation of ports involve number of environmental issues. Indian Port managers and others connected with ports industry are being subjected to a critical review of the environmental impact of port construction and operations in the recent years.

All Port and Harbour projects will require the following prior environmental clearances from Ministry and Environment Forests (MoEF).

- Coastal Regulation Zone (CRZ) Clearance as envisaged in CRZ Notification 2011 (S.O.19 (E) dt.6-01-2011), for locating any fore shore activities in CRZ.
- Environmental Impact Assessment (EIA) Clearance as envisaged in Environmental Impact Assessment of Development Projects Notification 2006 S.O.1533 (E), dt. 14th September 2006 as amended in 2009, for all new projects/activities listed in the Schedule attached to the notification.

An attempt has been made in this paper to outline the various aspects of environmental impacts relating to construction and operation of Ports and Harbours and the clearances required from Ministry of Environment and Forests (MoEF). An over view of National and International Legislations on Environment relating to Ports and Harbours is also presented.

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1. INTRODUCTION

The ancient Indian treaties viz., "Vedas" and "Upanishadas" (2500–1500 B.C) have references relating to conservation and protection of plants, animals and environment.

Concern about man's impact on the environment dates from the work of the classical geographers of the nineteenth century.

The 'Environment' as defined in the Environmental Protection Act (EPA) includes water, air and land and the inter-relationship which exists among and between water, air and land and human beings, other living creatures, plants, microorganisms and property.

'Environment' is also defined as 'All the physical, chemical, biological and social factors likely to affect directly or indirectly, immediately or later on all living beings'.

'Environmental Pollutant' means any solid, liquid or gaseous substances present in such concentrations as may be or intend to be injurious to the environment.

'Environmental Impact Assessment' (EIA), is a procedure for bringing out the potential effects of human activities on environmental systems. The EIA is meant for inter-comparison of the developmental options and screening of alternate sites for locating the projects.

The Environmental Impact Assessment (EIA), is to be followed by the preparation of the Environmental Impact Statement (EIS) which is the final analysis to an EIA and the preparation of Environmental Management Plan (EMP).

Thus, the Environmental Impact Assessment (EIA) is an important management tool for ensuring the optimal use of natural resources for sustainable development. Environmental Management Plan (EMP) is the study of the unintended consequences of a project. Its purpose is to identify, examine, assess and evaluate the likely and probable impacts of a proposed project on the environment and thereby, to work out remedial action plans to minimize adverse impact on the environment.

2. ADMINISTRATION OF GOVERNMENT POLICY ON ENVIRONMENT

The primary responsibility for administration and implementation of the Government of India's policy with respect to environmental management, conservation, ecologically sustainable development and pollution control rests with the Ministry of Environment and Forests (MoEF) Government of India.

Established in 1983, MoEF is the agency primarily responsible for the review and approval of EIA pursuant to Government of India (GoI) legislation.

The EIA Notification 2006 not only reengineered the entire EC process specified under the EIA Notification 1994 but also highlighted the need to introduce specific sectors to be brought in the ambit of the EC process based on their extent of impacts on environment.

The Environmental Assessment Notification 2006 S.O.1533 (E), dt. 14th September 2006 as amended in 2009, issued under Environment (Protection) Act 1986, has made it mandatory to obtain prior environmental clearance (EC) for scheduled development projects. The EIA Notification 2006 has notified 39 developmental sectors which require prior environmental clearance. The development activities are listed in the schedule attached to the notification.

The notification has classified projects based on the capacity, under two Categories 'A & B', which has been further categorised as 'B1 or B2'. Category 'A' projects (including expansion and modernization of existing projects) require clearance from Ministry of Environment and Forests (MoEF), Govt. of India (GoI) and for Category 'B' from the State Environmental Impact Assessment Authority (SEIAA), constituted by the Govt. of India.

For technical appraisal of projects, sector specific Expert Appraisal Committees (EACs) have been constituted in the Ministry for consideration of Category 'A' projects. These sectoral Committees are for Industrial, Thermal Power & Coal Mining, Non-Coal Mining, River Valley, Infrastructure & CRZ, and Construction projects. The Ministry of Environment and Forests (MoEF) has so far constituted 25 State level Environmental Impact Assessment Authorities (SEIAAs) and State Expert Appraisal Committees (SEACs) to appraise 'B' Category projects.

3. ENVIRONMENTAL GUIDELINES

The MoEF has brought out EIA Sector Specific Manuals for various sectors. "The Environmental Impact Assessment Guidance Manual for Ports and Harbours" was issued during February 2010.

These guidance manual assist the project authorities in planning and for carrying out the

- Environmental Impact Assessment (EIA) and
- Formulating the Environmental Management Plan (EMP).

The publication "Environmental Considerations for Port and Harbour Developments – World Bank Technical Report No. 126, 1990" provides an extremely useful 'Check List' to be followed for the clearance of World Bank funded projects.

4. NATIONAL AND INTERNATIONAL LEGISLATIONS ON ENVIRONMENT

Government of India has laid out various policy guidelines, acts and regulations pertaining to sustenance of environment at the coastal area.

In addition to this, Central Government, State Government and various national and international policy guidelines are laid out to restrict development activities and the pollution in the coastal areas, as currently, over 40% of the world's population lives within 100 km of the coast.

4.1 National Environmental Legislations

The National Environmental Legislations which include the Act and the Rules are as under:

- The Water (Prevention and Control of Pollution) Act 1974
- The Water (Prevention and Control of Pollution) Rules 1975
- The Water (Prevention and Control of Pollution) Cess Act 1977
- The Water (Prevention and Control of Pollution) Cess Rules 1978
- The Air (Prevention and Control of Pollution) Act 1981
- The Air (Prevention and Control of Pollution) Rules 1983
- The Environmental Protection Act (EPA) 1986

- The Environmental Protection Rules (EPA) 1986
- The National Environmental Tribunal Act 1995
- The Forest (Conservation) Act, 1980
- The Wild Life (Protection) Act, 1972
- The Motor Vehicles Act, 1988
- The Ancient Monuments and Archaeological Sites and Remains Act, 1958 and
- Hazardous Wastes (Management and Handling) Rules, 1989.

4.2 International Environmental Legislations

The International Environmental Legislations which are applicable to Ports and Harbours are as under:

• **MARPOL Convention, 1973/78:** The MARPOL Convention, is an international convention which includes regulations that are aimed at preventing and minimizing pollution from ships both accidental pollution and that from routine operations.

It is a combination of two treaties adopted in 1973 and 1978 respectively and updated by amendments through the years.

This international convention was adopted in 1973 at the International Maritime Organization (IMO) and covered pollution by oil, chemicals, harmful substances in packaged form, sewage and garbage.

• **Ballast Water Management Convention, 2004:** The International Maritime Organisation (IMO) has setup "International Convention for the Control and Management of Ship's Ballast Water and Sediments, 2004" for preventing the introduction of unwanted organisms and pathogens from ship's ballast water and sediment discharges. This is aimed to arrest the potentially devastating effects of the spread of harmful aquatic organisms carried by the ballast water.

• **International Ship and Port Facility Security Code (ISPS Code):** In order to mitigate terrorist attacks on Maritime Industry, the ISPS Code was adopted by a Conference of Contracting Governments to the International Convention for Safety of Life at Sea. (SOLAS) 1974, convened in London during December 2002. The purpose of the code is to provide a standardized, consistent framework for evaluating risk, enabling governments to offset changes in threat with changes in vulnerability for ships and port facilities.

5. ENVIRONMENTAL CLEARANCES FOR PORT AND HARBOUR PROJECTS

All Port and Harbour projects will require the following prior environmental clearances from MoEF.

- CRZ Clearance as envisaged in CRZ Notification 2011, (S.O.19 (E) dt.6-01-2011) for locating any fore shore activities in CRZ.
- EIA Clearance as envisaged in Environmental Impact Assessment Notification 2006 (S.O.1533 (E) dt.14-09-2006) as amended in 2009, for all new projects/activities listed in the Schedule to the notification.

The Ports and Harbours are classified Under section 7(e) of the Schedule to the notification. Ports with a cargo handling capacity greater than 5 million tonnes per annum (MTPA) are classified under Category 'A' and all these projects or activities shall require prior Environmental Clearance from the MoEF.

In the case of Ports with a cargo handling capacity of less than 5 MTPA, are classified under Category 'B' and will require clearance from State Level Environment Impact Assessment Authority (SEIAA).

Environmental Clearance for Ports and Harbours is required for

- Construction Phase
  [including Capital Dredging] and also for
- Operation Phase
  [including Maintenance Dredging].

5.1 CRZ Notification 2011 (S.O.19 (E) dt. 6-01-2011)

The Central Government had issued a Notification 'Coastal Regulation Zone (CRZ) Notification, 2011' (S.O.19 (E) dt. 6-01-2011), for the protection of the coastal and marine environment and has declared the coastal stretches of the country and the water area up to its territorial water limit, excluding the Islands of Andaman and Nicobar & Lakshadweep and the marine areas surrounding these Islands upto its territorial limit as Coastal Regulation Zone (CRZ) and restricts the setting up and expansion of any industry, operations or processes and manufacture or handling or storage or disposal of hazardous substances.

The CRZ Notification was first issued in 1991 (S.O. 114 (E) dt. 19-02-1991 and was amended from time to time. The recent amendments are

- 2002 (S.O. 470 (E) dt. 21-05-2002 and
- 2011 (S.O.19 (E) dt. 6-01-2011).

As per, S.O.19 (E) dt. 6-01-2011, CRZ Clearance is required from MoEF, for locating any fore shore activities in the CRZ relating to Ports and Harbours.

However, the notification has specified a list of 15 petroleum and chemical products permitted for storage in the CRZ, except CRZ – I (A).

The procedure for CRZ Clearance for Permissible Activities is detailed in Annexure – A.

5.1.1 Classification of coastal regulation zones

For the purpose of conserving and protecting the coastal areas and marine waters the CRZ area have been classified as fallows.

- CRZ – I - (A) The areas that are ecologically sensitive and geomorphological features which play a role in the maintaining the integrity of the coast.
- CRZ – I - (B) The Area between Low Tide Line and High Tide Line.
- CRZ – II The areas that have been developed upto or close to the shoreline.
- CRZ – III The areas that are relatively undisturbed and those do not belong to either CRZ – I or II, which include coastal zone in the rural areas (developed and undeveloped)

and also areas within municipal limits or in other legally designated urban areas, which are not substantially built up.

- CRZ – IV
  (a) The water area from the low tide line to twelve nautical miles on the seaward side.
  (b) Shall include the water area of the tidal influenced water body from the mouth of the water body at the sea upto the influence of tide which is measured as five parts per thousand during the driest season of the year.
- CRZ – V Areas requiring special consideration for the purpose of protecting the critical coastal environment and difficulties faced by local communities *viz.,*
  - CRZ areas falling within municipal limits of the Greater Mumbai.
  - CRZ of Kerala and
  - CRZ of Goa.

5.2 Environmental Impact Assessment Notification 2006 (S.O.1533 (E) dt.14-09-2006)

The Central Government had issued a Notification "Environmental Impact Assessment 2006 (S.O. 1533 dt. 14-09-2006) which imposes restrictions and prohibitions on the expansion and modernisation of any activity or new projects, unless environmental clearance is accorded by the Central Government.

An amendment has also been issued during 2009.

The procedure for Environmental Impact Assessment clearance and also the Generic Structure of Environmental Impact Assessment for Ports and Harbours is presented in Annexure–B.

6. STAGES IN PRIOR ENVIRONMENTAL CLEARANCE PROCESS

The Environmental Clearance Process for new projects will comprise of a maximum of four stages, all of which may not apply to a particular case.

- Stage I: Screening (only for Category B projects)
- Stage II: Scoping
- Stage III: Public Consultation and
- Stage IV: Appraisal

Stage (I) – Screening

In case of Category 'B' projects, this stage will entail the scrutiny of an application, seeking prior environmental clearance made in Form – 1, by the concerned SEAC for determining whether or not, the project or activity requires further environmental studies for preparation of an Environmental Impact Assessment (EIA) for its appraisal prior to the grant of Environmental Clearance, depending upon the nature and location specificity of the project. The project requiring an Environmental Impact Assessment report shall be termed as Category 'B1'and remaining projects will be treated as Category 'B2' and will not require Environmental Impact Assessment report.

Stage (II) – Scoping

"Scoping" refers to the process by which the Expert Appraisal Committee (EAC), determine detailed and comprehensive Terms of Reference (TOR) addressing all relevant environment concerns for the preparation of an Environmental Impact Assessment (EIA) report, in respect of the project for which prior environmental clearance is sought. The EAC will determine the TOR on the basis of the information furnished in the prescribed Application Form – 1 including TOR proposed by the Applicant. The EAC may also make a site visit by a subgroup of EAC if considered necessary.

The TOR will be conveyed to the applicant by the EAC, within 60 days of the receipt of Form – 1. If the TOR is not finalized and conveyed to the applicant within 60 days of the receipt of Form – 1, the TOR suggested by the applicant shall be deemed as the final TOR approved for the EIA studies.

Stage (III) – Public Consultation

"Public Consultation" refers to the process by which the concerns of the local affected persons and others who have plausible stake in the Environmental Impacts of the projects or activity are ascertained with a view to taking into account all the material concerns in the project or activity design as appropriate. All Category 'A' and Category 'B1' projects will require public consultation except for few of the projects specified in the notification.

After completion of the public consultation, the applicant shall address all the environmental concerns expressed during this process and make appropriate changes in the draft EIA and EMP.

Stage (IV) – Appraisal

"Appraisal" means the detailed scrutiny by the EAC of the application and other documents like the final EIA report, out come of the public consultation including public hearing proceedings. This will be done in a transparent manner in a proceeding to which the applicant shall be invited for furnishing necessary clarification in person or through an authorized representative.

On conclusion of this proceeding, the EAC concerned shall make categorical recommendation to the regulatory authority concerned either for grant of prior Environmental Clearance on stipulated terms and conditions or rejection of the application together with reasons for the same.

The appraisal of an application has to be completed by EAC within 60 days of the receipt of the final Environmental Impact Assessment report and other documents or the receipt of Form – 1 where public consultation is not necessary and the recommendations of EAC will be placed before the competent authority for final decision within the next 15 days.

The regulatory authority will consider the recommendation of EAC and convey its decision to the applicant within 45 days of the receipt of the recommendation of the EAC or in other words, within 105 days of the receipt of the final EIA report.

7. ENVIRONMENTAL IMPACT SURVEYS

The study of environmental impact surveys, aims at identifying the following aspects:

- Areas of Impact
- Types of Impact
- Measurement of Impact and
- Control of Impact.

Environmental Impact Assessment forms an essential and integrated part in the whole sequence of process that constitute the port project appraisal, planning, design and operation process. The national legislation/Govt. Acts relating to environment and pollution applicable to Ports and Harbours are:

- Indian Ports Act 1908
- Major Port Trusts Act 1963
- Coast Guard Act 1978
- Prevention of Water Pollution Act 1981
- Merchant Shipping Amendment Act 1983
- Environment Protection Act 1986
- Relevant Municipal Acts.

In addition the following International Convention are also applicable to port operations.

- MARPOL Convention, 1973/78
- Ballast Water Management Convention, 2004
- International Ship and Port Facility Security Code (ISPS Code).

8. CONCLUSION

- In a developing country like India, priorities are important in view of limited financial resources.
- However, environmental protection has to be given its due importance.
- Till recently serious thought has not been focused on environmental effects relating to construction and operation of Ports and Harbours.
- World over serious concern is being expressed over disposal of dredged materials at sea.
- Enough care has to be excercised in the choice of the appropriate dredging technology and selection of suitable spoil disposal sites.
- It is absolutely necessary to carry out systematic short term and long term studies/ monitoring relating to physical, chemical and biological effects due to construction and operation of Ports and Harbours.

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ANNEXURE – A

Procedure for CRZ Clearance for Permissible Activities

The procedure for clearance of permissible activities under CRZ notification is as under.

(i) The proponent has to apply with the below noted documents for seeking prior clearance under CRZ Notification to the concerned State or the Union Territory Coastal Zone Management Authority (CZMA).

  (a) Form I (as per Annexure IV of the Notification)

  (b) Rapid EIA report including marine and terrestrial component

  (c) Comprehensive EIA with cumulative study for projects which are classified as erosion prone areas by MoEF.

  (d) Disaster Management Report, Risk Assessment Report and Management Plan.

  (e) CRZ map indicating HTL and LTL demarcated by one of the authorized agency in 1: 4000 Scale

  (f) Project layout superimposed on the above map indicated at (e) above

  (g) The CRZ map covering 7 km radius around the project site.

  (h) The CRZ map indicating the CRZ- I, II, III and IV areas including other notified ecologically sensitive areas.

  (i) No objection certificate from the concerned State Pollution Control Boards or Union territory Pollution Control Committees for the projects involving discharge of effluents, solid wastes, sewage and the like.

(ii) The concerned CZMA shall examine the above documents in accordance with the approved CZMP and in compliance with CRZ Notification and make recommendations within a period of sixty days from date of receipt of complete application.

  (a) MoEF or State Environmental Impact Assessment Authority (hereinafter referred to as the SEIAA) as the case may be for the project attracting EIA Notification, 2006.

  (b) MoEF for the project not covered in the EIA Notification, 2006 but attracting Para 4 (ii) of the CRZ Notification.

(iii) MoEF or SEIAA shall consider such projects for clearance based on the recommendations of the concerned CZMA within a period of 60 days.

(iv) The clearance accorded to the projects under the CRZ Notification shall be valid for a period of five years from the date of issue of the clearance for commencement of construction and operation.

ANNEXURE – B

Procedure For Environmental Impact Assessment Clearance

A. Application for Environmental Clearance

The application seeking prior environmental clearance in all cases shall be made in the prescribed Form I Annexed to the notification, after identification of prospective site(s) for the project and/or activities to which the application relates, before commencing any construction activity, or preparation of land, at the site by the applicant. In addition a copy of the prefeasibility report shall also be submitted.

The four stages involved in the prior environmental clearance process in the sequential order are as under.

- Stage (I) – Screening (only for Category 'B' projects and activities)
- Stage (II) – Scoping
- Stage (III) – Public Consultation
- Stage (IV) – Appraisal

Stage (I) – Screening

In case of Category 'B' projects, this stage will entail the scrutiny of an application, seeking prior environmental clearance made in Form – 1, by the concerned SEAC for determining whether or not, the project or activity requires further environmental studies for preparation of an Environmental Impact Assessment (EIA) for its appraisal prior to the grant of Environmental Clearance, depending upon the nature and location specificity of the project. The project requiring an Environmental Impact Assessment report shall be termed as Category 'B1' and remaining projects will be treated as Category 'B2' and will not require Environmental Impact Assessment report.

Stage (II) – Scoping

"Scoping" refers to the process by which the Expert Appraisal Committee (EAC), determine detailed and comprehensive Terms Of Reference (TOR) addressing all relevant environment concerns for the preparation of an Environmental Impact Assessment (EIA) report, in respect of the project for which prior environmental clearance is sought. The EAC will determine the TOR on the basis of the information furnished in the prescribed Application Form – 1 including TOR proposed by the Applicant. The EAC may also make a site visit by a subgroup of EAC if considered necessary.

The TOR will be conveyed to the applicant by the EAC, within 60 days of the receipt of Form – 1. If the TOR is not finalized and conveyed to the applicant within 60 days of the receipt of Form – 1, the TOR suggested by the applicant shall be deemed as the final TOR approved for the EIA studies.

Stage (III) – Public Consultation

"Public Consultation" refers to the process by which the concerns of the local affected persons and others who have plausible stake in the Environmental Impacts of the projects or activity are ascertained with a view to taking into account all the material concerns in the project or activity design as appropriate. All Category ‘A’ and Category ‘B1’ projects will require public consultation except for few of the projects specified in the notification.

After completion of the public consultation, the applicant shall address all the environmental concerns expressed during this process and make appropriate changes in the draft EIA and EMP.

Stage (IV) – Appraisal

“Appraisal” means the detailed scrutiny by the EAC of the application and other documents like the final EIA report, out come of the public consultation including public hearing proceedings. This will be done in a transparent manner in a proceeding to which the applicant shall be invited for furnishing necessary clarification in person or through an authorized representative.

On conclusion of this proceeding, the EAC concerned shall make categorical recommendation to the regulatory authority concerned either for grant of prior Environmental Clearance on stipulated terms and conditions or rejection of the application together with reasons for the same.

The appraisal of an application has to be completed by EAC within 60 days of the receipt of the final Environmental Impact Assessment report and other documents or the receipt of Form – 1 where public consultation is not necessary and the recommendations of EAC will be placed before the competent authority for final decision within the next 15 days.

The regulatory authority will consider the recommendation of EAC and convey its decision to the applicant within 45 days of the receipt of the recommendation of the EAC or in other words, within 105 days of the receipt of the final EIA report.

B. Generic Structure of Environmental Impact Assessment Report

The Generic structure of Environmental Impact Assessment Report for Ports And Harbours is annexed in Appendix A.

APPENDIX – A

GENERIC STRUCTURE OF ENVIRONMENTAL IMPACT ASSESSMENT FOR PORTS AND HARBOURS

- Introduction
- Project Description
- Description of the Environment
    - Land Environment
    - Meteorological Data
    - Water Environment
    - Marine Environment

  - Air Environment
  - Biological Environment
  - Noise and Vibrations
  - Solid Waste Management
  - Socio Economic and Health Environment
- Anticipated Environmental Impacts and Mitigation Measures both for construction and operation of ports
- Environmental Monitoring Programme
- Technical Studies (if required on a case to case basis)
  - Mathematical and Physical Models for evolution of port layout
  - Simulation studies
  - Accretion and Erosion of coast line due to port construction
  - Types of dredging equipment proposed to be deployed to minimize pollution
  - Identification of dredge disposal sites (mathematical and if necessary site tracer studies)
- Analysis of Alternatives (Technology and Sites)
- Additional Studies
  - Public Consultation
  - Risk Assessment and Disaster Management
  - Social Impact Assessment, R & R Action Plans
- Project Benefits
  - Improvement in the physical infrastructure
  - Improvement in the social infrastructure
  - Employment potential
  - Other tangible benefits
- Environmental Cost Benefit Analysis (optional)
- Environmental Management Plan
- Summary and Conclusion
- Disclosure of Consultants Engaged.

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APPLICATION OF APQP, A QS-9000 TOOL FOR QUALITY IMPROVEMENT

SHANTANU CHAKRABARTI[1]

ABSTRACT

Various techniques and tools are being adopted today for minimising the product and process failures in any manufacturing industry, thereby improving the quality of the product. QS9000 quality system, first formulated by the three big auto makers in the world (Ford, GM and Chrysler) provides one such technique through APQP (Advance Product Quality Planning). This helps the organisations to develop a quality assurance system. This paper describes the technique of constructing the components of the system, *viz.,* Process Flow Chart, the Potential Failure Mode Effect Analysis and the Control Plan. The Control Plan is the basis of developing finer operational control in the form of Standard Practice Instructions or Work Instructions for the shop floor. The paper then discusses a case study describing the application of the technique to a Continuous Galvanising Line, which helped in bringing down rejections due to one particular cause. The basics of the technique along with the necessary formats and the tables combined with the example of the application should enable any other production or processing line to adopt this practice for upgradation of quality of its product.

Key Words: QS9000, APQP, PFMEA, CONTROL PLAN, QUALITY.

1. INTRODUCTION

Manufacturing systems are designed to satisfy customers' quality and reliability expectations at a competitive price. In order to achieve this, it is required to associate the characteristics with the steps in the process, identify the key characteristics as well as the sources of variation, determine methods to control the variations, thereby gradually standardising the process so as to ensure that customers' expectations are continually met. It is this systematic approach to analysing, documenting, controlling and improving a process, which 'Advanced Product Quality Planning' [APQP] provides, for which Process flow, FMEA and Control Plan form the logical steps.

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APQP is one of the mandatory requirements for QS9000, one of the stepping stones mainly for automobile manufacture industry; though it has been superseded by TS16949, APQP, or precisely this technique remains as a tool for new product development and can also be applied to an existing process line; the main objective is to continuously upgrade the product and/or the process quality.

In a bid to produce the best quality products at Cold Rolling Mill Complex of Tata Steel, this technique was adopted which resulted in establishing the product quality over the years in a systematic objective way. The APQP process involves three basic steps, namely:

1. Preparing the Process Flow diagram
2. Analysing the Potential Failure Modes and their effects (Process FMEA)
3. Making plans for controlling all potential and actual deviations in the process which are affecting the product quality (Control Plan).

2. SCOPE OF THIS PAPER

This paper in its first section explains the basic technique of that part of APQP, which deals with Process Flow Chart, Potential Failure Mode & Effect Analysis (PFMEA) and Control Plan. It explains the technique in order to make it applicable to any processing lines. In the second part of the paper, the experience pertaining to the Continuous Galvanising Line # 1 (CGL#1) is described as an example of implementation.

3. MAKING THE PLAN

Any process can be described as a ‘work flow,’ which cuts across departments or functions; it is the method by which products are produced or services are delivered. Here, each of the production activities is analysed in a chronological sequence, noting the incoming sources of variation which may affect the quality at every stage, writing all the process variables and defining the desired outcomes in terms of product quality for each process. This helps the plant operations team visualise and analyse all their processes and also assess the impact of each sub-process on the overall process. It is a kind of proactive defect prevention, compared to the system of reactive defect detection at the end of a process. It works on the premise of building warning mechanisms in the system to give signals at early stages of the process by which the defects can be totally prevented or substantially minimised. In this section, each process is detailed out into a set of inter-related activities and in the subsequent steps (FMEA and Control Plan), the effects and their controls are identified.

3.1 The Process Flow Chart

The Process Flow chart **[See Fig 1-PFLOW]** breaks down the operation into identifiable sub-processes; it is essential at this stage to check if each sub-process has some identifiable change occurring during the process. The process flow chart also lists the **desirable outcomes** from

FORM NO. CRMC/FORM-123						
PROCESS FLOW CHART FOR CGL1						
LINE NAME : CONTINUOUS GALVANISING			Process Owner :Unit Manager CGL # 1		Doc. No. : CRMC / APQP- CGL / PFLW . 004	
CORE TEAM : ABC, DEF. GHK			Contact no : 51002	Original date: DDMMYY	Revision Date : ddmmyy	
Number	Op # / Brief Desc.	Desired Outcome	Incoming Sources of Variations	Process Characteristics	Process Flow Symbol	RISK ASSESSMENT
1						LOW/Medium/HIGH
2						

FIG. 1

the operation (*like shining shoe after polishing or completely dried strip after drying chamber*) and the parameters that affect the operation, (*like hot air temperature and flow rate affecting the drying rate or right proportion of air and fuel for perfect combustion*). It also enlists the **incoming sources of variation** for each step (*like wet coal in a power station creating problem of combustion,* or *poor shape of cold-rolled strip before hot dip coating*). It also assesses the risk level associated with the operations (as low, medium and high) which helps in developing subsequent documents.

3.2 Failure Mode Effect Analysis (FMEA)

Once the Process Flow chart has been prepared, the Process FMEA needs to be made. [**See Figure 2-FMEA**] This document is considered to be the most crucial, as the effects of each potential failure are anlaysed here with respect to the next process, customers and end use of the product. A cross-functional team comprising members from concerned departments is formed. This team decides the basis for finalising the appropriate controls for the operator (Control Plan) for improving the ultimate quality of the product. Taking each activity from the process flow chart, the failure modes are analysed under the following column headings:

(a) **Title of the operation**, as enlisted in column 1 of the flow chart.

(b) **Product characteristics** lists the desired outcome of the process, from the second column of the chart. e.g. cleaned surface, good adherence, dry passivated surface. The desired outcome of any activity must be achieved at the end of that activity/process, as any stage-wise deviation will have a cumulative impact on the final product quality.

(c) **Potential failure modes** describes the situations when the desired outcomes are not obtained: entries in this column are negative characteristics of the preceding column; e.g. surface **not** cleaned of oil/iron fines, poor adherence, wet surface after passivation etc. The common process failure modes include wrong sizing, misalignment, eccentricity, uncleaned surface etc, while typical product modes include breaking, deforming, leaking, corroding, cracking, bending etc. Answers to questions like "How can the product/process fail to meet the desired specifications?" or "What would a customer (end user, subsequent operation or service) consider objectionable?" will bring forth the possible failure modes. This becomes the foundation for establishing a defect prevention system, which is further strengthened by the effect analysis.

(d) **Potential effects of failure:** Typical potential effects of failure include stoppage of line, noisy operation, strip breakage, poor appearance, unhappy customer etc. It lists the consequences of the failure modes (described in the previous paragraph) under 3 headings *viz.,*

   (i) Next Process(NP) – if it is going to jeopardise/totally stop/lead to severe disorder.

   (ii) Customer (C): if he is going to be dissatisfied leading to partial (or) total rejection of the lot.

   (iii) Application or end use (A): if the listed failure is going to adversely affect the product in the long run in its use, (e.g., Galvanised sheets may rust, painting may fade).

FORM NO . CRMC/FORM-124																	
Process FMEA for CGL1																	
ITEM: CONTINUOUS GALVANISING LINE NO.1						FMEA NO: CRMC/APQP-CGL1/FMEA.NNn							Page of				
Core Team : SC, SB, AM		Process Responsibility : ABC				Original date: DDMMYY					REV NO: Date of Revision ddmmyy. no. NN Date :DdMmYy		PREPARED BY: DEF				
Process Function/ Requirements	Potential Failure Mode	Potential Effects of Failure	SEV	Class	Pot. Causes(s)/ Mechanism (s) of Failure	Occ	Current Process Control: Prevention	Current process control: Detection	DET	RPN	Recommended actions	Resp. and Target Date	ACTION RESULTS				
													Actions taken	SEV	OC	DET	RPN
		NEXT PROCESS	1 to 10	SC or CC		1 to 10			10 to 1								
		APPLICA-TION:															
		CUSTOMER :															

FIG. 2

(d) **Severity** ranks each effect of failure according to the seriousness, in a scale of 1 to10. If it results into a failure without warning, leading to loss of life/property/irreversible damage to machinery, or brings the process to a total stop, then the ranking is 10; (See guidelines in (**Table 1**). However, subjectivity cannot be completely ruled out here.

Table 1. *Severity Ranking*

Ranking	*Criteria*	*Effect/Impact*
1.	The minor or non-existent effect will hardly be noticeable. Customer/end user may not perceive the defect.	None
2-3	Minor disruption to production line; defect noticed by none, or only by discerning customers. Small portion may have to be reworked.	(Very) minor
4-5	Defects noticeable by most customers, may have to be reworked for attaining customers' satisfaction.	(Very) low
6	Minor disruption to production line. Reworking may be necessary for relieving customer discomfort; moderately hazardous.	Moderate
7	Minor disruption to line; product partly to be sorted & scrapped; end use may suffer in quality of operation. Customer unhappy.	High
8	Customer very much dissatisfied because of inoperable product; major disruption to line; product may have to be scrapped. Loss of primary function.	Very high
9	Failure involves potential safety problem with warning endangering machine/operator, or noncompliance to statutory regulations.	Hazardous with warning
10	Very high severity due to major line disruption causing loss of man, machine and money, or noncompliance to government regulations, occurring without any warning.	Hazardous without warning

(e) **Potential causes of failure** lists the possible reasons for the failure modes described in column C: Each failure mode is linked with one or more causes, as specifically stated as possible; e.g., bath temperature below minimum; line speed deviation, faulty instrument reading. It assumes that if a process is carried out under the right conditions required for the product quality, the product will always meet the desired result. Process Characteristics column of the process flow chart is used in building up this column, as the factors detailed in the flow-chart are responsible in controlling the process/product quality. Hence each factor has to be enlisted in this column as the potential cause of failure; in addition, the clauses under the incoming source of variation column are to be analysed here to see how they could cause the specific failure. Some of the typical potential causes of failure are *inaccurate measurement, mishandling, lack of operator training, improper heat treatment,* *no lubrication* etc. Only specific reasons are to be listed, like poor control/substandard material.

(f) **Occurrence** column records the relative occurrence in a scale of 1 to 10; it is a measure of the likelihood **[See Table 2]**. A high occurrence number means that the process controls are not adequate and product quality consistency cannot be ensured.

Table 2. *Occurrence Ranking*

Rank	*Criteria*	*Failure Rate Per 1000 Pieces*
1	Remote probability of failure	< 0.01
2-3	Very low to low probability of failure	0.1-0.5
4-5-6	Moderate(low/medium/high) chance	1/2/5
7-8	High-Frequent chances of failure	10/20
9	Very high chances of failure	50
10	Very high chances in major proportion with recurring history	>100

(g) **Current method of control** describes the existing technique of either detecting the cause of the failure if it happens and/or for preventing the cause from occurring; these are respectively type **'D'** (Detection) & type **'P'** (Prevention) control. D-type includes the detection of both the failure and that of the cause, P-type is preventive control for which no subsequent control plan needs to be made. [An appropriate analogy in explaining the difference between the two types of control is the traffic signal ('P' type) vis-a-vis the traffic police ['D' type]. The adequacy of the process controls along with their limits to meet certain product quality requirement is analysed here which gives an idea to the operator regarding the control limits of the parameters. It also helps in identifying further controls.

(h) **Detection Number** is the ranking allotted to each of the controls, according to their capability of detecting either the failure or its potential cause, in a scale of 10 to 1. The higher the probability of detection, the lower is the number and vice versa. These numbers are allotted on the basis of **Table 3** but an element of minor uncertainty cannot be ruled out here. There is no Detection Number for P-type control, as preventive controls do not fall under detection. This number indicates the degree of accuracy and promptness with which any deviation in a process parameter/defect can be detected in the in-process stage so that corrective action can be taken. In case the detection is very poor, the operator must exercise sufficient control (e.g., 100% sampling or increasing the inspection frequency etc.) to avoid any product failures or, to install controls which could immediately detect the problem. However, it has to be established over a period of time based on the review of adequacy of each process control.

Table 3. *Detection Ranking*

Ranking	*Detection*	*Criteria*	*Suggested Range of Detection Methods*
10	Almost Impossible	Absolute certainty of non-detection.	Cannot detect or is not checked.
9	Very Remote	Controls will probably not detect.	Control is achieved with indirect or random checks only.
8	Remote	Poor chance of detection.	Control through visual inspection only.
7	Very Low	Poor chance of detection.	Control through double visual inspection only.
6	Low	May detect.	Control through charting methods, such as SPC (Statistical Process Control).
5	Moderate	May detect.	Control through variable gauging, or GO/No GO gauging on 100% of the parts after parts have left the station.
4	Moderately High	Good chance to detect.	Error detection in subsequent operations, OR gauging performed on setup and first-piece check
3	High	Good chance to detect.	Error detection in-station, or in subsequent operations by multiple layers or acceptance supply, select, install, verify. Cannot accept discrepant part.
2	Very High	Almost certain to detect.	Error detection in-station (automatic gauging with automatic stop feature). Cannot pass discrepant part.
1	Very High	Certain to detect	Discrepant parts cannot be made beacause item has been error-proofed by process/product design.

(i) **RPN:** [Risk Priority Number] is the product of the three numbers or ranks, *viz.*, **S**everity, **O**ccurrence, and **D**etection. This number indicates the relative risk associated with the potential failure mode. While RPNs used to form the basis to prioritise the potential failure modes, and the ultimate objective is to reduce the absolute value of the RPNs, it is always important to monitor any trend in the occurrence of any failure to verify the effectiveness and adequacy of the controls and install further controls.

(j) **Recommended Actions** tabulates the steps to be followed in case of a deviation from the control method; [e.g., dilution of the passivating solution in the tank if the solution concentration is higher than the permitted level]. Here all the actions needed to strengthen the process control must be documented with a target date. Regular review is a must to ensure the compliance and to assess the efficacy of the controls. However the priority of the actions is to be decided by the severity rankings and/or the occurrence numbers.

(k) **Responsibility** is earmarked by name and any specific one-time action must have a target date to make the recommendation meaningful.

The older method of selecting the process for focus and action was based on judgment of the RPNs, e.g., once all the RPNs from the FMEA are calculated, they are arranged from high to low and then summed up. Generally, a cut off at 80% cumulative value (e.g., 1600 when ΣRPN = 2000) was set for designing additional controls on the 'Vital Few'. The ultimate objective is to reduce the RPN. Since 'Severity' is constant for any effect of failure and the 'Detection' value also does not vary for a specific kind of control, it is the 'Occurrence', whose values should be brought down through regular reviews and better control methods. An example of how the RPN was reduced over time in a production line through appropriate control measures is presented.

3.3 The Control Plan

Once the exercise of FMEA is over, a **Control Plan** needs to be developed. It is the written summary of the entire system as described in the Process Flow chart and detailed in the PFMEA, for controlling the variation of all product and process characteristics. **This plan acts as a contract between the manufacturer and the customer.** It is the actual blue print of the entire process control which serves as the mother document for framing the detailed working instructions (SPI: Standard Practice Instructions) for the operator for day-to-day operations. This would provide all requisite information required for producing the quality desired from the process and suited to the customers' need.

The advantages of having an adequately defined Control Plan are:

(a) Increased productivity from lower maintenance, lower downtime and lower rejections.

(b) Improved product quality through focus on process control, defect prevention and standardisation of documentation through continuous improvement and minimising of avoidable causes.

The fundamental layout of a control plan consists of columns, which contain information headings as listed below sequentially: [See Fig. 3-CPLAN]

(a) **Process Number:** It establishes the linkage with the item in the Process Flow chart and PFMEA.

(b) **Product characteristics:** This column enlists the desired outcomes or product characteristics from the FMEA; positive characteristics are copied in this column.

(c) **Process Description:** Explains briefly the nature of the business/sub-process with a clear cut statement of the objective; (e.g., coating with zinc in the zinc pot.).

			CONTROL PLAN Number: CRMC/APQP-CGL1/CPLN.NNN					1 Page of	
		Original Date: DDMMYY Rev. Date: DdMmYy Revision No.--XX							
		Methods							
Process	Special Char. Class	Mistake proofing Technique	Product/ process Specification/ Tolerance	Evaluation Measurement Technique	SAMPLE		Control method	Reaction Plan	Corrective Action
					SIZE	FREQ			

FIG. 3

(d) **Manufacturing Device** tabulates the hardware i.e., the machine tools & jigs used in the operation (like 'pot rolls', 'sink rolls', 'air knife', 'molten zinc pot' for Galvanising etc.).

(e) **Class:** This column is a repetition of the one in PFMEA, which prioritises the severity of the failure modes. For example, any process for which the severity is 8 or 9 or 10. as per Table no 1, the class is either significant (SC) or critical (CC), only if SEV is 10 However a failure mode can be significant (SC), even with a SEV of 6 or 7, provided the occurrence is more than 3. [However, these quantitative indicators are line-specific and may not be identical between lines. Hence it is important to predefine these terms in the Quality Manual for the particular production line]. This column helps identify the failure modes which need to have special controls, as the significant and critical characteristics are the salient features for controlling the quality of product.

(f) **Current Process Control** column lists the two different types of control (P & D) from the FMEA, while the corresponding recommended actions from FMEA are copied into the Control Method, Sample Size and Frequency column of the Control Plan, against each process characteristics.

(g) **Evaluation** or measurement technique enlists the equipment used for controlling the product/process characteristics (like ICP spectrometer for zinc bath chemistry analysis, Radiometric gauge for coating thickness measurement, Temperature indicator for zinc bath etc.). If visual inspection is used in place of any tool/technique, it has to be mentioned

(h) **Product/Process specification/tolerance:** This is where the limits of operation are quantitatively specified (like temperature limits for zinc bath, percentage concentration of passivating agent, line tensions at various sections etc.) This column is to be left blank if no such limit exists. **This is the only quantifying column in the entire document.**

(i) The **sample size and the frequency** of evaluation need to be specified to indicate the degree of control. A continuous line producing cold rolled or galvanised coil or purifying flowing gas for fuel applications, will specify these parameters differently from a line producing fixed number of nuts and bolts, or number of vehicles in an automobile assembly line.

(j) **Control Method** column specifies the tools for controlling the variation. Typical entries are 'training quality check-sheets', 'set-up/operation instruction', 'control charts', PLCs, etc. When selecting the method of control, the main issues are: process control in preference to product control, prevention to detection, error proofing to inspection and meeting customer requirement

(k) The **Reaction Plan** column lists the corrective actions taken to bring the process back to control when a deviation occurs.

Table 4 summarises the different parameters as they appear in the three documents discussed till now and may serve as a checklist for the beginners or the practitioners.

Table 4. *Look Up Chart For APQP Attributes*

Aspects Of Apqp	*Appears In*		
	Process Flow	*FMEA*	*Control Plan*
Operation	#	#	
Product Characteristics	#	#	
Process Characteristics	#		
Symbols & Risk Assessment	#		
Incoming Sources of Variation	#		
Potential Failure Mode		#	
Potential effects of failure		#	
Potential Causes of failure		#	
Severity, Occurrence, & Detection number		#	
Current Method of Control		#	#
RPN		#	#
Manufacturing Hardware			#
Class (SC/CC)		#	#
Product/Process tolerance			#
Measuring Technique			#
Responsibility			#
Reaction Plan			#
Failure Mode Codes		#	
Failure Cause Codes		#	

3.4 Codes of Failures and of Failure Causes

To make the FMEA user-friendly, each potential failure mode in the FMEA document is numbered in a predefined fashion, (e.g., CGL1, CGL2, etc., for a Continuous Galvanising Line), while the assignable causes to the failures are also coded in a different sequence, (like CGL1C, CGL2C etc.). However there is no hard and fast rule for the numbering system; it is only to expedite data collection and analysis and is left to the discretion of the team that prepares these documents.

4. DATA COLLECTION AND ANALYSIS

A standard format for collection of data from a line can be designed by the Cross Functional Team. Quantity of the defective/downgraded material over a period is assessed and recorded with the codes of failure modes and potential causes. At the end of the defined period, usually a month or two, depending on the status of the line, the data are analysed to see, if

- The occurrence number needs to be changed
- The current control method was sufficient to arrest/ detect the failure
- Any additional controls are necessary to reduce/ avoid the possibility of such failures in future;

- Any specific reaction plan needs to be designed and implemented within a time frame.

However, the format of data collection cannot be universally the same, as the product lines and process lines differ from industry to industry, or even in the same industry. So the data collection format can be suitably modified to cater to the need of the APQP.

5. APPLICATION OF THE METHODOLOGY AT CONTINUOUS GALVANIZING LINE # 1

Hot dip galvanising is one of the most common ways of coating a steel substrate with zinc for surface protection against corrosion. Tata Steel installed a 100,000 tpa continuous galvanising line (CGL # 1) producing coated steel strips for engineering and construction industries, in February, 2000. A second line CGL # 2 for auto-industry and white goods was commissioned in June 2001. The entire CRM Complex to which these plants belong, was certified in March 2001 for QS-9000, the stringent international quality standard, meant for supplying to leading auto-makers of the world.

[**See Fig. 4** for a block diagram of the line-layout of the galvanising line #1] Coils of cold rolled steel strip, in widths ranging from 800 to 1050 mm and in thickness from 0.2 to 0.8 mm are loaded into the Pay-Off Reels (**POR**), which uncoils the strip. Small portions at the end of the coil are cut off due to thickness variation and the front end of the new coil is welded at the **welding** station to the tail end of the preceding coil to maintain continuity. The strip now passes through an **alkali tank** for removing oil and dirt from the surface, via intermediate rotating & steering units. Degreasing is followed by rinsing and drying, after which the strip enters a horizontal **furnace** for heating, cleaning and/or stress relieving. The strip leaves the furnace and passes through a molten zinc bath for **galvanising**, followed by **air cooling, water quenching** and drying. It then passes through the chromating or **passivating** tank, the **logo marking** station and the final **recoiler.**

While setting up this galvanising line in Tata Steel, it was a challenge for the operation crew to ramp up production and simultaneously improving the quality. It was more difficult as the crew was largely inexperienced in operating the line and any one defect (out of many possible defects in hot dip galvanising) could make the product 'seconds' or even scrap. Each tonne of seconds cost the company approximately Rs. 2500 in revenue in 2000-01.

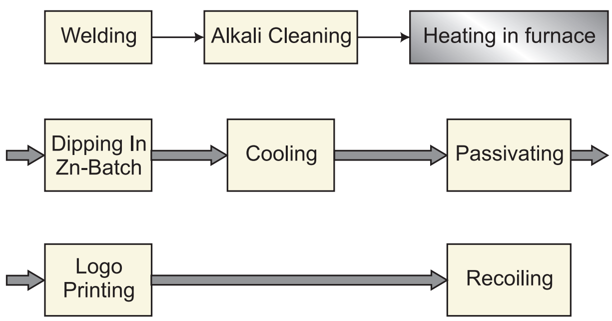

FIG. 4 SCHEMATIC LINE LAYOUT OF CGL#1

Here APQP proved to be a powerful tool to the operation team in understanding each and every detail of the process and activities, their impact on product quality and taking steps to avoid those problems in order to ensure higher production of prime quality.

5.1 Process Flow, FMEA & Control Plan at CGL#1

CGL1 is a continuous line wherein there are different workstations. The raw material is processed at these stations for upgrading the product quality. As the line operation is continuous, a hold-up at any workstation will have a detrimental effect on the raw material as well as the product quality. So in order to achieve the desired quality levels a process flow diagram is made indicating the various workstations. [See Sample Process Flow Chart in **Fig. 5** with the mandatory columns.

The effect of the operations of these workstations on the raw material, next process, product, end use and customer is collated in the form of a process FMEA. A part of the FMEA for the CGL#1 is shown in **Fig. 6**. This represents the assessment of the operations with the SEV, OCC & DET numbers adjudged through team discussions on expected effects, probability of happening and detection. The critical and the significant characteristics of the line have been identified as **WELDING** and **ANNEALING**.

The Control Plan was made based on the controls stated in the FMEA. **Fig. 7** depicts part of a sample control plan for CGL#1, developed on the basis of the FMEA, These controls define the parameters to be maintained while processing, in order to obtain the desired quality and the method to control the same. The plan also indicates the actions to be taken in case of failure of equipment or a control. These actions are indicated in the Reaction Plan and also captured in the Standard Practice Instructions.

Having created these documents [shown in Fig 5, 6 and 7], there were bigger challenges to overcome

(a) Improving these documents based on line running experience

(b) Spreading the knowledge among all the operation crew.

It required a strong commitment, regular follow up, capturing of initial failure data and regular review of all the data and updating the three documents by the team. The result through the deployment of this approach was more than encouraging: seconds generation in CGL#1 came down from 21% to less than 3% less than a year. All these were made possible by the effective use of the APQP tool, which helped the entire team in learning the process very fast in a structured fashion.

6. ACTUAL APPLICATION

After the FMEA and Control Plan were made, the failure codes and the cause codes were separately identified. In CGL#1, whenever there is a process failure, it leads to product failure. Product failure could also happen whenever manual controls fail. These failures are captured in the exit section of the line. The cause codes and the failure codes are assigned and noted in the exit section log book. These data are fed into a computer, which is programmed to collate the data and give the revised *occurrence number* based on the number of times the failure has taken

Form No. CRMC/FORM-123						
PROCESS FLOW CHART FOR CGL1						
LINE NAME: CONTINIOUS GALVANISING			**Process Owner: Head CGL**		Doc. No.: CRMC/APQP-CGL/PFLW.004	
CORE TEAM: SC, PSSG			Contact no: 51002	Original date: 01/07/2000	Revision Date: 12/09/06	
Number	Op # /Brief Desc.	Desired Outcome	Incoming Sources of Variations	Process Characteristics	Process Flow Symbol	Risk Assessment
1	CR Coil Receipt and Inspection	1.1) No coil collapse 1.2) Coil is not rusty 1.3) No edge ripples 1.4) No saw tooth edges 1.5) No edge cut/damage	1.1) ID Collapse 1.2) Rusty Coil 1.3) Coil with edge ripples 1.4) Coil with saw tooth edges 1.5) Coil with edge cut/damage	• Operator Skill		Low
2	Coil Preparation and welding	2.1) Coil centered on POR. 2.2) No gauge variation 2.3) Perfectly squared ends 2.4) Overlap as per set value uniform through out the width 2.5) Weld Strength	2.1) Improper coil centering 2.2) Off gauge in CR 2.3) Camber 2.4) Improper squaring 2.5) Improper setting of weld parameters	• Operator Skill • Entry loading permissive • Welding parameters and permissives		High
3	Alkali cleaning	3.1) Clean surface free from grease, rolling oil 3.2) Dry strip 3.3) No carryover of alkali on the strip surface	3.1) Improper cleaning 3.2) High surface impurity 3.3) Improper squeezing	• Alkali concentration temperature • Hot air temp. • Squeeze and brush roll condition (inc gap) • Spray pressure and condition of spray		Medium
4	Annealing	4.1) Hardness 90-100 HRB for FH 55-65 for soft 4.2) Clean surface. 4.3) Strip Temperature at snout exit (T-465 ± 25°C)	4.1) Input CR coil hardness 4.2) High oil on CR even after alkali cleaning 4.3) Steel composition 4.4) Gauge variation	• Variation CV of CO gas • Line speed • Dew point RTF. Snout • HNx flow and composition • Furnace pressure • Furnace permissive		High
5	Galvanising (Hot dipping in Zinc bath)	5.1) Uniform coating weight 5.2) Good spangles 5.3) Good adherence 5.4) Surface free from defects like edge over coating dross pickup, pimples, angles hair mark etc.	5.1) Strip Shape, Coating Control 5.2) Improper cleaning in furnace 5.3) Strip Temp. 5.4) Strip Defects	• Bath composition • Bath & strip temperature • Line speed • Air knife gap angle and pressure. • Strip Tension • Operator skill • Coating measurement closed loop control		High

FIG. 5 A SNAP SHOT OF THE PROCESS FLOW CHART OF CGL#1

Form no. CRMC/Form-124

Process FMEA for GGL1

Item: Continuous Galanising line No.1 | FMEA No: CRMC/Apop-CGL1/EMEA.005 | Page of

Core Team: SB/PSSG/Dr.SC | Process Responsibility: P.S.S. Gane sh. contact no: 51126/9234560768 | Original Date: 07/12/2000 | Rev. no.10 :1209/2006 | Date | Prepared by: P.S.S.Ganesh.

Process/ Function Requirements	Potential Failure Mode	Potential Effect of Failure	SEV	Class	Pol. causes(s)/ Mechanism (s) of Failure	OCC	Current Process control- Prevent	Current Process control- Detection	DET	RPN	Recomme- nded action	Resp. and Target Date	Action Results				
												Actions taken	Actions taken	SEV	OCC	DET	PRN
G1-CR Inspection	G1.1.1 Colipsed coil	Next Process. col cannot be loaded onto the POR	B	SC	Improper coling tension at PLTCM	0	None	Project composed col from schedule	1	0	Composed cots not to be run		Col supplied from TCM/TCL coil reject al entry-TCM/TCL informed to take back the coil	8	0	1	
		Application: NIL															
		Customer: NIL															
G2 Coil Preparation and welding	G2.5 Poor weld Strength	Next Process. strip breakage	10	CC	G2.5.1 Improper setting of current & speed	0	Look up table review after trials in each shutdown.	Reverse joging the welded strip to give a jerk	3	0			GB Action points impierented	10	0	3	
			10		G2.5.2 Welded wheel, anvil plate & clamp plate in poor condition (GC 20)	0	Daily maintenance check list	Weld burn and failure of weld	3	0			GB Action points implemented				
			10		G2.3.1 Improper Squaring Tapered edges	1		Visual inspection of every weld overlap (tapered weld)	8	90			GB Action points implemented	10			
			10		G2.5.3 Qty. & Rusty surface	0		Visual inspection and filter paper test Data available from supplier.	3	0			PLTCM coil, Feedback given to PLTCM for Corrective action	10			
			10		G2.2.1 Oil-gauge at strip ends	0	Head end trickress measurement. For tail end before feeding the coil to POR thickness						PLTCM coil, Feedback given to PLTCM for Corrective action				
			10		G2.2.1 Strip ends not at the centre at the line (shifted end)	1		Visual inspection	1	10	Tail indexing machine should be properly aligned						
		Customer															
		Ni															
		Application															
		Ni															
G3 Alkali Cleaning	G3.1 Oily and dirty surface (G13)	Next process															
		Uncoated spots			G3.1.1 High amount of oil on strip		Input cil on CR from PLTCM/TRY/TCL				Cr with high of content not to be processed.						
		Poor adhesion and back spot	8	SC	G3.1.3 Akali conc. Temp not as per control limits	2	Addition phiosophy	Lab losting support and term gauge	5	90	Alkali charging practice charge. Preparation tank to be instated for proper mixing of	1st part completed. 2nd partoy MSd 06 PSSG	To maintain the alkali concentration in each shift. one alkali bag (50 kgs) in each shift is added	7	1	2	14
		Mini spangies (Export & Domestic)			G3.1.5 Squeeze & brush rol condition poor (GC-28		Fokw maintenance standard as per omms	Visual inspection of sqeeze coils during shutdown			Inspect & replace sqeeze coils as por the standard. Clean the square rolts surface with water during		Regular high pressure jet cleaning in every weekly shutdown 2 nos. of drainage pipe of 6 inchos have been				

FIG. 6 A SNAP SHOT OF THE FMEA CHART OF CGL#1

place. It also calculates the RPN. For all the cause codes, for which the *occurrence no* is 3 or greater than 3, a plan is made indicating the actions to be taken, responsibility and the target date. This *occurrence number* is then reviewed every month to check the effectiveness of the actions

FORM NO: CRMCFORM-125

Core Team: SC, PSSG — CONTROL PLAN FOR CGL1

CONTROL PLAN Number: CRMC/APQP-CGL1/CPLN. 003

Technologist Cold Rolled/coated Product Date	Date		Process Owner: HEAD CGL			Original Dat 01/07/2000	Rev. Date 12.09.06	Revision No. 06	
			Contact Number: 51002						

Part Process No.	Process Name/ Operation description	Machine devices (Tool for mfg.)	Characteristics: No.	Characteristics: Product	Characteristics: Process	Special Chart Class	Mistake proofing technique	Methods	Methods: Evaluation measure-ment technique	Methods: Sample SIZE	Methods: Sample FREQ	Methods: Control Method	Reaction Plan	Corrective Action
2	Call Preparation and Welding	Welder		Weld Strength	Correct Welding	SC	Automation & interlock	Nil	Visual	One Observation	Every COL	Testing weld strength by reverse logging	Reweld as indicated SPL No.	Alarm analysis and failure analysis by EEI
					Proper Squaring		Visuals	Nil	Visual	One Observation	Every COL	Visual inspection or every weld	Adjust as per SPL No. SPL/ CGL-1-ENT/OP 006	Shear gap checked and adjusted by Mech
					Oily and rusty surface				Chemical Analysis report by TCM	Established by TCM (<500mg/m^2)	As per PLTCM sampling plan	Sampling Control at PLTCM	Coils with excess oil will be unusual coil in system	Action by PLTCM
					Oil gauge at strip ends		Strip thik measurement	0.01 mm	Digital Micrometer	One reading to head end	Every non P2 TCM Coil	Off gauge value in L-3	Remove by shearing as per SPL NO SPL/ CGL-1 FNT/OP CO9	Feedback by PLTCM
								Nil	Visual	One observation	Once in a day	Inspection of wheel & anvi	Check as in SPL/CGL-ENT/OP CO9	Verifying the weld wheel condition by maintain
					Proper setting of current & speed		Ammeter	Lock up table	Visuals	One observation	Every day Col	Parameter are take from back up table	Adjust setting as per Spl No. SPL/CGL-1-ENT/OP CO9	Review the welding parameter table
					Operator training			Nil	Nil		Job rotation and PT	Job rotation and PT	Manual operation station change	Deployed with most experime-nted operator
					Strip not at Centre of line		Visuals	Nil	Visuals	Test & Observation (200 min)	Every Col	Visual	Remove and adjust manually	FOR adjustment
					Punch No: Lifted for punching		Automation and interlocks	Nil	Visuals	Once after punching	Every Col	Visual	Correct manually for value stand	Analysis by EEI of events
3	Alkali Cleaning	Alkali tank		Clean surface oil 200 mg/m^2 Fe-180 mg/m^2	Alkali conc temp.		Lab test and field instrument	40-100 gms/ltr 75 ± 20ºC	Filtration process in the lab and temp.	500 mg each of Alkali and hot rinse water	Once in a Shift	Alkali conc. tested once a digit & Temp. locally	Maintain Conc & temp. as per SPL NO SPL/ CGE-1 ENT/OP003	Addition of water or Alkali according to result
	Alkali Cleaning	Circulation Pump		Dry Strip	Hot air Temp		Temp. meter		Dual gauge	One reading	Once in a Shift	Local indication	Maintain Temp. as per SPL NO SPL CGL-1-ENT OP.003	Adjust the steam pressure
					Squeeze & Brush roll condition		Visuals	Nil	Visual	One observation of filter paper rubbing	Once in a Shift	Check for carry over level visually	Stop alkali hot rinse in case of carry over	Roll change and pass line verification Shut down

FIG. 7 A SNAP SHOT OF A CONTROL PLAN OF CGL#1

taken. If the action plan is not effective, brainstorming sessions are held so as to have better ideas to address the problem. Data sheets are filled up from the every day operations and at the end of each month, the FMEA and Control Plan are revised, if there is any significant change in the process/ control/ occurrence/tolerance.

An example is given in **Table 5** wherein FMEA helped in reducing the occurrence number of product failure on account of marks on the pot roll (Cause Code GC-56), which helps in moving the strip through the molten zinc bath. **Figure 8** captures the continuous improvement in the total tonnage produced at CGL#1, from April, 2000, till March, 2002, as well as the substantial downtrend in the percentage seconds (non-prime), ever since the FMEA and Control Plan were put in place and got under regular review. The system of capturing the failure data and reviewing them periodically is fully in place for more than a decade now; Control Plan is changed only when new processes are introduced, newer controls are adopted or the frequency and/or the sample size is changed.

Table 5. *Action Table for Equipment performance improvement*

Month	*Occurrence No*	*Actions Taken & Observations*	*Actions to be Taken*
Oct 2000	6		Check alignment of sink roll after placement
Nov 2000	5	Alignment checked at site whenever sink roll is replaced. problems faced whenever stellite bushes were used	Usage of can alloy bushes
Dec 2000	4	Only canalloy bushes were used	Check assembly thoroughly before and after placement
Jan 2001	5	Assembly checked before and after placement. Twice scrap dia rolls were used due to lack of spares	More spare rolls to be ordered. Scrap dia rolls to be discarded
Feb 2001	5	Spare rolls ordered	Scrap dia rolls to be salvaged by welding a sleeve as due to long delivery period of rolls
Mar 2001	4	1 no salvaged roll used	Arms to be checked for straightness as the trend shows rotation problem only while using one particular set of arms
Apr 2001	4	Arms straightened . Problem persisted	New arms to be ordered and higher dia sink roll to be used
May 2001	4	New arm and 495 dia roll ordered.	New arm with stiffners to be made ready and put into use in june 2001
June 2001	1	New arms with stifeners and 495 dia roll put into oprn and gave highest sink roll life of 7800 tons	

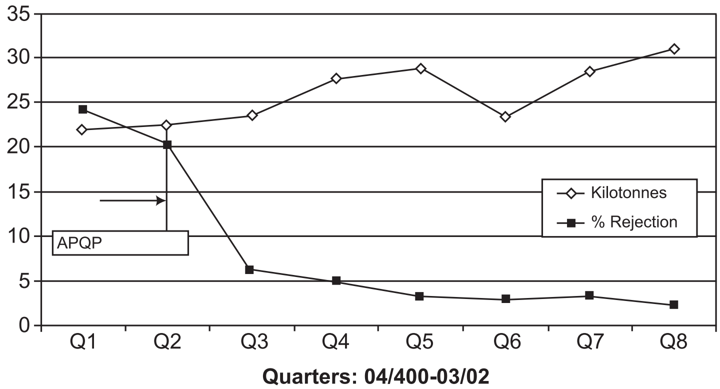

FIG. 7 IMPROVEMENT IN CGL#1

7. CONCLUSION

The success of any methodology lies in its ability to facilitate easy understanding of the process complexities, identifying appropriate controls, the extent to which these controls can be established in the processes. A good quality product can be produced only if we have a perfectly controlled process. The APQP technique serves both the objectives. It facilitates the understanding of the process by the production and the maintenance teams by breaking down even the most complex process into a set of simple and logically sequenced activities. It also evaluates the role and impact of each activity in the sequence and establishes appropriate controls to prevent process deviations and product defects through a cause–effect analysis at each stage of production. The exercise of making an elaborate Control Plan based on the Failure Mode Effect Analysis thus not only controls the process, but also ensures the desired quality of the product. Continuous reviews at fixed intervals (based on the criteria developed while constructing the documents), help achieve this feat in any process line. This requires a reliable process and product failure data collection and analysis system, which needs to be monitored on a regular basis.The Cold Rolling Mill Complex of Tata Steel, in an attempt to secure the QS 9000 certification, learned this technique and applied it to all its lines, There have been remarkable improvements in the lines as the RPNs slowly started coming down. As experienced particularly in the CGL#1, which was the first to incorporate this practice, this technique has proved to be effective in all the product lines through a systematic deployment and regular reviews, as the seconds generation has drastically reduced from around 30% to less than 3%.

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