Necessity is the mother of innovation - an example

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Prologue:

In the context of technology development, 'invention' may be seen as creation of a hitherto unknown concept, design, material, or process etc., through the all important one percent inspiration 'gifted' to the inventor (seeker of answers) by evolutionary processes of Nature, and who subsequently by his/her own ninety nine percent 'perspiration', successfully achieves the end result. Inventors are rare persons, born too few and far between, although their inventions can have tremendous impact on society and mankind. By contrast, 'innovation'[1] is a work-around for any obstacles that we may face in the way of technology development. It is generally a case of developing an alternative design, material or manufacturing process when indigenising a component or system for which we do not have in our country, industrial infrastructure to the same extent a sour collaborator's designers from whom we obtained the design. Problem solving innovations are more common place than inventions, and are being implemented all the time around us - if only we take the trouble to recognise them - often yielding huge positive outcomes. This article is about a small innovative idea[2]which although might look simple and obvious in retrospect, did result in saving a make-or-break situation.

Introduction:

Because of their ability to effectively use limited resources of Natural Uranium, the Pressurized Heavy Water Reactor(PHWR) concept, based on the CANDU reactor system developed by Canada, has been chosen to be the basis for nuclear power in our country. Collaboration agreement (1960s) between India and Canada envisaged almost complete Canada-supply for the first Unit at Rajasthan (RAPS-1). Recognising the importance of achieving self-sufficiency in these high-technology areas, Dr Bhabha and his associates had included in the collaboration agreement, provisions for increased India-supply of materials, equipment and components for RAPS-2. Further, the agreement envisaged that India could use the Canadian designs, even beyond RAPS2 (with further indigenous

[1] **Innovation** (Wikipedia) is the process of making changes to something established by introducing something better and, as a consequence, new.

[2] 'One small step for Indian PHWR!' (with due apologies to Mr. Neil Armstrong http://www.nasa.gov/mission_pages/apollo/apollo11_audio.html)

innovations and adaptations) for constructing more PHWR units at Kalpakkam (Tamil Nadu) and elsewhere in India.

PHWRs are well-known for their neutron economy, contributed to a large extent by the on-power refuelling capability that the design is endowed with. Fuel in the form of half a metre long 'bundles' are placed inside horizontal tubular assemblies called Coolant Channels (Fig. 1).Heavy Water at high pressure and temperature flows through each of these channels, picking up the (heat) energy liberated as a result of nuclear fission in the fuel.

In order to refuel the reactor without shutting it down (that is, to carry out on-power refuelling), it is necessary to gain access to the fuel bundles inside each Coolant Channel. Two remotely operated, automatic, computer controlled Fuelling Machine (FM) Heads, functioning in unison, are used for this purpose. The first FM Head, clamped to one end of a channel, gains access into the Coolant Channel by removing the Canada-invented ,ingenious, self-energised[3] sealing mechanism (called Sealing Plug), and subsequently removing another similar mechanism used as a shield against nuclear radiations streaming axially from the channel (called Shielding Plug). Sealing and Shielding Plugs are identified in Fig. 1, as are the Fuel Bundles. The FM Head at the upstream end, then pushes new fuel into the channel while the second FM Head, clamped to the downstream end of the same channel, after removing identical Sealing and Shielding Plugs at that end, receives the spent fuel. Fuel received in the downstream FM Head is subsequently discharged to the Spent Fuel Storage Bay for safe underwater storage. When refuelling operations on a channel are completed, the FM Heads safely reinstall the Shielding and Sealing Plugs at both ends before unclamping and proceeding to refuel the next channel. All the operations have to be carried out remotely and automatically in order to ensure utmost reliability and safety. The Fuel Handling System comprises of several complex systems and sub-systems involving almost all aspects of engineering, including high precision mechanical engineering, advanced oil and water hydraulics, computer control etc.

Design and safe operation require the Sealing Plugs to be precision engineered and manufactured. A cross section of a typical Sealing Plug (in this case for 540 MWe PHWR at Tarapur 3&4) is shown in Fig. 2. Sealing Plugs for 220 MWe PHWRs are slightly smaller, but utilise the same principle of operation.

The Sealing Plug Assembly, as installed in the End Fitting of the Coolant Channel is shown in the top half of the cross sectional view in Fig. 2. In this condition, it is required to withstand hydrostatic loads acting on the Seal Disc (Item 5 in Fig. 2) which provides sealing against high pressure coolant heavy water. For this purpose, a set of six Jaw Segments are expanded into a groove (with one side of it being conical) in the End Fitting, by pulling the Spider outwards using three telescopic co-axial Rams in the FM Head. To withstand the high hydrostatic force and share the load equally, the Jaw Segments need to

[3]'Self-energising' refers to the capability of the sealing element to automatically generate increasing gasket seating force with increasing pressure of the fluid being sealed, thereby ensuring that when fluid pressure increases, leakage past the sealing surface does not increase.

move uniformly outward. Moreover, the conical surface at the outer periphery of the Jaw Segments (see Fig. 3) should bear uniformly against the conical face of the groove in the End Fitting. To uninstall the Sealing Plug from the End Fitting for refuelling, the FM Head Rams push the Spider inwards to collapse the Jaw segments. Lower half of the cross sectional view of the Sealing Plug Assembly in Fig. 2 shows the Jaw Segments in the collapsed condition. Again, the Jaw Segments must move uniformly inwards, so as to ensure that in the fully retracted condition, none of them are projecting into the groove in the End Fitting and are well inside the outer diametre of the Sealing Plug. Clearly, to achieve uniform, smooth movement of the Jaw Segments and to safely withstand the high forces operating on the Sealing Plug, apart from use of high strength stainless steel material and robust design, they must also be manufactured to high precision.

In order to achieve their uniform and precise movement, each of the six Jaw Segments of a set are provided with a contoured non-circular hole (commonly referred to as a 'slot') comprising of two straight sides, connected at the top and bottom by two concentric circular arcs as shown in Fig. 3.Size of each slot is approximately 13 mm wide by 10 mm high by 18 mm long. It is essential that all the slots are located such that their common pitch circle is concentric with the conical surface at the outer periphery. Furthermore, all the internal surfaces of the slots need to have a smooth finish in order to minimise friction during their movement. Finally, the angle at which the slot (which engages with the 'finger' of the mating component, namely 'Spider' -- see item 3 in Fig. 2) must be identical in all the Jaw Segments. The design envisages that the six Jaw Segments are not interchangeable; that is, all six Segments must stay together during manufacture and assembly. One Segment from a set is not to be interchanged with another of a different set. The Jaw Segments are made of Precipitation Hardened Stainless Steel, as are most of the other parts.

The Shielding Plug is similar in construction to the Sealing Plug, but is smaller in overall diametre and has a set of only three Jaw Segments. Although this article mainly describes certain manufacturing aspects of Jaw Segments of Sealing Plugs, similar requirements and constraints are applicable to Shielding Plugs too.

How the 'necessity' arose:

We started our efforts towards indigenous manufacture of Sealing and Shielding Plugs in early 1970's. Readers may please keep in mind the very limited extent of nascent industrial infrastructure, particularly for precision manufacture, that existed in our country at that time.

Our efforts in indigenous manufacture began with attempts to use the manufacturing process sheets furnished by the Canadian Supplier of Sealing and Shielding Plugs for RAPS-1 as per the requirements of the Purchase Orders placed on him. From the beginning we realised that the manufacture of Jaw Segments could become be a critical path activity. Very soon it became evident that the processes used by the Canadian manufacturer could not be followed in India, because he had used spark erosion technique whereby all six slots were 'sunk' simultaneously using six electrodes moving in unison.

Hectic efforts to locate manufacturers in India having spark erosion machines of the required capacity were not encouraging. Extensive trials undertaken to make prototype pieces, limited only to the slot, just to determine the different spark erosion parameters, were unsuccessful in terms of achieving accuracy and surface finish. Time required to complete even a single slot and electrode wear were other major issues. There was no question of sinking six slots simultaneously as was done in Canada for RAPS-1 because spark erosion machine having the requisite capacity was not available at that time.

Thus, broaching became the selected method for making the contoured non-circular slots. When contacted, the initial reaction of the supplier of special purpose broaches in India (who also had an appropriate broaching machine so that he could be given single point responsibility not only to supply the broaches but also carry out the broaching operations) was: "we have never machined stainless steel nor have we supplied broaches for use with this material". However, they subsequently agreed to work with their foreign collaborators and attempt indigenous manufacture of the required broaches.

Sustained discussions with the broach manufacturer brought to light that their collaborator's effort in the past to manufacture broaches for this application was not very successful since the broaches, even though properly designed and made of the highest quality tool steel available at that time, frequently tended to break during the broaching operation. This, apart from increased cost of tooling and decreased productivity, often additionally resulted in unacceptable damage to the component being broached.

It was this feedback from the broach manufacturer which presented the 'necessity' that led to our 'innovation'.

The 'Eureka!' moment:

Feedback as above was indeed very discouraging. Having failed to develop spark erosion technique, inability to make the slots even by the second alternative, namely broaching, would mean that in order to complete manufacture of Sealing and Shielding Plug assemblies in India, at least the finish machined Jaw Segments need to be imported. This was not found desirable, since, we could be faced with difficult-to-resolve issues due to potential incompatibility with mating components manufactured by a different manufacturer, when the Jaw Segments are finally put together with their other mating parts, to make up the respective Plug Assemblies. The only other alternative appeared to be to import complete Sealing and Shielding Plug Assemblies, manufactured abroad. Not only would this have been a more costly proposition, but would also have meant that remaining machining operations that could otherwise have been carried out in India are actually done abroad. These scenarios would have led to big setback to our resolve to develop indigenous capability to manufacture precision machined components, considering that construction of many more PHWRs to follow RAPS 2 were on the anvil.

We were quite determined to spare no efforts to make a success of indigenous manufacture of the Sealing and Shielding Plugs.

In pursuance of this aim, a detailed analysis to find out the possible reasons why frequent failure of the broaches took place, was undertaken along with the broach manufacturer, who incidentally, was also quite keen to participate in our Nuclear Power Programme. Apart from (a) normal tool wear and (b) mishandling of the broach during use, we felt that there might have been some non-optimal features in the broaching process itself that led to frequent failures experienced by the foreign collaborator.

Some of the requirements dictated by the design and dimensional constraints of the slot are:

(a) As previously described, to get the required dimensional accuracy, the slots for all six Jaw Segments must be made while they are integral as a single 'Jaw Blank'. The Jaw Segments are to be parted from the Jaw Blank only as a final operation after the slots and all other related features have been finish machined.

(b) The broaching tool would be slender and hence a pull-type broaching machine is to be used. No problem here since such a (horizontal) machine of the requisite capacity was available with the broaching manufacturer.

(c) In order to reduce the load on the broach, and to achieve the final surface finish as specified, each slot is to be made using a set of multi-pass broaches, whereby only limited material is removed from the slot surfaces in each pass (See Fig. 3). Also, coolant/lubricant oil to be supplied at the tool-and-job-interface in copious quantity, should be carefully selected, having requisite properties.

(d) In order to enable accurate insertion of the shank of the broach through the component and grip it in the chuck of the broaching machine, precisely located drilled and reamed circular pilot holes need to be pre-machined for each slot.

It is in this requirement (d) above that we located a potential cause for frequent failure of the broaches. Drilling and reaming of the six pilot holes in the Jaw Blank, corresponding to each slot, was being carried out in a vertical drilling/reaming machine using an indexing fixture that would allow successive location of the centre of each of the six holes to be machined, concentric to the spindle of the drilling machine.

On the other hand, broaching of the slots in the Jaw Blank was being made in a different machine (essentially a setup which is distinctly different from that for drilling and reaming) using a different indexing fixture. Even if both the fixtures are made to high accuracy, because they were different from each other, due to tolerance stack-up, indexing operation at the broaching machine may not have positioned the pilot hole at the ideal position with respect to the axis of pull of the broaching machine ram. This misalignment might have caused the broaching tool to bend to an unacceptable extent (even if only small in terms of dimensional errors), resulting in failure of the broaching tool.

Once this issue was identified as a possible cause for frequent broach failure, we suggested to the broach manufacturer that he should design and use a unified ,precision manufactured, indexing fixture that can be mounted on a vertical drilling/reaming machine as well as on a horizontal broaching machine (See Fig. 4).

Agreeing to give it a try, he designed and manufactured such a fixture in addition to a prototype set of multi-pass broaches. Needless to say this effort proved successful, although the special coolant/lubricant used in the broaching operation needed to be imported, as it was not available in India at that time. Tool wear and tear and broach breakages were brought down to acceptable levels.

A similar strategy was adopted for the manufacture of Shielding Plug Jaw Segments too.

Epilogue:

Implementation of the concept of combined Drilling-plus-Broaching Fixture went a long way in enabling us to satisfactorily manufacture Sealing and Shielding Plug Assemblies for the first time in India.

Since then, using this combined fixture concept, a total of nearly 19,000 Jaw Blanks (of Sealing and Shielding Plugs put together) for 14 reactors have been successfully broached.

Of course, there were several other technology-related problems too, not discussed in this article, which needed to be resolved and overcome in economically achieving our goals.

Among many examples, big and small, involved in indigenous technology development of On-power Fuel Handling Systems for PHWRs, is the development of Precipitation Hardening Stainless Steels by MIDHANI which has given us, to a very great extent, independence from having to import this important raw material.

Certainly, technology development is not static. By about 2005, several Indian manufacturers had acquired suitable Spark Erosion/Wire cutting machines. At the present time, slots in the Jaw Segments are spark eroded / wire cut, much as it was done in Canada for RAPS 1.

Acknowledgement:

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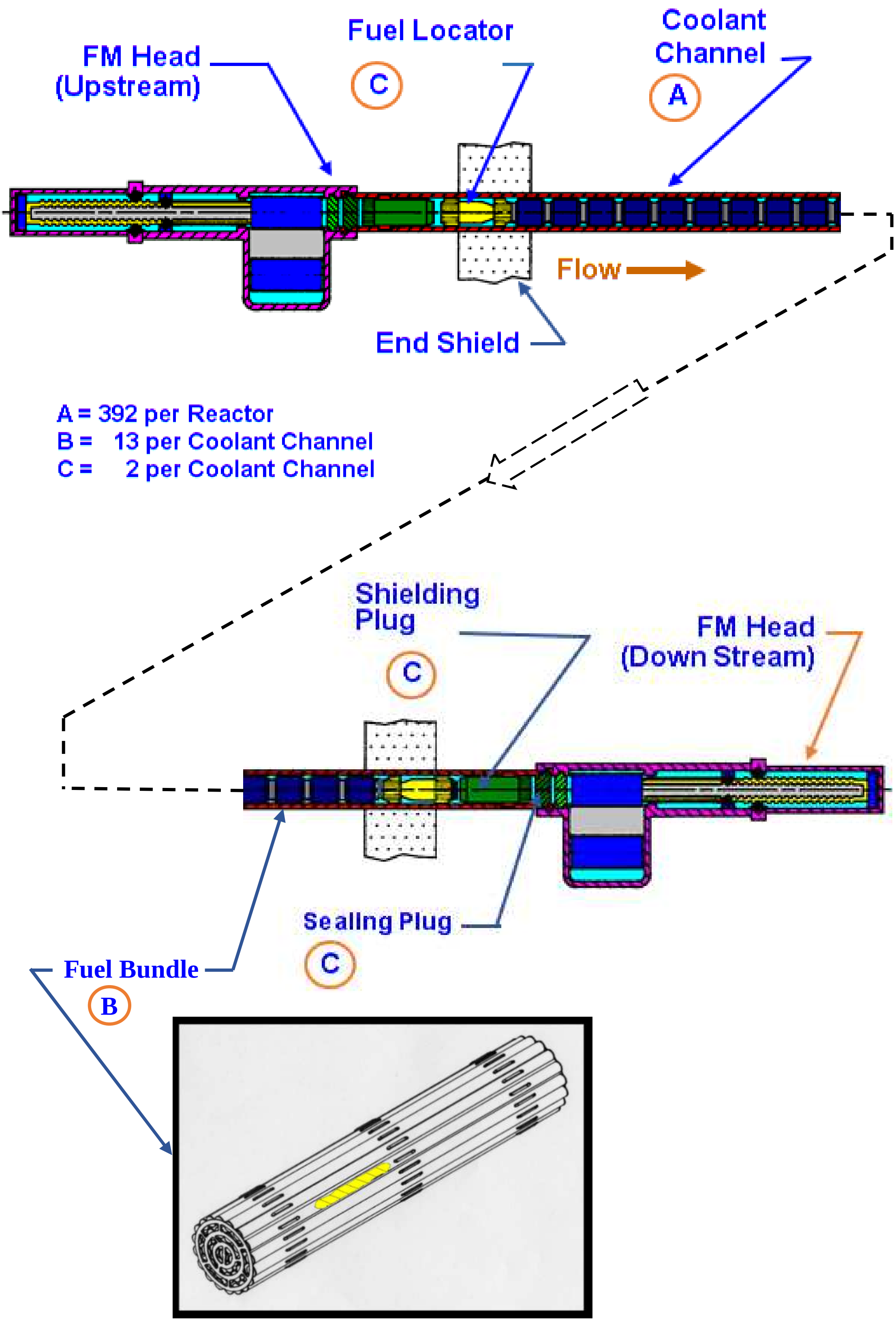


Fig 1 540 MWe PHWR Coolant Channel

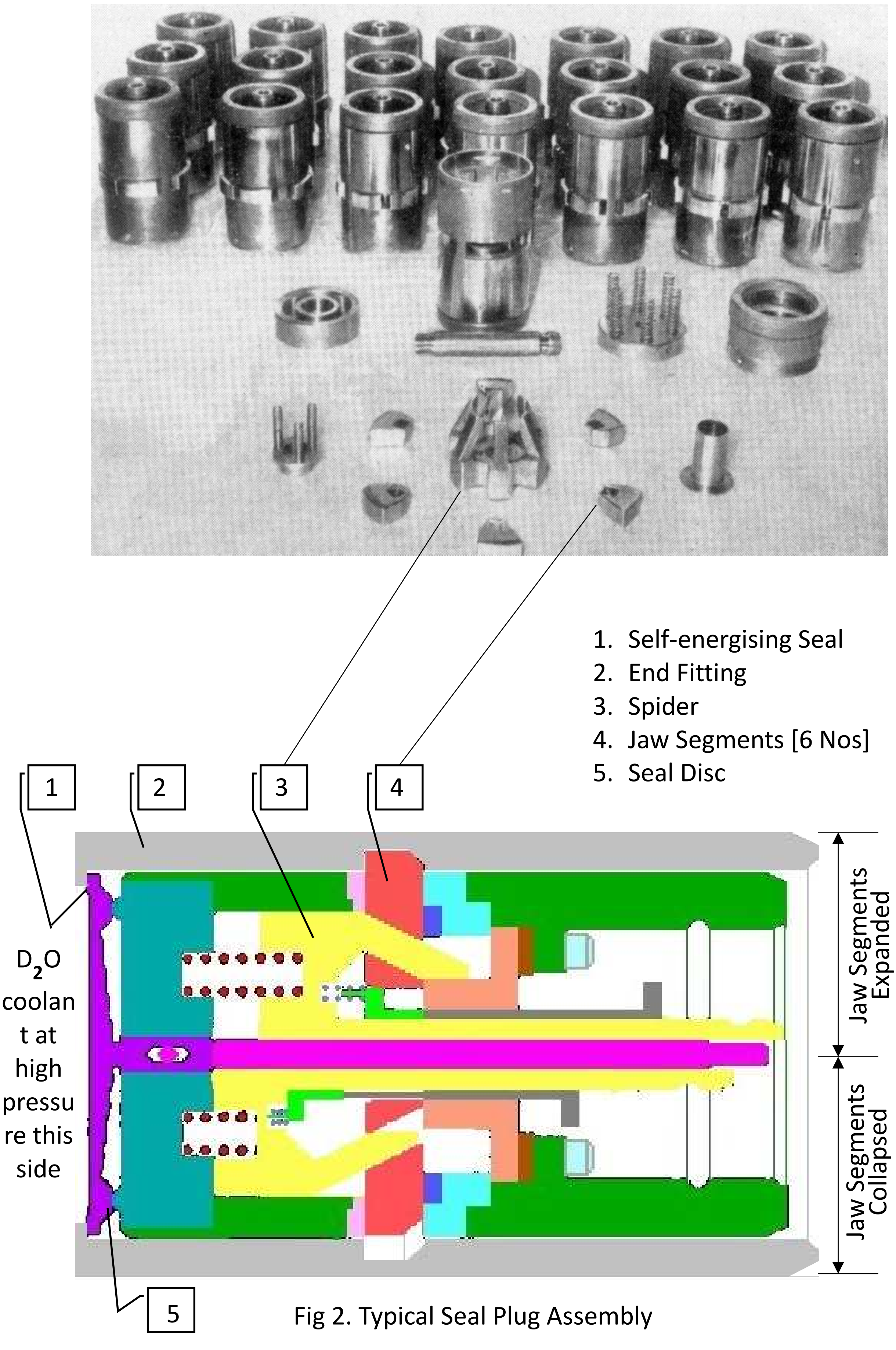


Fig 2. Typical Seal Plug Assembly

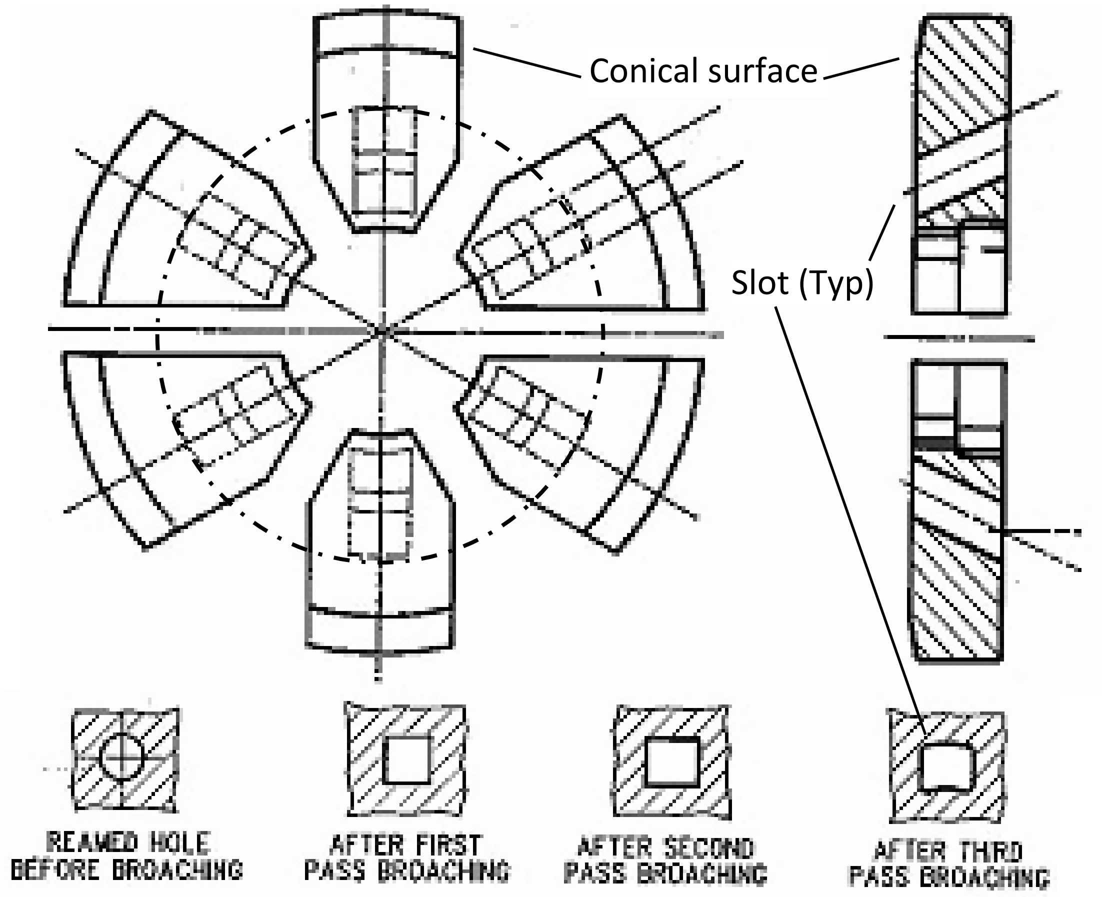
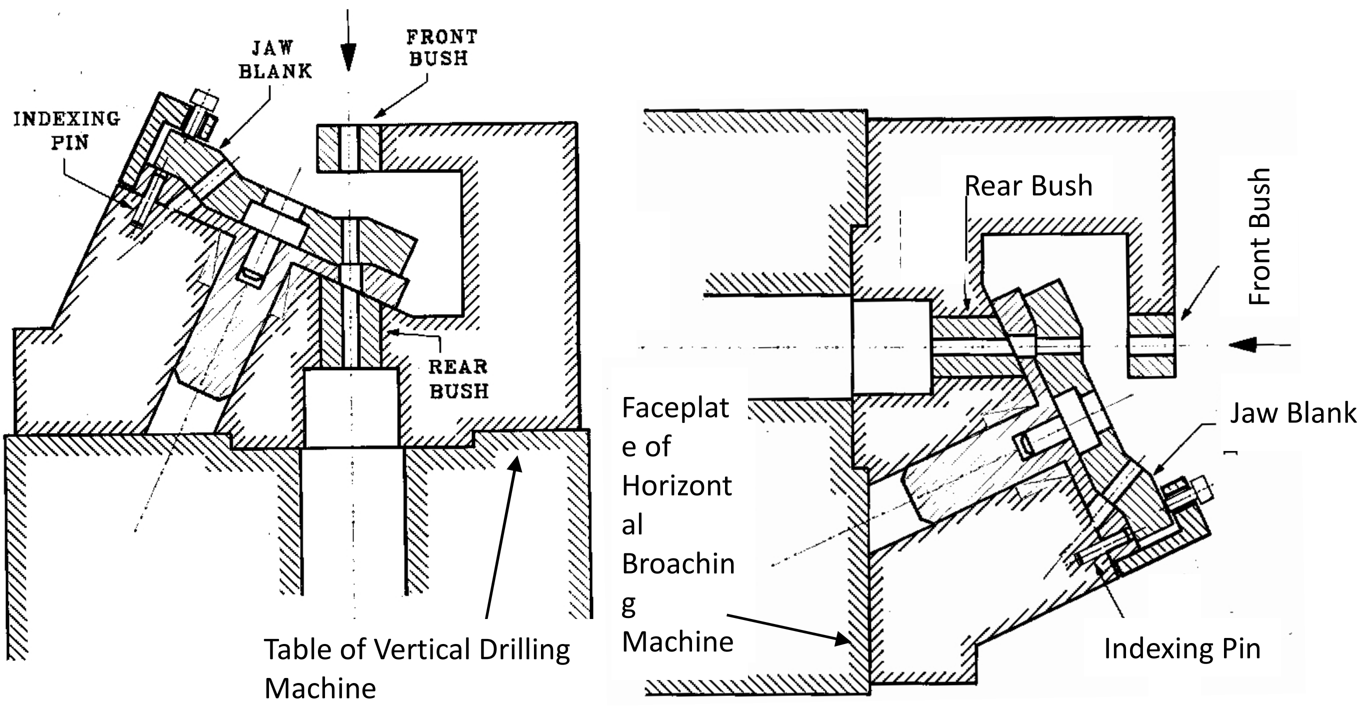


Fig 3. Jaw Segments and Broaching Passes

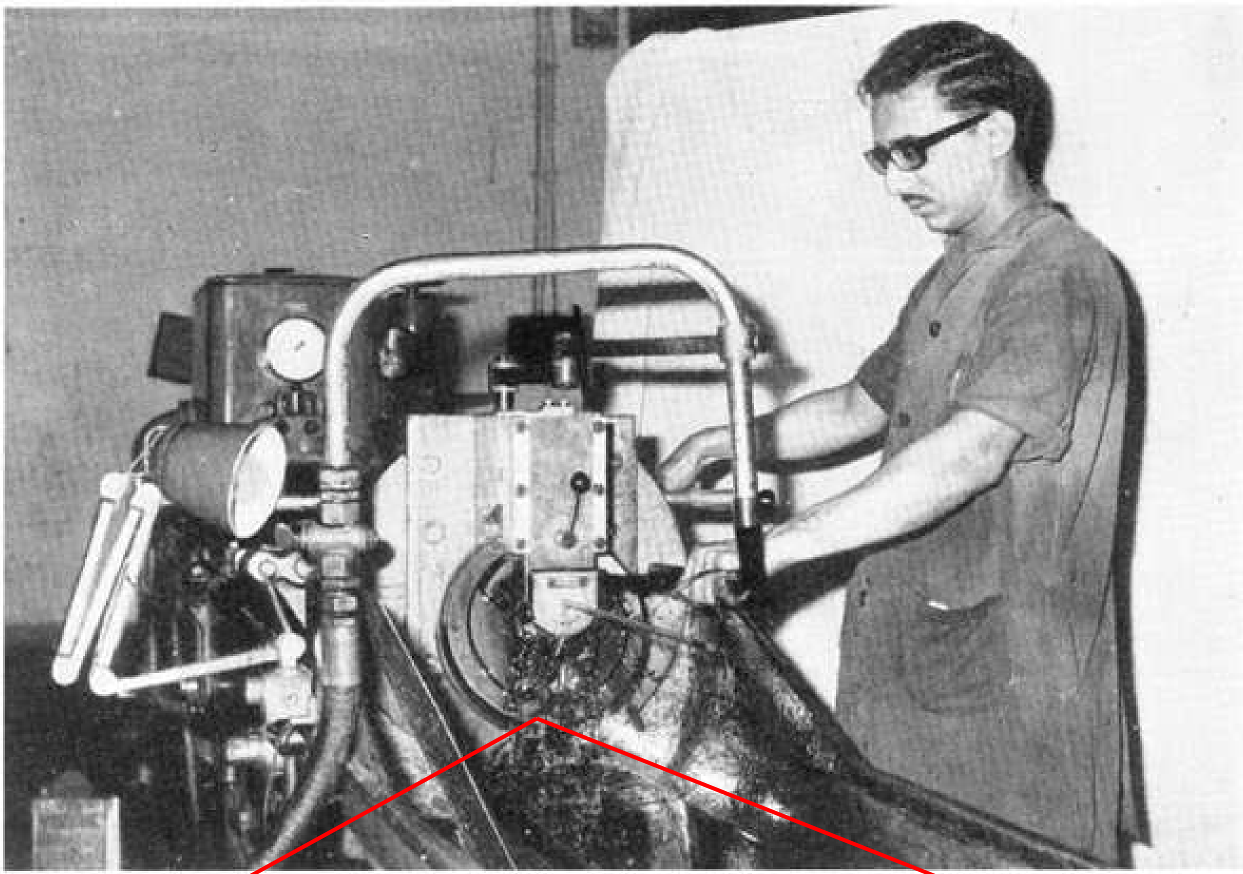


Drilling Configuration

Broaching Configuration

Fig 4. Drilling and Broaching Fixture (Conceptual)

Jaw Segments being broached in Horizontal Broaching Machine



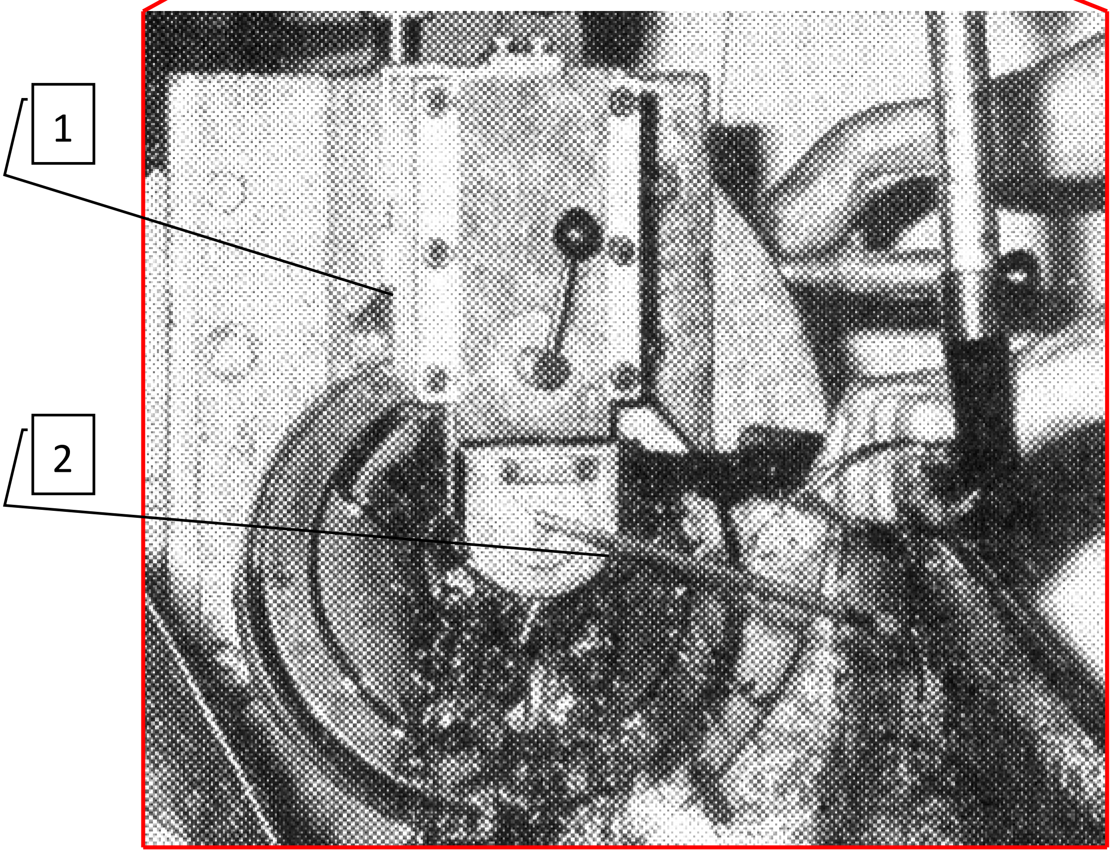


Fig 5. Enlarged View of Fixture [1] and Broach [2]