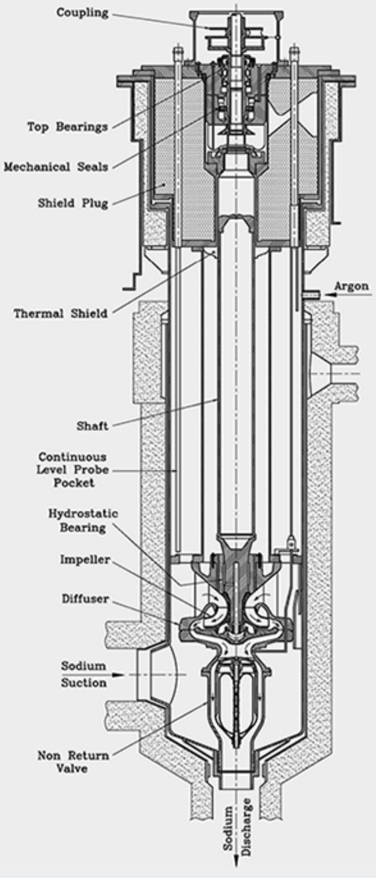
Centrifugal Pumps for Sodium Cooled Reactors



R.D. Kale

B.K. Sreedhar

CRC Press
Taylor & Francis Group

Centrifugal Pumps for Sodium Cooled Reactors

This comprehensive introduction to centrifugal pumps used in sodium-cooled fast reactors discusses the special attributes of centrifugal pumps, design features, manufacturing requirements, instrumentation, and operating experience. It covers the characteristics of mechanical pumps, used as the main coolant pumps in fast reactors.

Key Features

- Covers description of pumps in various reactors highlighting the special features of the pumps and providing an overview of futuristic design concepts.
- Discusses the aspects related to the design, manufacture, testing, instrumentation, and operating experience of centrifugal sodium pumps.
- Highlights the challenges in centrifugal sodium pump testing.
- Presents topics such as cavitation testing for critical applications and thermodynamic effect on pump cavitation.
- Real-life case studies are included for better understanding.

This book gives a detailed overview of the design, manufacture, testing, and operating experience of the main coolant pumps used in sodium-cooled nuclear reactors. It further discusses the special type of pumps used in fast reactor power plants to circulate liquid sodium through the core. The text examines the challenges in centrifugal sodium pump testing and types of test facilities around the world. Real-life examples are used to highlight important aspects. It is primarily written for senior undergraduate, graduate students, and academic researchers in the fields such as mechanical engineering, nuclear engineering, and chemical engineering.

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CRC Press
Taylor & Francis Group
Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business

Front cover image: Indira Gandhi Centre for Atomic Research

First edition published 2024
by CRC Press
2385 NW Executive Center Dr, Suite 320, Boca Raton, FL, 33431

and by CRC Press
4 Park Square, Milton Park, Abingdon, Oxon, OX14 4RN

CRC Press is an imprint of Taylor & Francis Group, LLC

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ISBN: 978-1-032-46053-6 (hbk)
ISBN: 978-1-032-60735-1 (pbk)
ISBN: 978-1-003-46035-0 (ebk)

DOI: 10.1201/9781003460350

Typeset in Sabon
by SPi Technologies India Pvt Ltd (Straive)

To the memory of my late wife Mrs. Lata Kale, and my sons, Udayan and Kedar.

— R. D. Kale

To the loving memory of my late parents Kongot Balagopalan and Kondapurath Devayani, whose unwavering love and support continue to inspire me.

— B. K. Sreedhar

Contents

Foreword

This book on *Centrifugal Pumps for Sodium-Cooled Reactors* by Mr. R. D. Kale and Dr. B. K. Sreedhar is an important contribution towards making an authentic, experience-based resource available to practitioners, R&D personnel, academics, and students interested in the field of centrifugal pumps for pumping sodium and similar fluids. This is a highly specialised area where there is a paucity of literature, and this book would help bridge the void in a significant way.

India, moving ahead with indigenous development of advanced technologies in critical areas, is a matter of high importance from the perspective of avoidance of vulnerabilities at the national level, maintaining a strategic edge, and of course, domestic value addition. Our Atomic Energy, Space, and Defence programmes have been engaged in mastering several such critical technologies. A number of agencies outside these programmes, including industries and academia, are deeply connected and involved in such efforts. It is necessary that there is growth and continuity in terms of HRD activities in these areas across different organisational domains. Books like this serve as important resource materials for such purposes.

In particular, the development of dynamic equipment such as a pump is full of significant challenges. Apart from the development of materials, design of various parts as well as the system as a whole, and their manufacture into required shapes for various components conforming to required specifications, such efforts also involve the design of several kinematic pairs working together. A successful development thus necessitates deeper insights into issues related to disciplines like hydrodynamics, structural dynamics, tribology, manufacturing, and materials. Further, the design and development of pumps meant for nuclear reactors, that too for pumping very reactive fluids like sodium, need extreme care and qualification in terms of their functional and safety performance. The availability of a book written by authors involved in developing this kind of equipment in the country would fulfil a much felt need of younger professionals who might want to get into this area. The value of this book is even greater considering that sodium-cooled fast reactors are expected to be set up in large numbers as a part of the second stage of India's nuclear power programme, and we expect industry and academia also to be a part of this process in addition to work within the Department of Atomic Energy.

I wish to compliment the authors for their efforts in bringing out such a valuable book and feel confident that it would be an important addition to the limited literature on the subject.

Anil Kakodkar
Former Chairman Atomic Energy Commission, India

Preface

More than two decades ago, the first author, while in service at the Indira Gandhi Centre for Atomic Research (IGCAR), Kalpakkam, had compiled a document with his colleagues titled "History Document on Design and Development of Primary Sodium Pump".

This document detailed the efforts invested in the development of the primary sodium pump for the Prototype Fast Breeder Reactor (PFBR) project. At that time, he had also prepared another document called "Design Manual of Primary Sodium Pump" for the benefit of the engineers who would be entrusted with the construction and commissioning of this component. The roots of this book lie somewhere in these works.

Although there is a library of books on the topic of centrifugal pumps, it is surprising that there is no book devoted to mechanical or centrifugal sodium pumps. We have come across only a single book on the topic of nuclear reactor coolant pumps in the Russian language. This book includes a brief discussion on sodium coolant reactor pumps. Unfortunately, no English translation of the book has been published, and the original itself is now hard to come by.

The present book, *Centrifugal Pumps for Sodium-Cooled Reactors*, consists of ten chapters. Unlike other published books on centrifugal pumps, which focus on the calculation of design parameters, discuss pump characteristics, selection of bearings, seals, drives, general pump troubleshooting, and so on, we focus instead on issues that a sodium pump designer is confronted with when he embarks on the journey from scratch. For instance, the chapter on design discusses the choices available to the designer on the location of the pump, the hydraulics, the mechanical aspects, etc. Abundant examples of design choices from pumps of various reactors are provided to reinforce a technical point.

The book, in its ten chapters, provides a comprehensive review of the pump designs used in fast reactors around the world, the options available to the designer, the challenges in manufacture and in testing, and the operating experience of these pumps over a span of more than half a century.

Each chapter is provided with a reference list for the benefit of readers who wish to study a particular topic in further detail. Another feature of the book is the presentation of details of pump components, such as special bearings, shaft sealing, and pump supports. These are supplemented with neat sketches to aid in a better understanding of their complexities. We also include a chapter that discusses, in brief, the main coolant pumps of water-cooled reactors. The purpose of including a discussion on water-cooled reactor pumps is to bring together important topics about these pumps to benefit readers conversant with water-cooled reactors but with little access to information on such pumps.

The authors believe this chapter will interest engineers working in nuclear plants in India, in particular.

In the final chapter, considering the ongoing R&D efforts worldwide, we attempt to predict the features of a sodium pump of the future.

The authors have many years of experience in the field of nuclear engineering, with a particular focus on the design and testing of centrifugal pumps for fast reactors and test loops. They draw on this wealth of experience to carve out a lucid picture of the design, manufacture, testing, instrumentation, and operation of centrifugal sodium pumps over the last 60 years and collate the details in an easy-to-understand manner between cover and cover.

Knowledge in any field, especially technical, is gained not just from formal education or perceptive wit. Equally important is our understanding of the experience of others and our own. This sublime Sanskrit shloka eloquently captures the essence of the learning process:

> आचार्यात् पादमादत्ते पादं शिष्यः स्वमेधया ।
> सब्रह्मचारिभ्यः पादं पादं कालक्रमेण च ॥
> AchAryAt pAdamAdatte, pAdam shiShyaH swamedhayA |
> sa-brahmachAribhyaH pAdam, pAdam kAlakrameNa cha ||

In translation:

From the teacher one-fourth is learnt, one-fourth using one's intelligence, one-fourth is learnt from colleagues, and one-fourth only with time.

The authors are indebted to Dr. Anil Kakodkar, former Chairman, Atomic Energy Commission (AEC), and Secretary to the Department of Atomic Energy (DAE), and presently member AEC, for graciously penning the foreword to the book.

Acknowledgements

The authors acknowledge the contributions of their former colleagues, Messrs A.S.L Kameswara Rao, S. Baskar, K. Balachander, Chander Raju, late S. Asok Kumar, K.V Sreedharan, P. Ramalingam, and R. Prabhakar, towards the design and development efforts for the main coolant pumps of PFBR.

The authors also appreciate the pioneering contributions of Kirloskar Brothers Limited, Pune (KBL), India, and, in particular, Mr. S.G. Joshi, Hydraulics expert and formerly Vice-President, KBL, Pune, in the development and manufacturing efforts of the main coolant pumps of PFBR.

The authors are grateful to the Director, Indira Gandhi Centre for Atomic Research (IGCAR), Kalpakkam, India, the management of IGCAR, and the Department of Atomic Energy, Mumbai, India, for permission to publish this book.

Many people have helped in the writing of this book. The authors place on record their sincere thanks to the following colleagues:

Mr. A. Kolanjiappan for his dedicated efforts in producing the sketches for the book.
Ms. S. Saravanapriya for typing the initial drafts of some of the book's chapters.
Mr. K.V Sreedharan for sharing technical information and clarifications on technical issues.
Mr. S. Chandramouli for clarifications on sodium loop operation.
Dr. G. Vaidyanathan for his guidance on issues related to publishing and obtaining copyright permissions.

While utmost efforts are made to weed out errors, the authors remain wary of the venerable Edward A. Murphy Jr.'s eponymous law. Readers are welcome to email the authors about any inconsistencies/mistakes in the book, and the corrections will be done at the earliest opportunity.

R. D. Kale, *Pune*
Dr. B. K. Sreedhar, *Kalpakkam*

Authors

Mr. R. D. Kale graduated in Mechanical Engineering from the Indian Institute of Technology (IIT), Kanpur, in 1966. He completed a one-year orientation course in Nuclear Science and Engineering as part of the 10th batch of the Training school at the Bhabha Atomic Research Centre and started his career in BARC. He was deputed to CEN de Cadarache, France, where he worked along with French specialists as part of the Indian design team for the design Fast Breeder Test Reactor under a collaborative project with the French atomic energy establishment from May 1969 to June 1970. He moved to the Indira Gandhi Centre for Atomic Research (IGCAR), Kalpakkam, in 1971 and worked for a few years initially on the detailed design of some reactor components and preparation of their technical specifications.

He spent the next 28 years establishing water and sodium test facilities to test fast reactor components. These included a large sodium test facility in a 43 m high building for testing full-scale reactor components in sodium and later a dedicated Steam Generator Test Facility for testing a sector prototype of the once-through sodium/water steam generator of the 500 MWe sodium-cooled power plant. He spearheaded the indigenous development of sodium centrifugal pumps for the Prototype Fast Breeder Reactor (PFBR) that culminated in the manufacture of both the primary and secondary centrifugal pumps by the Indian industry. He has several publications in reputed journals, seminars, and international conferences. He has published many articles in newspapers on nuclear power and safety. He retired in the grade of Outstanding Scientist. He was the Associate Director of the Engineering Development Group and Director of the Engineering Services Group at the time of superannuation. Post retirement he worked as Member, Project Design Safety Committee of the Atomic Energy Regulatory Board (AERB) for PFBR.

He has also authored a book in Marathi titled *Adhunic Hindu Dharma, Kaani Kasa?* translated as *Modern Hinduism, Why and How?*. In press, his recent book in Hindi is titled *Meri Yatra, 1857 kaAnkhoDekha Hal*, translated into English as "*My Journey, an eyewitness account of the 1857 freedom struggle*". The book is a translation of the Marathi title

Maza Pravas that traces a priest's journey from Penn Tahasil near Mumbai to Jhansi and other holy places in North India in the backdrop of tumultuous events in the first war of Indian independence in 1857.

He is a fellow of the prestigious Indian National Academy of Engineering (INAE), member of the Institution of Engineers, India, member Indian Institute of Chemical Engineers, and a member of the Indian Nuclear Society.

Dr. B. K. Sreedhar is in the grade of Outstanding Scientist and is the Director of the Fast Reactor Technology Group at IGCAR, Kalpakkam. He graduated with a gold medal in Mechanical Engineering from the University of Calicut in 1989. He completed the year-long orientation course in Nuclear Engineering as part of the 33rd batch of the BARC Training School and joined IGCAR in 1990. He started his career in the indigenous hydraulic development of primary and secondary coolant pumps for the PFBR. He was later involved in the in-sodium testing of full-scale mechanisms/machines of PFBR. He is also engaged in development work towards realising oil-free pumps using active magnetic bearings and ferrofluid seals.

He has a postgraduate degree from the Indian Institute of Technology (IIT), Madras specialising in Hydroturbomachines, and a doctorate from the Homi Bhabha National Institute (HBNI), Mumbai. He has published several papers in refereed journals and national/international seminars and conferences.

He is a fellow of the prestigious Indian National Academy of Engineering (INAE), fellow of the Institution of Engineers, India, and a member of the Indian Nuclear Society.

Chapter 1

Introduction to centrifugal sodium pumps in fast reactors

1.1 INTRODUCTION

Fast neutron reactors constitute the critical second stage in India's three-stage nuclear power programme.

1. In the first stage, Pressurised Heavy Water Reactors (PHWR) fuelled by natural uranium are employed to generate power. These reactors are known as thermal reactors because the average energy level of the neutrons is equal to that of the atoms of the surrounding medium (at ordinary temperatures, the average energy of thermal neutrons is ~ 0.04 eV). In PHWR, the fissile isotope uranium-235(U235) (0.7% in natural uranium) present in natural uranium undergoes fission to produce power. The process also generates a small fraction of plutonium-239(Pu239) by the neutron absorption of uranium-238(U238) (which isotope constitutes the bulk of natural uranium).
2. Pu239 recovered from the first stage is used along with depleted uranium, mainly U238 (mixed oxide fuel), to produce power in fast neutron reactors that mark the second stage. These reactors are known as fast reactors because the energy level of the neutrons is in the range of 10–100 keV. In particular, the fission of Pu239 not only produces power but the accompanying high yield of neutrons results in the conversion of fertile U238 to fissile Pu239, thus producing more fuel than is consumed (these reactors are therefore also known as 'breeders'). This stage is critical due to the potential of generating power while producing more fissile material (Pu239) and because the technology, once perfected, can convert fertile thorium-232(Th232) (abundantly present in India) to fissile uranium-233(U233).
3. Fissile U233 from the second stage fuels reactors (both thermal and fast reactors) to generate electricity, thus utilising the large thorium-232 reserves in India. Table 1.1 [1] shows the potential power generation in the three stages. The importance of fast reactors to India's energy security is evident from the electricity potential of FBR's and Thorium breeders.

DOI: 10.1201/9781003460350-1

Table 1.1 Enhancing electricity potential with fast breeder reactors

Fuel type of reactor	*Quantity tons*	*Electricity potential GWe-yr*
Uranium – metal	61,000	
In PHWR		328
In FBR		42,200
Thorium – metal	225,000	
In breeders		150,000

1.2 FAST REACTOR LAYOUT AND ITS INFLUENCE ON PUMP DESIGN

Fast Reactors do not use a moderator to slow down the neutrons produced during fission because the neutron yield is high when Pu fissions with high-energy neutrons (up to 2.9 neutrons/fission) [2]. Furthermore, the parasitic cross-sections of materials are low at high neutron energies. On the other hand, the fission cross-section of fertile U238 is significant at high neutron energies, enabling the generation of more fissile material (by transmutation of U238 to Pu239) than is consumed. The absence of a moderator makes these reactors of high-power density[1] when compared to heavy water and light water reactors. Therefore, the coolant used in these reactors should possess good heat transfer characteristics coupled with minimal neutron energy moderation, thus limiting the choice of coolant to liquid metals. Sodium is the preferred choice among liquid metals because of its high thermal conductivity (100 times higher than water), high boiling point, moderate specific heat and low neutron energy moderation.

There are two different configurations in the layout of a fast reactor: loop-type concept and pool-type concept. In a loop-type reactor, the reactor vessel, containing the core immersed in a pool of sodium, the intermediate heat exchanger (IHX), and the main sodium pump are connected by piping of the primary circuit (Figure 1.1). The pump is located in a separate tank adjoining the reactor vessel, with the pump suction in contact with the liquid in the tank and the pump discharge joined to the system piping (sump type concept) or with the pump suction linked to the system piping and the pump discharge connected to the sump (piped concept). Since the primary pump is located outside the reactor pool, the designer has the option of locating it in either the hot leg or the cold leg. The run of piping from the reactor vessel outlet to the inlet of the IHX is the hot leg, while that connecting the IHX outlet to the reactor vessel inlet is the cold leg.

In contrast, the pool-type concept (Figure 1.2) houses the reactor core and the entire primary circuit and its components (pump and IHX) in a pool of sodium. In the pool-type reactor, since the primary pump is immersed in the sodium pool, the sizing of the pump directly affects the size of the main vessel and, therefore, the capital cost of the reactor. However, the pool type concept restricts the option of locating the primary pump to the cold pool only.

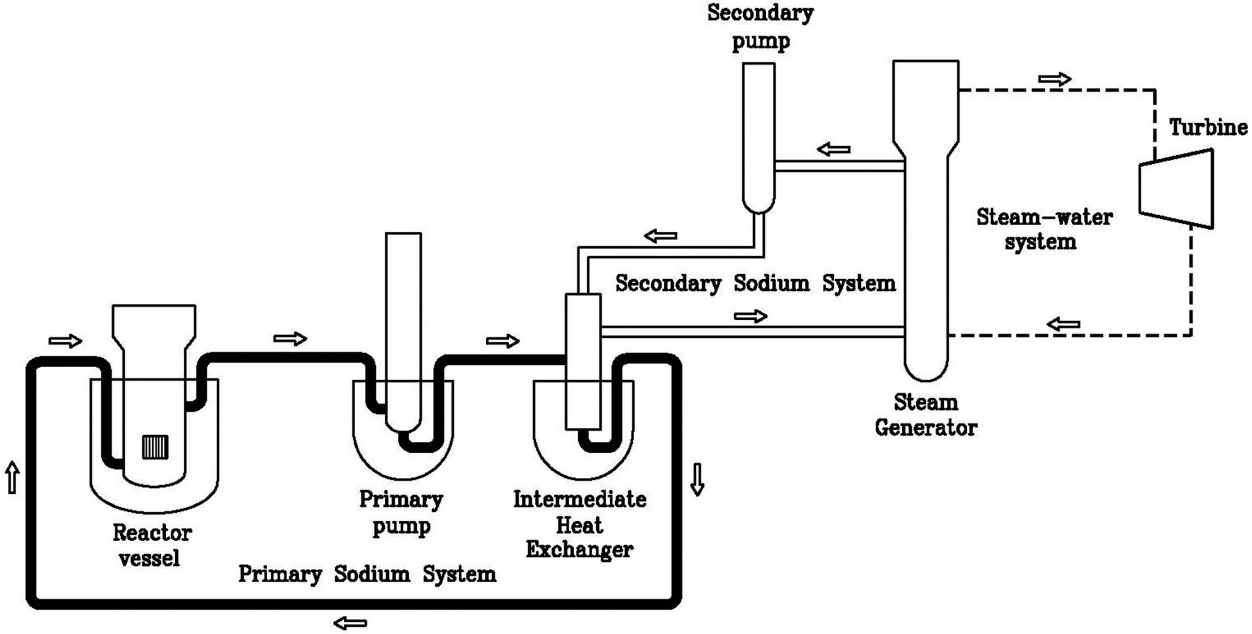

Figure 1.1 Loop-typeconfiguration.

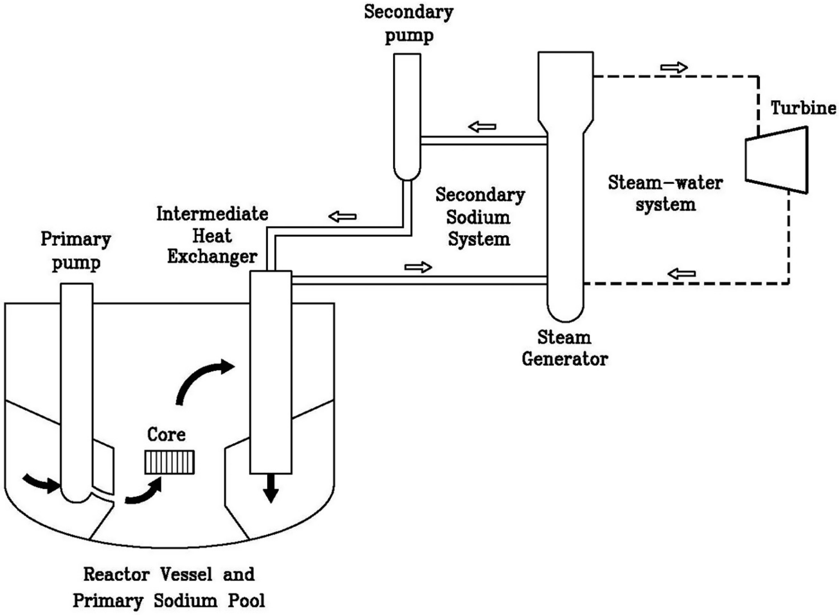

Figure 1.2 Pool-typeconfiguration.

The advantages and disadvantages of locating the pump in the cold leg are discussed in Chapter 2. Table A1.1 in Appendix 1 gives the types of fast reactors designed/installed/operated.

1.2.1 Types of pumps for liquid sodium pumping

Essentially, two types of pumps, mechanical and electromagnetic, are used to pump liquid sodium in the various reactor cooling circuits. In the mechanical pump, the pressure to circulate the coolant is produced by rotodynamic action. The rotation of the impeller, mounted on the pump shaft, imparts kinetic energy to the liquid which is transformed to pressure energy in the stationary diffuser.

Liquid sodium is pyrophoric and is to be perfectly sealed from the atmosphere. In the mechanical pump, sodium is sealed from the atmosphere using either a hermetically sealed arrangement or the shaft emerging from the pump casing is sealed at the shaft-casing interface using a seal. The canned motor pump is an example of the hermetically sealed arrangement. The rotor assembly, comprising the impeller mounted on the rotating shaft, is immersed in sodium. The rotor (armature) is shielded from the pumped liquid by a thin sheeting, while the stator is protected from the pumped liquid by a thin can of negligible electrical conductivity welded to the pump body. The rotor is supported by sleeve bearings at either end of the armature.

A fraction of the liquid from the pump discharge is diverted through the clearance between the rotor and stator, cooling them in the process; the other stream of liquid is used to lubricate the sleeve bearings. Both streams return to the impeller suction. The EBR-II primary pumps, manufactured by Byron Jackson Pump company for Atomics International, are canned motor units. In this particular design, the pump casing is integral to the pump tank, which contains sodium topped by inert gas – the pump shaft passes through a gas-tight housing consisting of a labyrinth seal. The motor is enclosed in a sealed housing, and the gas pressure in the housing is equalised with that in the liquid tank, thus avoiding the need for a mechanical seal. The electrical connections to the motor penetrating the motor housing are seal welded. The motor bearings are conventional, lubricated bearings, and the bearing in sodium is of hydrostatic type [3].

In the case of pumps with seal, direct sealing of sodium from the atmosphere is avoided by making the pump of vertical construction. A vertical arrangement permits free level of sodium in the pump barrel topped by inert (argon) cover gas. The inert cover gas acts as a buffer fluid between the free surface of sodium in the pump and the atmosphere, easing the difficulty in sealing. The sealing of the cover gas space from the atmosphere is achieved by means of mechanical seals mounted on the shaft. A repair seal for the shaft is additionally provided to isolate the pump internals, during replacement of the main seal, without disturbing the pump from the circuit. This design is the most popular and almost universally used for both primary and secondary sodium pumps. Mechanical pumps are also classified on the basis of the length of the shaft as either long shaft pumps or short shaft pumps. Long shaft pumps are provided with a bearing in the pumped liquid, whereas short shaft pumps have overhanging impeller. Most of the pumps used in sodium-cooled reactors are of the long shaft type (e.g., RAPSODIE, SuperPhénix, PFR, FBTR, PFBR). Examples of short shaft pumps are the main and auxiliary sodium pumps of the Sodium Reactor Experiment (SRE) reactor.

The electromagnetic pumps (EM) operate on the principle of interaction of current carrying conductor (in this case, the liquid metal) with a magnetic field. Compared to mechanical pumps, the main advantage of these pumps is the freedom from penetration of the pump boundary (such as is required for the shaft in a rotating equipment) and the absence of moving parts. This simplifies the design and makes the pumps almost maintenance free. EM pumps are broadly divided into conduction pumps and induction pumps. Conduction pumps are further classified into DC conduction Pumps and AC conduction pumps. Example of DC conduction pump used in a fast reactor is the primary pump of the EBR-I plant. Induction pumps are classified as AC linear and AC rotary pumps. The Flat Linear Induction Pump (FLIP) and Annular Linear Induction Pump (ALIP) belong to the category of AC linear pumps. The largest AC linear induction pump (FLIP) used in a sodium-cooled reactor is that used in the EBR-II secondary circuit.

In India, annular linear induction pumps have been successfully developed up to a capacity of 170 m^3/h at a pressure of 4 bars. Use of large capacity EM pumps is limited because of their rather low efficiency,[2] possible instability from magnetohydrodynamic effects and absence of inherent inertia required for coolant flow coast down in the event of pump de-energising (trip). The economic trade-off of using EM pumps instead of mechanical pumps could be significant if improvements in these areas are realised. Table A1.1 in Appendix 1 summarises the type of pumps used in various experimental, prototype, and commercial reactors.

The main circulating pumps in a fast reactor plant are complex units with dedicated auxiliary systems, special instrumentation and many unique technical features (see Figure 1.3).

1.3 DESIGN CONSIDERATIONS FOR MAIN COOLANT PUMPS (MCP) OF FAST REACTORS

Pumps are the heart of a power plant; more so in sodium-cooled reactors what with the high-power density of the core, the harsh operating conditions, and the reactive nature of the liquid sodium coolant. The economic penalties resulting from downtime of these large power plants demand high reliability of the main coolant pumps and make the design and operation of these pumps a challenge. The design considerations of centrifugal pumps for sodium application are dictated by the unique operating environment and so these pumps have design features that are not common in conventional pumps.

(a) Material of construction: The material used for construction is to have good strength at high temperature as well as good machinability and weldability. It is to be chemically resistant to sodium, decontaminating alkali/acid solution and steam/water washing media. The material used for construction of hydraulic parts is to have good resistance to erosion at high sodium velocities and particularly to cavitation damage. As a rule, austenitic stainless steel with various kinds of thermal or thermochemical treatment is used. Hardfacing is employed in parts that require enhanced hardness. Special care is exercised in manufacture which includes raw material inspection, casting, fabrication, machining and heat treatment (e.g., of the long rotating shaft), quality control and inspection after manufacture, and lastly balancing of the rotating assembly.

(b) Compactness: The sizing of the pumps have a strong influence on the main vessel size (in the case of pool-type reactors) and the reactor capital cost. Hence the design is optimised to permit operation at the maximum speed possible. However, this aggravates the danger of cavitation during operation because the Net Positive Suction head (NPSH)[3] available is modest.

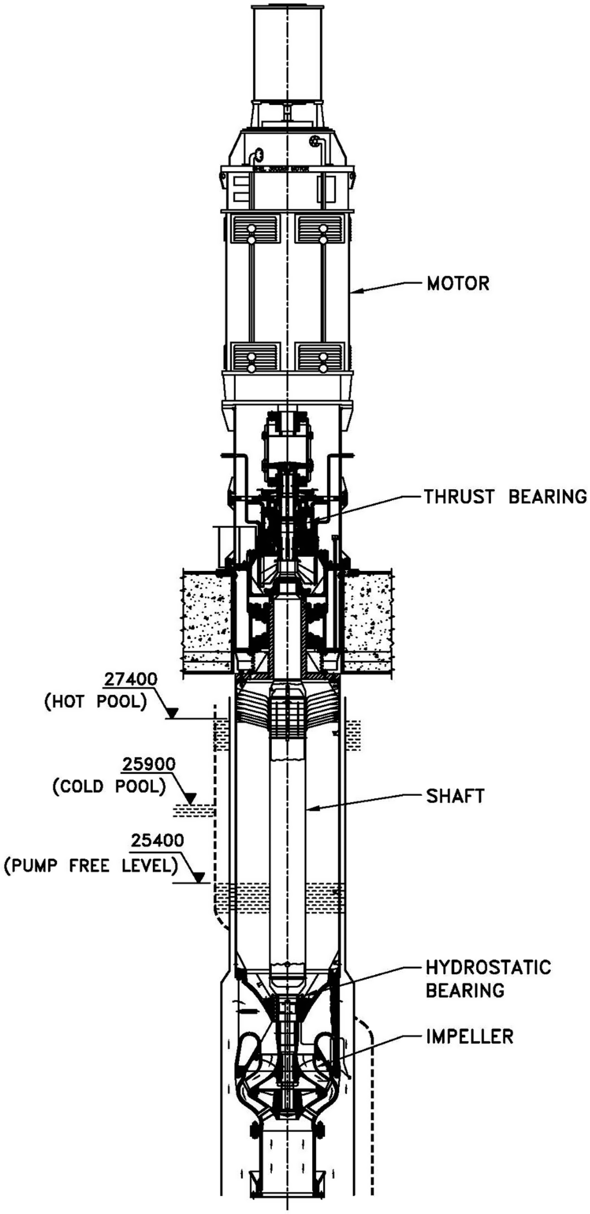

Figure 1.3 Primary sodium pump of the Prototype Fast Breeder Reactor (PFBR).

(c) Long shaft with composite construction: The shaft is normally supported by two bearings one within sodium and the other in the cover gas space. In order to achieve maximum submergence a long shaft is used thus increasing the span between the bearings resulting in lowering of the critical speed of the rotating assembly. The shaft is therefore fabricated by welding together solid and hollow sections in order to raise the critical speed above the operating speed.

(d) Bearing under sodium: Conventional grease lubricated, antifriction bearings cannot be used to support the rotating assembly under sodium. Therefore, hydrostatic bearing which uses the high-pressure liquid feed from the pump discharge is used to support the rotating assembly. Since the load bearing capacity of the bearing is proportional to the pump speed there is some rubbing of rotating and stationary parts of the bearing during start-up/final stage of coastdown of the pump. These surfaces are therefore hardfaced to ensure adequate wear resistance. The bearing is designed to meet the following requirements:
  (i) Have minimal wear of bearing working surfaces for specified lifetime taking into account the significant number of starts/stops.
  (ii) Permit pump operation at any speed within the boundaries of the working envelope.
  (iii) Allow for reverse rotation as far as possible.
  (iv) Consume a minimal quantity of pumped liquid for feeding the hydrostatic bearing.

(e) Quick acceleration during start-up and gradual coasting down: The design of the motor permits rapid acceleration during start-up so that the duration of rubbing at the under-sodium hydrostatic bearing surface is minimal. A flywheel is provided on the rotating assembly to provide adequate rotational inertia and achieve gradual coasting down of the pump flow rate in the event of motor trip under emergency conditions.

(f) Non-return valve: The primary radioactive system is provided with multiple pumps operating in parallel to guarantee redundancy and ensure adequate core cooling in the event of single pump failure/loss of power supply. Under such conditions, the flow rate delivered by the operating pumps gets partly diverted through the stopped pump bypassing the core. This bypassing of the core is prevented by using a non-return valve at the pump discharge (e.g., in the RAPSODIE primary pump), which acts as a "flow diode" permitting flow through the pump in only the forward direction.

(g) Seal: Leak tightness of the pump is paramount because liquid sodium catches fire on exposure to air. The task of sealing is simplified by making the pumps of vertical construction with the free surface of sodium topped by inert (argon) cover gas and sealing the cover gas, instead of sodium, from the atmosphere. Moreover, all joints under sodium are of welded construction. The sealing is done using multiple mechanical seal arrangement equipped with a dedicated lubricating oil supply system.

(h) Capacity regulation by speed control: Capacity regulation in sodium pumps is achieved by varying the speed of the pump and not by throttling the discharge valve. Valves in sodium systems are restricted to minimise the possibility of leakage of sodium to the atmosphere from valve failure, thus improving system reliability, and avoiding energy loss due to valve throttling.

(i) Hydraulic characteristics: The arrangement consists of multiple pumps operating in parallel. The pump hydraulics is designed to achieve stable, drooping performance characteristic so that the pumps operate at the same duty point. Since capacity regulation is achieved by speed variation, the pump characteristics are designed to allow operation over a wide range of speeds (typically 15%–100% of rated speed) and over a range of flow rates (at a given speed). The latter criterion makes possible operation of the system in the event of (i) one pump trip or (ii) lower system resistance (e.g., duct or plenum failure).

(j) Other considerations: The overall design of the pump should facilitate easy assembly and disassembly for maintenance. Unlike conventional pumps, the sodium-wetted pump is to be cleaned from wet sodium using a special process (e.g., water-vapour/CO_2 process) before it is disassembled for maintenance. To prevent sodium accumulation in crevices/narrow regions, all sodium-wetted parts are designed to facilitate the complete drainage of sodium.

1.4 SUMMARY

The thermal energy generated by nuclear fission in the core of a fast reactor is transferred by liquid sodium to the conventional steam-water circuit to drive the turbogenerators and produce power. Either mechanical or electromagnetic pumps can be used to circulate liquid sodium in the primary and secondary circuits. Mechanical centrifugal pumps are preferred over electromagnetic pumps because of their proven design, high efficiency, rugged construction, and freedom from maintenance. Unlike conventional pumps used for water applications, sodium centrifugal pumps have unique design features and engineering requirements.

NOTES

1 Power density is a measure of the volumetric heat release rate in the core. Fast reactors are relatively compact to reduce fuel cost and neutron moderation. The typical power density in a sodium-cooled commercial fast breeder reactor is as high as 500 MW(thermal)/m^3. In comparison, the power densities in thermal reactors are approximately 100 MW(thermal/m^3 for pressurised water reactors, about 55MW(thermal)/m^3 for boiling water reactors, and about 19 MW(thermal)/m^3 for PHWRs.

2 The efficiency of electromagnetic pumps ranges from 5% to 45%, whereas that of centrifugal pumps of similar capacity is around 80% to 85%.

3 The Net Positive Suction Head (NPSH) is the total energy at the pump suction and is a measure of the cavitation performance of the pump. There are two types of NPSH, viz. NPSHA – Net Positive Suction Head Available and NPSHR – Net Positive Suction Head Required. NPSHA depends on the piping layout while NPSHR is controlled by the design of the pump impeller. To avoid cavitation, NPSHA > NPSHR.

REFERENCES

1. S.A. Bharadwaj, Indian Nuclear Power Programme – Past, Present and Future, *Sadhana*, 38: Part 5, 775–793, October 2013.
2. S. Glasstone and A. Sesonske, *Nuclear Reactor Engineering*, 3rd edition, C.B.S. Publishers and Distributors.
3. D.R. Nixon and C.C. Randall, Survey of Sodium Pump Technology, Report no. WCAP-2255 prepared for the New York Operations Office, U.S. Atomic Energy Commission, Under A.E.C. Contract AT (30-1)-3123, June 1963.

Introduction to centrifugal sodium pumps in fast reactors

S.A. Bharadwaj , Indian Nuclear Power Programme – Past, Present and Future, Sadhana, 38: Part 5, 775–793, October 2013.

S. Glasstone and A. Sesonske , Nuclear Reactor Engineering, 3rd edition, C.B.S. Publishers and Distributors.

D.R. Nixon and C.C. Randall , Survey of Sodium Pump Technology, Report no. WCAP-2255 prepared for the New York Operations Office, U.S. Atomic Energy Commission, Under A.E.C. Contract AT (30-1)-3123, June 1963.

Description of centrifugal sodium pumps

F.M. Mitenkov , E.G. Novinsky and V.M. Budov , Main Circulation Pumps for Atomic Power Stations, edited by F.M. Mitenkov , member, Academy of Sciences, U.S.S.R. , 2nd Edition, ENERGOATOMIZDAT, Moscow, 1990.

S.A. Belov , F.M. Mitenkov , E.G. Novinski , G.M. Nikolushkin and G.P. Shishkin , Design and experimental development of sodium pumps, Paper no. 121, Liquid Metal Engineering Technology, proceedings of the third international conference held in Oxford on 9–13 April 1984.

Status of Liquid Metal Cooled Fast Reactor Technology , IAEA-TECDOC-1083, April 1999.

B.P.S. Rao , S. Ghosh , M. Mannaru and R. Chandramohan , Manufacture of F.B.T.R. Sodium Pumps, Pumping Equipment in Nuclear Industry and Thermal Power Plants, Proceedings of National Symposium, ed. R.D. Kale , February 24–25, 1994 , B.A.R.C., Bombay.

J.R. Davis , G.E. Deegan , J.D. Leman and W.H. Perry , Operating experience with sodium pumps at EBR-II, Report no. ANL/EBR-027, October 1970.

W. Babcock , State of Technology Study–Pumps: Experience with High Temperature Sodium Pumps in Nuclear Reactor Service and their Application to FFTF, Report no. BNWL-1049 UC-80, Reactor Technology, December 1969.

P.G. Smith , Experience with High Temperature Centrifugal Pumps in nuclear reactors and their application to molten salt thermal breeder reactors, ORNL-TM-1993, September 1967.

R.W. Atz and M.J. Tessier , High Temperature Testing of a Sodium Pump, Presented at A.S.M.E. Winter Annual Meeting, December 1978 .

M.C. Zerinvary and J. Wasko , “F.F.T.F. Primary Pumps Point Way to Design for Tomorrow’s Liquid Sodium Handling”, Power (N.Y.), 120(7), 54–57.

M. Guer , W. Raczynski and G. Keyser , SNECMA-Bergeron Sodium Pumps Development Stage Seen in the Light of The Phenix Experiment, C109/74, Pumps for Nuclear Power Plants, University of Bath, 22–24 April 1974.

Fast Reactor Database 2006 Update, Report no. IAEA-TECDOC-1531, December 2006.

J.M. Laithwaite , L. Bowles and F.M. Delves , Sodium Pumps for Fast Reactors, Paper no. IAEA-SM-130/10, Proceedings of a symposium on Progress in Sodium-Cooled Fast Reactor Engineering, Monaco, 23–27 March 1970.

L.F. Bowles and D. Taylor , The Sodium Pumps for the P.F.R, Nuclear Engineering, May 1967.

J.M. Laithwite and A.F. Taylor , Hydraulic Problems in the P.F.R. Coolant Circuit, Proceedings of a symposium on Progress in Sodium-Cooled Fast Reactor Engineering, Monaco, March 1970.

S.G. Joshi , A.S. Pujari , R.D. Kale and B.K. Sreedhar , Cavitation Studies on a Model of Primary Sodium Pump, Proceedings of FEDSM’02, The 2002 Joint US ASME European Fluids Engineering Summer Conference, July 14–18, 2001 , Montreal, Canada.

K.V. Sreedharan , S. Athmalingam , V. Balasubramaniyan , A.S.L.K. Rao , P. Chellapandi and S.C. Chetal , Design and Manufacture of Sodium pumps of 500 MWe Prototype Fast breeder Reactor (P.F.B.R.), 20th Annual Conference of Indian Nuclear Society, January 4–6, 2010 , Chennai, India.

H. Noel and G. Pasqualini , Fabrication and Testing of Main Sodium Pumps of Super Phénix-1, Nuclear Technology, 68: 2, 153–159, 1985. DOI: 10.13182/NT85-A33551

Roger Morriset , Maurice Gravier , Jean-Marc Canini , Pool Type Breeder Primary and Secondary Sodium Pumps: Design Developments, Proceedings of Symposium on Fast Breeder

Reactors: Experience and Trends, Lyons, 1985.
W. Marth , A Review of the Collaborative Program on the European Fast Reactor (EFR), Presented at the Annual Meeting of IWGFR, April 1992 .
Unusual Occurrences During LMFR Operation , Proceedings of a Technical Committee meeting held in Vienna, 9–13 Nov. 1998 , Report no. IAEA-TECDOC-1180.
A.A. Rinejski , Fast Breeder Reactors: Advanced Concepts for Economic Design, SCUAE, USSR, April 1990.

Design of centrifugal sodium pumps

S. Lazarkiewicz and A.T. Troskolanski , Impeller Pumps, Pergamon Press, 1965.
A.J. Stepanoff , Centrifugal and Axial Flow Pumps, Wiley, 1975
J.F. Gulich , Centrifugal Pumps, Springer, 2008
K.M. Srinivasan , Rotodynamic Pumps (centrifugal and axial), New Age International Private Limited, 2008.
I.J. Karassik , J.P. Messina , P. Cooper and C.C. Heald , Pump Handbook, 3rd edition, McGraw Hill, 2001
A.H. Church , Centrifugal Pumps and Blowers, Krieger Publishing Company, 1972
Addison , Centrifugal and Other Rotodynamic Pumps, Chapman and Hall, 1966.
V.S. Lobanoff and R.R. Ross , Centrifugal Pumps: Design and Application, 2nd edition, Gulf Publishing Company, Houston, Texas.
V.M. Cherkassky , Pumps, Fans and Compressors, Mir Publishers, Moscow, 1985.
A.G. Salisbury , Current Concepts in Centrifugal Pump Hydraulic Design, Paper no. C177/82, IMechE Conference Publications 1982-11.
W. Babcock , State of Technology Study - Pumps Experience with High Temperature Sodium Pumps in Nuclear Reactor Service and their Application to F.F.T.F., BNWL-1049, December 1969.
Fast Reactor Database 2006 update , No. IAEA-TECDOC-1531, International Atomic Energy Agency, December 2006.
J.M. Laithwite and A.F. Taylor , Hydraulic Problems in the P.F.R. Coolant Circuit, Proceedings of a Symposium on Progress in Sodium Cooled Fast Reactor Engineering, Monaco, March 1970 .
W. Raozynski , J.P. Delisle , and J.L. Befree , L’Evolution des Pompes a Sodium de Rapsodie a Phenix et a la Filiere, Proceedings of a Symposium on Progress in Sodium Cooled Fast Reactor Engineering held by the International Atomic Energy Agency in Monaco, 23–27 March 1970 .
R.M. Chabassier , J.J. Balteyron and J.F. Roumailhac , from Phenix to SuperPhénix: Mechanical Structures Assuring Reactor Vessel Tightness at Main Sodium Pump Penetrations, F2/6, International Conference on Structural Mechanics in Reactor Technology (SMiRT 4), San Francisco. 1977.
J.R. Davis , G.E. Deegan , J.D. Leman and W.H. Perry , Operating Experience with Sodium Pumps at EBR-II, Report no. ANL/EBR-027, Argonne National Laboratory, October 1970.
D.J. Kniley , W.J. Carlson , E. Ferguson and O.G. Jenkins , Mechanical Elements Operating in Sodium and Other Alkali Metals, Vol II, Experience Survey, Report no. LMEC-68-5, June 1970.
K.V. Sreedharan , S. Athmalingam , V. Balasubramaniyan , A.S.L.K. Rao , P. Chellapandi , S.C. Chetal , Design and Manufacture of Sodium Pumps of 500 MWe P.F.B.R., I.N.S. Annual Conference (INSAC-2009), January 2010 , Chennai, India.
J. Guidez and G. Prele , Superphénix: Technical and Scientific Achievements, Atlantis Press, 2017.
F.M. Mitenkov , E.G. Novinsky , V.M. Budov , Main Circulation Pumps for Atomic Power Stations, edited by F.M. Mitenkov , member, Academy of Sciences, U.S.S.R., 2nd Edition ENERGOATOMIZDAT, Moscow, 1990.
R.W. Atz and M.J. Tessier , High Temperature Testing of a Sodium Pump, Presented at A.S.M.E. Winter Annual Meeting, December 1978 , A.S.M.E. Publication No. 78WA/NE12, 1978.

C.K. Keshava Kumar , K.V. Sreedharan , A.S.L.K. Rao and S.C. Chetal , Design and Selection of Slip Joint for Sodium Pump, 32nd National Conference on Fluid Mechanics & Fluid Power, December 2005 , Osmanabad, India.

Manufacture of centrifugal sodium pumps

F.W. Kamber , Steel castings for Nuclear Power Plant Pumps, Paper 93/74, Proceedings of Institution of Mechanical Engineers, 1974, U.K.

R.D. Kale , A.S.L.K. Rao , S. Baskar , K.V. Sreedharan and K. Balachander , Mechanical Design Features of a High-Temperature Reactor Coolant Pump, All India Conference on Pumps, Organised by The Institute of Energy management, Mumbai, India, April 25 & 26, 1997.

B.P.S. Rao , S. Ghosh , M. Mannaru and R. Chandramohan , Manufacture of F.B.T.R. Sodium Pumps , Proc. of National Symposium on Pumping Equipment in Nuclear Industry and Thermal Power Plants, February 24–25, 1994 , B.A.R.C., Bombay, India.

Centrifugal sodium pump testing

American National Standard for Rotodynamic Pumps for Hydraulic Performance Acceptance Tests , ANSI/HI 14.6-2016.

Stephen Lazarkiewicz and Adam T. Troskolanski , Impeller Pumps, Pergamon Press, 1965.

Sokolov Kestin and Wakeham , Viscosity of Liquid Water in the Range -8oC to 150oC, Journal of Physical and Chemical Reference Data, 7: 3, 1978, pp. 941–948.

John C. Crittenden , R. Rhodes Trussell , David W. Hand , Kerry J. Howe and George Tchobanoglous , MWH's Water treatment: principles and Design, 3rd edition, John Wiley & Sons.

Joanne K. Fink and Leonard Leibowitz , Thermophysical Properties of Sodium, ANL_CEN-RSD-79-1.

Yves Lecoffre , Cavitation Bubble Trackers, AA Balkema/Rotterdam/Brookfield, 1999.

M.C. Zerinvary and E.W. Wagner , Development of an 85,000 gpm (19303 m3/h) LMFBR Primary Pump, Paper no. 115, Proc. of Liquid Metal Engineering and Technology, Vol. 2, Proc. of the Third International Conference held in Oxford on 9–13 April 1984, BNES, London.

S.G. Joshi , A.S. Pujari , R.D. Kale and B.K. Sreedhar , Cavitation Studies on a Model of Primary Sodium Pump, Proceedings of FEDSM02, The 2002 joint US ASME European Fluids Engineering Summer Conference, July 14–18, 2002 , Montreal, Canada.

J.F. Gulich , Quantitative Prediction of Cavitation Erosion in Centrifugal Pumps, IAHR Symposium, paper no. 42, 1986.

G. Ghia , V. Cela , P. Casalini , G. Mengoli and R. Rappini , Construction, Installation and Sodium Testing of a Test Section Simulating the Rotating Parts of SuperPhénix Primary Pump (PIVOTERIE-1), Proceedings of Second International Conference on Liquid Metal Technology in Energy Production, Ed. J.M. Dahlke , pp. 11–10 to 11–15, August 1980 .

E.A. Belov , F.M. Mitenkov , E.G. Novinski , G.M. Nikolushkin and G.P. Shishkin , Design and Experimental Development of Sodium Pumps, Paper no. 121, BNES, Oxford, UK, 9–13 April 1984.

Quarterly Technical Progress Report , NAA-SR-12585, Liquid Metal Engineering Center (LMEC), July–September, November 1967.

Quarterly Technical Progress Report , LMEC-68-20, Liquid Metal Engineering Center (LMEC), April–June, October 1968.

O.J. Faust (Ed.), Sodium-Nak Engineering Handbook, vol. III, Sodium Systems, Safety, Handling and Instrumentation, Gordon and Breach, Science Publishers, Inc., 1978.

H. Dieckamp , B. Wolfe and R.W. Dickinson , Development and Testing of Sodium Components, Conf 710901 n.d.

J.T. Cochran , G.G. Glenn , W.J. Purcell , R.W. Smith and E.A. Wright , CRBRP Main Sodium Pump Test Experience, Paper no. 113, Proceedings of Liquid Metal Engineering and

Technology, BNES, London, 1984.

C. Dunn and M.J. Gabler , Development of an 85000 gal/min Inducer Pump for LMFBR, Paper no. 113, Proceedings of Liquid Metal Engineering and Technology, BNES, London, 1984.

K. Mente , H. Reimann , R. Fakkel , M. Heslenfeld , Testing of a Prototype Sodium Pump, INTAT 75.9, February 1974.

R.H. Fakkel , C.J. Hoornweg , W.K. Mendte , M. Jansing , H.J. Lameris , J.P. Vroom and M.H. Heslefeld , Development, Design, Construction and Full Scale Sodium Testing of a Prototype Sodium Pump for a LMFBR Power Plant, Paper no. C108/74, Pumps for Nuclear Power Plants, IMechE Convention, University of Bath, 22–24 April, 1974.

P.H. Delves and G. Seed , Operating Experiences with the Prototype 0.45m3/s Sodium Pump, Paper no. C104/74, Pumps for Nuclear Power Plants, IMechE Convention, University of Bath, 22–24 April, 1974.

Y. Oda , A. Suzuki , S. Kawahara , N. Sagawa , T. Komatsu and Y. Ito , Development of Mechanical Sodium Pump, Proceedings of Symposium on Sodium Cooled Fast Reactor Engineering, Monaco, 23–27 March 1970 .

T. Contardi , L. Rapezzi , P. Le Coz , Y. Tigeot , C. Partiti , M. Zola and P. Denimal , Sodium Test of the Superphénix Full Size Primary Pump Shaft on the CPV-1 Test Rig at ENEA-Brasimone, Paper no. 117, Proc. of Liquid Metal Engineering and Technology, Vol. 2, BNES, London, 1984.

P. Courbiere and P. Lecoz , Cavitation in Pumps: Research and Development in France, IWGFR Specialists’ Meeting on Cavitation Criteria for Designing Mechanisms Working in Sodium Application to Pumps, Interatom GmbH, Federal Republic of Germany, October 28–29 1985.

W. Marth , A Review of the Collaborative Programme on the European Fast Reactor (EFR), Annual Meeting of the International Working Group on Fast Reactors (IWGFR), 1991, IAEA, Vienna.

R.H. Fakkel , Sodium Pump Development, Proceedings of Symposium on Sodium Cooled Fast Reactor Engineering, Monaco, 23–27 March 1970 .

A. Sheth , Parametric Study of Sodium Aerosols in the Cover-Gas Space of Sodium Cooled Reactors, Document no. ANL-75-11, Argonne National Laboratory, Argonne, Illinois, March 1975.

R.W. Atz , Performance of HNPF Prototype Free Surface Sodium Pump, Report no. NAA-SR-4336, June 1960.

P.G. Smith , Experience with High Temperature Centrifugal Pumps in Nuclear Reactors and their Application to Molten Salt Thermal Breeder Reactors, ORNL-TM-1993, September 1967.

Orville S. Seim and Robert A. Jaross , Characteristics and Performance of 5000 gpm AC Linear Induction and Mechanical Centrifugal Sodium Pumps, Proceedings of 2nd United Nations Conference on the Peaceful Uses of Atomic Energy, Vol. 7, pp. 88–93, September 1–13, 1958 .

Sodium Pump Development and Pump Test Facility Design , Report no. WCAP-2347, Westinghouse Electric Corporation, August 1963.

J.M. Laithwaite , L. Bowles and F.M. Delves , Sodium Pumps for Fast Reactors, Paper no. IAEA-SM-130/10, Proceedings of a Symposium on Progress in Sodium Cooled Fast Reactor Engineering, Monaco, 23–27 March 1970 .

K.G. Eickhoff , J. Allen and C. Boorman , Engineering Development for Sodium Systems, paper 5B/5, Proceedings of the London Conference on Fast Breeder Reactors, BNES, May 1966 .

Seed, Bowles, McLeod, Design, Testing and Commissioning of Sodium Pumps for the 600 MW(t) Prototype Fast Reactor, Paper no. C106/74, Pumps for Nuclear Power Plants, University of Bath, 22–24 April, 1974.

S.T. Brewer , Three Decades of Breeder Technology in the United States of America, Proceedings of an International Conference on Advanced Systems and International Co-operation, Vol. 5, Vienna, 1983.

R.W. Atz and M.J. Tessier , High Temperature Testing of a Sodium Pump, Presented at ASME Winter Annual Meeting, December 1978 , ASME Publication No. 78WA/NE12, 1978.

R.J. Dowling , R.L. Ferguson and S.A. Weber , Experience in the Design, Construction and Testing of the FFTF Heat Transport System, Proceedings of International Symposium on Design, Construction and Operating Experience of Demonstration LMFBR’s, Bologna, Italy, 10–14 April, 1978 .

Status of Liquid Metal Cooled Fast Reactor Technology , IAEA-TECDOC-1083, April 1999.

Toshihiro Odo , Nobutaka Ohkuma , Masaaki Ebashi , Tomoyuki Yamada , Kinya Ogawa and Takuho Miyagi , Design and Construction of Heat Transport Systems of the Prototype Fast Breeder Reactor MONJU, International Conference on Fast Reactors and Related Fuel Cycles, Vol. 1, November 1991 , Kyoto, Japan.

J.R. Davis , G.E. Deegan , J.D. Leman and W.H. Perry , Operating Experience with Sodium Pumps at EBR-II, Report no. ANL/EBR-027, October 1970.

T.P. Ross , Primary Sodium System Pumps in the Enrico Fermi Atomic Power Plant, APDA-309, Atomic Power Development Associates, Inc., June 1969.

W. Raozynski , J.P. Delisle , and J.L. Befree , L'Evolution des Pompes a Sodium de Rapsodie a Phenix et a la Filiere, Proceedings of a symposium on Progress in Sodium Cooled Fast Reactor Engineering held by the International Atomic Energy Agency in Monaco, 23–27 March 1970.

K. Mendte , DEBENE Status on Cavitation in Sodium pumps, IWGFR Specialists' Meeting on Cavitation criteria for Designing Mechanisms Working in Sodium Application to Pumps, Interatom GmbH, Federal Republic of Germany, 28–29 October, 1985.

R. Buonamici , Fast Flux Test Facility Sodium Pump Operating Experience-Mechanical, Presented at US/UK Specilaists' Meeting on Sodium Pumps, San Jose, California, November 1987 .

Y. Ojiri , A. Suzuki , Y. Ito and S. Sakamoto , Development of Mechanical Sodium Pump, C110/74, Pumps for Nuclear Power Plants, University of Bath, 22–24 April, 1974.

M. Kambei and M. Kamei , Cavitation tests for "JOYO" Primary and Secondary main Circulating pumps, IWGFR Specialists' Meeting on Cavitation criteria for Designing Mechanisms Working in Sodium Application to Pumps, Interatom GmbH, Federal Republic of Germany, 28–29 October, 1985.

M. Guer , W. Raczynski and G. Keyser , SNECMA-Bergeron Sodium Pumps Development Stage Seen in the Light of the Phenix Experiment, C109/74, Pumps for Nuclear Power Plants, University of Bath, 22–24 April, 1974.

P. Courbiere , Superphénix 1 Sodium Pumps: Cavitation and Scale Effects, IWGFR Specialists' Meeting on Cavitation Criteria for Designing Mechanisms Working in Sodium Application to Pumps, Interatom GmbH, Federal Republic of Germany, 28–29 October, 1985 .

W. Marsh , A Review of the Collaborative Programme on the European Fast Reactor (EFR), Report no. IWGFR 83, Annual meeting of the International Working Group on Fast Reactors, Tsuruga, April 1991 .

Centrifugal sodium pump instrumentation

O.J. Faust (Ed.), Sodium-Na–K Engineering Handbook, vol. III, Sodium Systems, Safety, Handling and Instrumentation, Gordon and Breach, Science Publishers, Inc., 1978.

G.E. Turner , Liquid Metal Flow Measurement (Sodium) State of the Art Study, Report no. LMEC-Memo-68-9, Liquid Metal Energy Center, 1968.

W.R. Miller , High Temperature Pressure Transmitter Evaluation, Report no. ORNL-2483, Oak Ridge National Laboratory, 1958.

Clyde C. Scott , Fermi Process Instrumentation, Proceedings of the Symposium on Liquid-Metal Instrumentation and Control, Idaho Falls, Idaho, March 1–2, 1967 .

G.E. Turner , SCTI Sodium Instrument Operating Experience, Proceedings of the Symposium on Liquid-Metal Instrumentation and Control, Idaho Falls, Idaho, March 1–2, 1967

R.H. Greene , D.A. Casada , C.W. Ayers , C.C. Southmayd , Detection of pump degradation, NUREG/CR-6089 ORNL-6765, Oak Ridge National Laboratory, August 1995.

Operating experience of reactor centrifugal sodium pumps

J.R. Davis , G.E. Deegan , J.D. Leman and W.H. Perry , Operating Experience With Sodium Pumps at EBR-II, Report no. ANL/EBR-027, October 1970.

B.C. Cerutti , G.E. Deegan , J.D. Nulton , W.H. Perry and R.E. Seever , Removal and Repair of EBR-II Primary Sodium Pump No. 1, Report no. ANL-7835, May 1972.

Sodium Pump Development and Pump Test Facility Design , Report no. WCAP-2347, Westinghouse Electric Corporation, August 1963.

D.J. Kniley , W.J. Carlson , E. Ferguson , and O.G. Jenkins , Mechanical Elements Operating in Sodium and other Alkali Metals, Vol. II, Experience Survey, LMEC-68-5, June 1970.

J.G. Duffy , and H.A. Wagner , Operating Experience with Major Components of the Enrico Fermi Atomic Power Plant, Proceedings of a Symposium on Performance of Nuclear Power Reactor Components, Prague, 10–14, November 1969 .

W. Babcock , State of Technology Study-Pumps: Experience with High Temperature Sodium pumps in Nuclear Reactor Service and their Application to FFTF, BNWL-1049, December 1969.

P.G. Smith , Experience With High Temperature Centrifugal Pumps in Nuclear Reactors and their Application to Molten Salt Thermal Breeder Reactors, ORNL-TM-1993, September 1967.

L. Vautrey , Fast Reactor Development in France, IWGFR First Annual Meeting, Vienna, March 1968 .

L. Vautrey , The Development of Fast Neutron Reactors in France from March 1969 to March 1970, IWGFR Third Annual Meeting, Cadarache, March 1970 .

Operational and Decommissioning Experience with Fast Reactors , Proceedings of a Technical Meeting held in Cadarache, Report no. IAEA-TECDOC-1405, France, 2002.

F. Asakura , The Experience of Experimental Fast Reactor JOYO Operation and Maintenance, International Conference on Fast Reactors and Related Fuel Cycles, Vol. 1, November 1991 , Kyoto, Japan.

Y. Matsuno , JOYO Operating Experience: 1977–1983, Liquid Metal Engineering Technology, Proceedings. of the Third International Conference held in Oxford on 9–13, April 1984 .

Masao M. Hori , and Yoshihiko Y. Nara , Operating Experiences of Experimental Fast Reactor JOYO, International Conference on Fast Reactors and Related Fuel Cycles, Vol. 1, November 1991 , Kyoto, Japan.

M. Sauvage , A.M. Broomfield , and W. Marth , Overview on European Fast reactor Operating Experience, International Conference on Fast Reactors and Related Fuel Cycles, Vol. 1, November 1991 , Kyoto, Japan.

C.V. Gregory , and C. Acket , Repairs in Fast Breeder Reactors: Experience to Date, Prospects Ffor The Future, International Conference on Fast Reactors and Related Fuel Cycles, Vol. 1, November 1991 , Kyoto, Japan.

Stuart A. Krieg , James D. Thomson , Fast Flux Test Facility Replacement of a Sodium pump, HEDL-SA-3364-FP, DE 87 004092, Westinghouse Hanford Company, Salk Lake City, UT, March 1986.

C.J. Peckinpaugh , R.A. Bennett , and W.R. Wykoff , Fast Flux Test Facility (FFTF) Operational Results, Proceedings of International Conference on Nuclear Power Experience, Vol. 5, September 1982 .

Q.L. Baird and R.A. Harris , FFTF Operational Results: Startup to 1000 MWd/kg, Nuclear Safety, Vol. 26, No. 2, March–April 1985.

B. Rajendran , P.V. Ramalingam , T.R Ellappan, A.P. Chaba , R. Veerasamy , Amitava Sur & M.K. Ramamurthy , Experience Gained During the Commissioning of Sodium Systems of FBTR, 3rd National Symposium on Operating Experience of Nuclear Reactors and Power Plants, Bombay, 15–17, March 1989 .

B. Rajendran , S.K. Chande and S.B. Bhoje , Experience on Sodium Pumps in FBTR, Seminar on Movement of Fluids in Nuclear Industry, Indira Gandhi Centre for Atomic Research, Kalpakkam, India, November 7–8, 1990.

Liquid Metal Cooled Reactors: Experience in Design and Operation , IAEA-TECDOC-1569, December 2007.

Didier D. Dall'Ava , Laurent L. Martin , and Bernard B. Vray , 35 Years of Operating Experience of PHENIX NPP SodiumCooled Fast Reactor, Proceedings of the 17th International Conference on Nuclear Engineering, ICONE 17, July, 12–16 2009 , Brussels, Belgium.

A.D. Evans , J.M. Laithwaite , and D.A. Nunn , Design, Construction and Commissioning of PFR as at 14, December 1973, Proceedings of the conference on Fast Reactor Power Stations,

London, March 1974 .
A. Cruickshank , and A.M. Judd , Problems Experienced During Operation of the Prototype Fast Reactor, Dounreay, 1974-1994, IAEA TCM on Unusual Occurrences During LMFBR Operation: Review of Experience and Consequences for Reactor Systems, November 1998.
C.V. Gregory , A Review of the Operation of the Prototype Fast Reactor, Nuclear Energy, Vol. 31, no. 3, 1992, pp. 173–183.
S.A. Belov , F.M. Mitenkov , E.G. Novinski , G.M. Nikolushkin and G.P. Shishkin , Design and experimental development of Sodium Pumps, Paper no. 121, Liquid Metal Engineering Technology, Proc. of the Third International Conference held in Oxford on 9–13, April 1984 .
Status of Liquid Metal Cooled Fast Reactor Technology , IAEA-TECDOC-1083, April 1999.
M.F. Troyanov , and A.A. Rinejskij , Status of Fast Reactor Activities in the Russian Federation, 25th Annual Meeting of IWGFR, Vienna, 1992.
A.A. Rineisky , V.N. Chushkin , A.A. Kamaev , N.N. Oshanov , and O.A. Potapov , The Utility of BN-600 Reactor Operating Experience on the Choice of Design and Technological Decisions of Fast Reactors Under Design, Indo Soviet Seminar, Obninsk, March 1989.
https://issuu.com/johna.shanahan/docs/t9.1.potapov
Mark S. Smith , Darren H. Wood , and James D. Drischler , An Assessment of Liquid-Metal Centrifugal Pumps at Three fast Reactors, Nuclear Technology, Vol. 104, No. 1, Oct. 1993, pp. 118–127.

Cavitation in centrifugal pumps

M.S. Plesset , A.T. Ellis , On the mechanism of cavitation damage, Transactions of ASME 77, 1055–1084, 1955.
H. Addison , Centrifugal and other Rotodynamic Pumps, Chapman and Hall, 1966.
F.G. Hammitt , Detailed cavitation flow regimes for centrifugal pumps and Head vs NPSH curves, Report no. UMICH 01357-32-I, University of Michigan, December 1974.
C.E. Brennen , Hydrodynamics of Pumps, Concepts ETI Incorp. & Oxford University Press, 1994.
Proceedings of the IWGFR Specialists’ Meeting on Cavitation Criteria for Designing Mechanisms Working in Sodium Application to Pumps, Interatom GmbH, Federal Republic of Germany, 28–29 October 1985.
C. Gongwer , A theory of cavitation flow in centrifugal pump impellers, Transactions of ASME, 63, 29–40, n.d.
F.M. Mitenkov , E.G. Novinsky and V.M. Budov , Main Circulation Pumps for Atomic Power Stations, edited by F.M. Mitenkov , member, Academy of Sciences, USSR, 2nd Edition, ENERGOATOMIZDAT, Moscow, 1990.
R.T. Knapp , J.W. Daily and F.G. Hammitt , Cavitation, McGraw Hill, 1970.
B.K. Sreedhar , S.K. Albert and A.B. Pandit , Cavitation Damage–A Review, Wear 372–373, 177–196, 2017.
H.A. Stahl and A.J. Stepanoff , Thermodynamic Aspects of Cavitation in Centrifugal Pumps, ASME Journal of Basic Engineering, 78, 1691–1693, 1956.
A.J. Stepanoff , Cavitation in Centrifugal Pumps with Liquids Other than Water, ASME Journal of Engineering for Power, 83(1), 79–89, 1961.
A.J. Stepanoff , Cavitation Properties of Liquids, ASME Journal of Engineering for Power, 86, 195–199, 1964.
L.W. Florschuetz and B.T. Chao , On the Mechanics of Vapour Bubble Collapse, Journal of Heat Transfer, Transactions of ASME, 87(2), 209–220, May 1965.
R. Garcia , Comprehensive Cavitation Damage Data for Water and Various Liquid Metals Including Correlation with Material and Fluid Properties, PhD Thesis, University of Michigan, 1966.
R. Garcia and F.G. Hammitt , Cavitation Damage and Correlations with Material and Fluid Properties, Journal of Basic Engineering, 89(4), 753–763, December 1967.
H.S. Preiser , A. Thiruvengadam and C.E. Couchman III , Cavitation Damage in Liquid Sodium, Technical report 285-1, NASA CR-54071, April 1964.

A.J. Stepanoff and H.A. Stahl , Cavitation Criterion for Dissimilar Centrifugal Pumps, ASME Journal of Engineering for Power, 84(4), 329–336, October 1962.

S. Lazarkiewicz and A.T. Troskolanski , Impeller Pumps, Pergamon Press, 1965.

R.K. Turton , Rotodynamic Pump Design, Cambridge University Press, New York, 1994.

I.S. Pearsall , Cavitation, M&B Monograph ME/10, 1972.

S.G. Joshi , A.S. Pujari , R.D. Kale and B.K. Sreedhar , Cavitation Studies on a Model of Primary Sodium Pump, Proceedings of FEDSM02, The 2002 Joint US ASME European Fluids Engineering Summer Conference, July 14–18, 2002, Montreal, Canada.

J.F. Gulich , Centrifugal Pumps, Springer, 2008.

Main coolant pumps for water-cooled reactors

S.S. Sharma , S.G. Mhatre and M.M. Manna , Upgradation of design features of primary coolant pumps of Indian 220 MWe PHWR, Pumping Equipment in Nuclear Industry and Thermal Power Plants, Proceedings of National Symposium, BARC, Bombay, February 24–25, 1994 .

V. Misri , C.N. Bapat and V.K. Sharma , Primary coolant pumps for 500 MWe Pressurized Heavy Water Reactor (PHWR) – Specification, Design, Manufacturing and Testing Requirements – An Overview, Pumping Equipment in Nuclear Industry and Thermal Power Plants, Proceedings of National Symposium, BARC, Bombay, February 24–25, 1994 .

F.M. Mitenkov , E.G. Novinsky and V.M. Budov , Main Circulation Pumps for Atomic Power Stations, edited by F.M. Mitenkov , member, Academy of Sciences, USSR, 2nd Edition, ENERGOATOMIZDAT, Moscow, 1990.

Sodium pumps of the future

J.H. Boy , A. Kumar , P. March , P. Willis and H. Herman , Cavitation and Erosion Resistant Thermal Spray Coatings, Construction Productivity Advancement Research (CPAR) Program, US Army Corps of Engineers, Construction Engineering Research Laboratories, USACERL Technical Report 97/118, July 1997.

R. Sollars and A.D. Beitelman , Cavitation-Resistant Coatings for High Power Turbines, Civil Works Hydropower R&D Program, US Army Corps of Engineers, Engineering Research and Development Centre, ERDC/CERL, TR-11-21 n.d.

S.F. Shepelev , Status of BN-1200 Project Development, JSC Afrikantov OKBM (available at https://www.iaea.org/NuclearPower/Downloadable/Meetings/2015/2015-05-25-05-29-NPTDS/Russian_Projects/31_BN-1200_-_Obninsk_-_Shepelev_S.F._-_May_2015.pdf).

B.K. Sreedhar , Studies on Cavitation Erosion Resistance of Reactor Materials, PhD Thesis, Homi Bhabha National Institute (HBNI), Mumbai, India, 2016.

D.J. Clark and M.J. Jansen , An Overview of Magnetic Bearing Technology for Gas Turbine Engines, NASA/TM-2004-213177, ARL-TR-3254, http://gltrs.rc.nasa.gov. n.d.

I.J. Karassik , J.P. Messina , P. Cooper and C.C. Heald , Pump Handbook, 3rd Edition, McGraw Hill.

Y. Guojun , X. Yang , S. Zhengang and G. Huidong , Characteristic Analysis of Rotor Dynamics and Experiments of Active Magnetic Bearing for HTR-10GT, Nuclear Engineering and Design 237, 1363–1371, 2007.

L. Shi , S. Yu , G. Yang , Z. Shi and Y. Xu , Technical Design and Principal Test of Active Magnetic Bearing for the Turbine Compressor of HTR-10GT, Nuclear Engineering and Design 251, 38–46, 2012.

R. Nordman and M. Aenis , Fault Diagnosis in a Centrifugal Pump Using Active Magnetic Bearings, International Journal of Rotating Machines, 10(3), 183–191, 2004.

G. Schweitzer , Active Magnetic Bearings– Chances and Limitations, Proceedings of 6th International IFToMM Conf. on Rotor Dynamics. n.d.

B.K. Sreedhar , R. Nirmal Kumar , P. Sharma , S. Ruhela , J. Philip , S.I. Sundarraj , N. Chakraborty , M. Mohana , V. Sharma , G. Padmakumar , B.K. Nashine and K.K. Rajan , Development of Active Magnetic Bearings and Ferrofluid Seals Toward Oil-Free Sodium Pumps, Nuclear Engineering and Design 265, 1166–1174, 2013.

Y. Shimakawa , S. Kasai , M. Konomura and M. Toda , An Innovative Concept of the Sodium Cooled Reactor to Pursue High Economic Competitiveness, Nuclear Technology, 140, 1–17, October 2002.

T. Handa , Y. Oda , Y. Ono , K. Miyagawa , I. Matsumoto , K. Shimoji , T. Inoue , H. Ishikawa and H. Hayafune , Status of Integrated IHX/Pump Development for JSFR, Journal of Nuclear Science and Technology, 48(4), 669–676, 2011.