Articles

Prototype Fast Breeder Reactor

*Fast breeder reactor (FBR) is an important link in India's 3-stage nuclear power programme. Construction of India's first 500 MWe Proto-type FBR is to commence shortly. In this article, **S.B. Bhoje** details its features and the programme.*

Introduction

The present electricity generation capacity in India is 100 GWe. With a population of over one billion and a growing energy demand, India needs about 400 GWe capacity for a modest living standard for its people. This capacity would ensure the present world average electricity consumption of 2000 kWh per person per annum.

The total coal resource in the country is large, estimated to be 200 billion tonnes; but all of it cannot be used for electricity generation alone, as it is required for use as raw material in steel and chemical industries. The use of coal should be curtailed in the long run, in order to limit the emission of green house gases. The coal reserve is adequate to meet the energy demands for about seventy years if used for electricity production on the required scale (400 GWe). The oil and gas resources are less than two billion tonnes of coal equivalent (btce) each. As it is, 75% of current oil requirement is being imported; it cost the exchequer Rs.750 billion, (in 2000-2001). Apart from the high cost, pollution levels would also be such that their contribution to electricity generation may have to be reduced.

Hydel resource is clean and renewable, but is limited to 84 GWe even when fully exploited. At present only 25 GWe of the hydro potential is exploited and further growth is found difficult because of possible damage to environment and rehabitation.

Nuclear reactors based on Pressurized Heavy Water Reactor (PHWR) utilize natural uranium. In this case, only 0.6% of uranium gets used in energy production while in Fast Breeder Reactors the natural uranium utilization increases to over 75%. Thus, the use of uranium in FBR in effect enhances country's nuclear energy resource. If 3,60,000 t of thorium reserves are also considered, nuclear resources increase to 1,000 billion tonne coal equivalent (btce), making it much larger than the combined coal, oil and gas resources. Thus, it is a good strategy to generate energy through coal and nuclear energy, especially with the help of FBR, being the two large energy resources of the country. The adoption of this approach not only provides long term energy security and energy diversity, but also would ensure that the vagaries of the world fuel supply market do not affect the country.

India's uranium resource is estimated at 50,000 t. If this is invested in PHWR, it is possible to install about 12 GWe capacity and operate for 30 years. While by converting the abundant isotope U^{238} in natural uranium to plutonium using FBR, it is possible to install about 250 GWe capacity and operate over a few centuries. Therefore, India needs to develop FBR at the earliest.

Fast Breeder Technology

Fast Breeder Technology is a complex high technology. It uses plutonium as fuel and sodium as coolant. High quality stainless steels are the structural materials chosen because of their good compatibility with sodium and high temperature strength. A high quality of manufacturing with close tolerances also is essential to ensure reliable operation.

The thermal efficiency of the fast reactors is in the range of 40 – 45%, which results in better utilization of the resource, and consequent reduction of radioactive waste and thermal pollution. The radiation exposure to the operating personnel and radioactivity releases to the environment are very low in fast reactors, typically 1-2% of permissible limits. Because of high-energy neutron flux, the FBR can incinerate high level radioactive wastes arising from the reprocessing of spent fuel from thermal or fast reactors. It is one of the best means available for transmutation of long-lived fission products and burning of minor actinides. Therefore, it reduces the long term storage problems of radwaste.

India has already gained valuable experience by constructing and operating since 1985, a 40 MWt Fast Breeder Test Reactor (FBTR) at Indira Gandhi Centre for Atomic Research (IGCAR), Kalpakkam. FBTR is very similar to the French fast reactor, Rapsodie, which was designed during the early sixties and operated successfully during 1967-83. The main differences from Rapsodie are the addition of a steam plant and the use of carbide fuel.

The mixed carbide fuel has operated upto a peak burnup of 88000 MWd/t without any fuel pin failure. Two fuel subassemblies, one at 25,000 MWd/t and another at 50,000 MWd/t were taken out for examination in the hot cells at the radiometallurgical laboratory at IGCAR. The detailed investigations show that the fuel is capable of burnup upto 100,000 MWd/t.

Prototype Fast Breeder Reactor

As a logical follow-up of FBTR, it was decided to build a prototype reactor and a working group, constituted

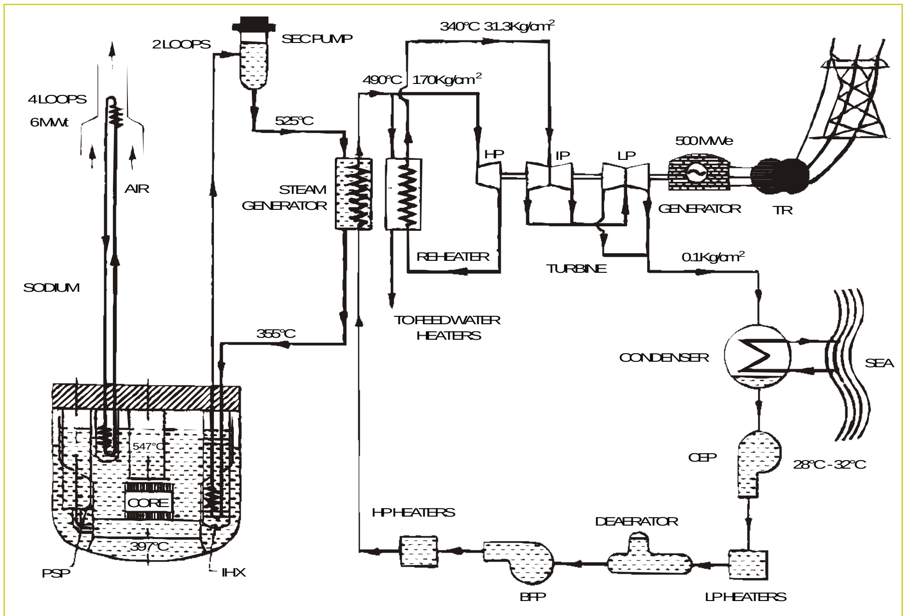


Fig. 1 PFBR Schematic Flow Sheet

for finalising the technical aspects of the prototype reactor including feasibility of indigenous design and construction, recommended a 500 MWe pool type Liquid Metal Fast Breeder Reactor (LMFBR). Detailed design work was taken up at the Indira Gandhi Centre for Atomic Research for 500 MWe Prototype Fast Breeder Reactor (PFBR). A schematic flow sheet of PFBR is shown in Fig 1. As PFBR would be the head of a series of atleast a few reactors, it was thought that cost effective design options have to be incorporated in the design. Design objective of minimising capital cost was pursued along with developing indigenous technology for manufacture of components and developing suppliers of raw materials

The main characteristics of PFBR are given in Table I.

Table I : Main characteristics of the PFBR plant	
Thermal power, MWt	1250
Electric output, MWe	500
Core height, mm	1000
Core Diameter, mm	1900
Fuel	$(Pu\text{-}U)O_2$
Pins per fuel subassembly	217
Fuel pin outer diameter, mm	6.6
Maximum neutron flux, $n/cm^2\text{-}s$	8×10^{15}
Fuel clad material	20% CW D9
Absorber material	enr. B4C
Primary circuit layout	Pool
Primary inlet / outlet temp, K	670 / 820
Steam temperature, K	766
Steam pressure, MPa	16.6
Containment Building	RCC Rectangular
Design Life	40 years.

The main materials of construction are modified, austenitic SS 316 LN and SS 304 LN, except for Steam Generator which uses modified 9 Cr. – 1 Mo (Grade 91) ferritic steel and top shield uses modified carbon steel A 516 Gr 65

The components are much bigger in size than in FBTR. For example main vessel in PFBR is 12.9 m diameter compared to 3 m in FBTR. Design features are different from FBTR in many cases like invessel fuel handling machines, SG etc., Also there is a need to follow the state of art in the manufacture and inspection of critical components to enhance reliability of operations for 40 years. Vertical cross section of reactor assembly is shown in fig 2.

Components like Main Vessel (MV), Safety Vessel (SV), Inner Vessel (IV), Roof Slab etc., can not be transported in a single piece from manufacturer's shop. Therefore, these components have to be manufactured in parts in shop and later on integrated in the site workshop. The dimensional details of some of the nuclear steam supply system (NSSS) components are given in Table- II.

Core consists of fuel, control, blanket, reflector and shielding sub-assemblies. The length of each fuel subassembly is 4.5m. The manufacture of fuel subassembly involves production of vacuum are remelted special SS D9 (15% Cr + 15% Ni + Mo + Si + Ti) forged bars, manufacture of seamless clad tubes of 6.6 mm OD x 0.45 mm wall thickness and hexagonal wrapper tubes of 131.3mm across flats and 3.2 mm wall thickness in 20% cold worked condition to very close tolerances and finally assembly of fuel and blanket pellets inside the clad tube and wrapping of spacer wires around the clad tube and subsequent welding.

Manufacture of MV, IV, SV involves die pressing of large size dished end petals to close profile of 0.2% tolerance on radius and rolled shells to 0.2% tolerance on radius and solution annealing of some of the petals. These vessels have large diameter and thin walls and require development of techniques to carry out dimensional inspection, welding, non-destructive examination of individual petals and complete vessel to maintain the profile of the vessel. Size of the petal is limited by availability of commercial plates (3.5m width, 8 to 10 m length) and press capacity. All welds are ground flush with the base

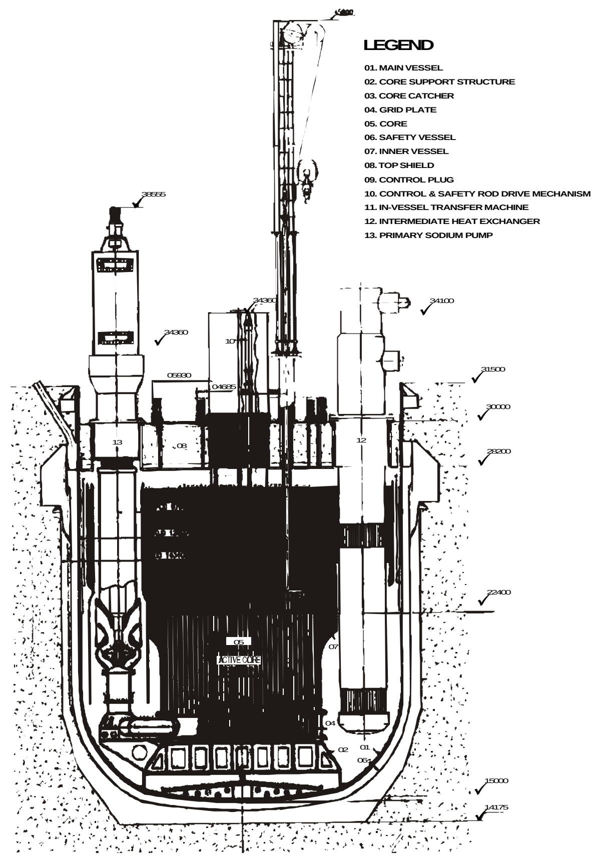


Fig. 2 Reactor Assembly

material or to the required radius and are examined by various NDE techniques and helium leak test under vacuum.

Grid plate is a box type structure with top and bottom plates of 6.8 m diameter and interconnected by sleeves of 1 m height. There are 1758 sleeves screwed on top and bottom plates. The manufacture of grid plate involves welding of thick plates and machining of 6.8 m dia flange to a flatness requirement of 0.05 mm, drilling of large number of holes on top and bottom plate with H7/g6 tolerances within 0.1 mm location tolerance, stress relieving heat treatment of plates for dimensional stability, colomonoy deposit on the plates and its subsequent stress relieving, chrome nitriding on the internal surfaces of sleeves. Technique is to be developed to carryout chrome nitriding on small diameter bores (78.8 mm ID) at a depth of around 400 mm.

Core support structure is a box type structure of 7.8 m dia, 1.8 m height and made from 25/30 mm thick SS 316 LN materials. There are a number of stiffeners and openings.

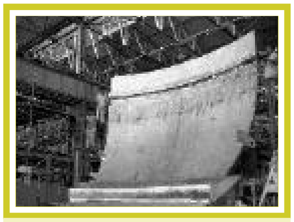
Roof slab is a box type structure filled with concrete. It is also made in sectors in shop floor and then integrated at site workshop before final assembly. The material of construction is special carbon steel to avoid lamellar tearing. Roof slab has a number of radial stiffners and T welds. These welds are highly restrained and also heavy welding is involved. The thickness of plates is limited to 30 mm so as to avoid requirement of post weld heat treatment. Close dimensional tolerances are required on profile in this case also.

The primary sodium pumps are vertical type mechanical, centrifugal pumps with a free sodium level and with inert cover gas and are driven by AC variable speed drive motors. Leak tightness is ensured at the shaft top between the argon cover gas and containment atmosphere by mechanical seals. The pumps are suspended from the reactor roof slab. Components requiring special manufacturing techniques are pump shaft, impeller and diffuser casting and hard faced hydraulic bearing. The pump shaft requires a highly controlled cylindricity during manufacturing, involving process of welding, heat treatment at 1050 deg C under inert atmosphere and final machining. The long shaft of 630 mm dia and 11 m length is dynamically balanced to ISO grade better than G 2.5 to minimize vibrations. The impeller (1850 mm dia), requires high quality stainless steel castings of radiography level II as per ASTM E 448/E 186.

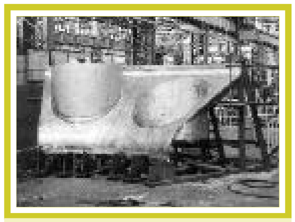
Steam Generator (SG) is one of the critical components of FBR. Even a very small leak of high pressure water/steam into the sodium can start a violent sodium water reaction and affect the plant availability. Manufacture of SG is a challenging task for the Indian industry because of complexity in design and need to ensure failure free operation. SG is a shell and tube type counter current flow heat exchanger with sodium on shell

TABLE - II - NSSS COMPONENTS

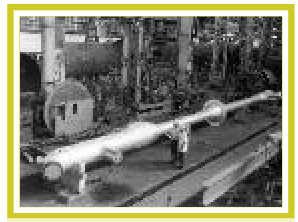
S.No.	Component			
		Diameter (m)	**Height (m)**	**Weight (m)**
1	Main Vessel	12.9	13.2	110
2	Safety Vessel	13.5	13.5	90
3	Inner Vessel	12.2	9.1	50
4	Roof Slab	12.9	1.8	250
5	Core Support structure	7.8	1.9	31
6	Grid Plate	6.8	1.0	80
7	Primary Sodium Pump	2.2	10.5	60
8	Intermediate Heat Exchanger	1.8	16.0	40
9	Steam Generator	1.2	25.0	35
10	Transfer Arm	1.6(width)	24.0	20
11	Inclined Fuel Transfer Machine	5.0(width)	21.5	150



Main Vessel Sector



Inner Vessel Sector



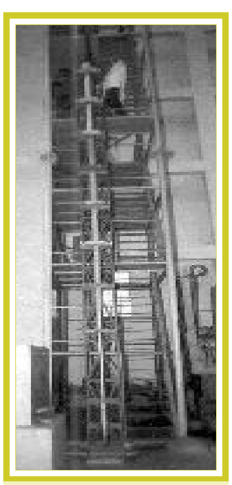
Steam Generator

Roof Slab Sector

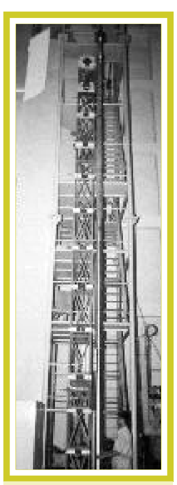
side and water on the tube side. Each tube is of 23 m length (without a weld) and is having a bend to accommodate differential thermal expansion between the tubes and shell and among the tubes. The material of construction is modified 9 Cr-1Mo (Gr 91). Based upon the operating experience of other reactors the type of weld joint chosen for the tube to tubesheet is a bore welded type with a raised spigot.

Each tube to tubesheet weld joint is subjected to 100% X-ray examination from the bore side by using high sensitivity microfocal rod anode X-ray machine. Each joint is subjected to a preheating and post weld heat treatment by using specially designed heaters under inert atmosphere. SG nozzles are not directly welded to stainless steel piping, as bimetallic welds are prone to premature failure due to thermal cycling. A trimetallic joint is chosen with an intermediate alloy 800 piece

The Intermediate Heat Exchanger (IHX) is of shell and tube type. It exchanges heat from radioactive sodium to non- radioactive sodium. The material of construction is SS 316 LN. The tubes of 0.8 mm wall thickness are attached to the tube sheet by rolled and welded joint. The weld with the tube sheet is an autogenous weld. For decay heat removal, there are two type of heat exchangers, i.e. sodium to sodium and sodium to air heat exchanger. The sodium to sodium heat exchanger is similar to IHX while sodium to air heat exchanger is a finned tube heat exchanger. The headers are with pullouts so that it can have a butt joint with the finned tubes.



CSRDM



DSRDM

There are two independent, fast acting, diverse drive mechanisms of absorber rods, called Control & Safety Rod Drive Mechanisms (CSRDM) and Diverse Safety Rod Drive Mechanisms (DSRDM). The mechanisms along with the respective absorber rods operating in fail safe mode ensure high reliability such that the overall non-availability is less than 10^{-6} per reactor year. The mechanisms mainly consists of two parts, viz., upper part and lower part. The lower part is partially immersed in hot pool sodium and the upper part is in Reactor Containment Building (RCB) environment. Height of each mechanism is about 11 m. Twelve mechanism (9 CSRDMs & 3 DSRDMs) are housed within the restricted space available in the control plug. Each mechanism is made up of about 300 machined and standard items that need stringent tolerances and tight quality control. The head of CSR is mechanically coupled with mobile assembly of CSRDM by gripper fingers. Gripper is operated manually from the top of CSRDM at a height of about 11 m. The mobile assembly of CSRDM is held by an electromagnet (EM). Motor drive subassembly rotates the screw in either direction to raise or lower the EM and hence the mobile assembly. On receiving the scram signal, the EM is deenergised and the mobile assembly of CSRDM along with CSR is released to fall under gravity. In case of DSRDM, Electromagnet (EM) at the lower end of the mobile assembly holds the head of DSR. DSR is parked above the core during normal operation and is always within its sheath. Motor drive subassembly rotates the screw in either direction to lower the mobile assembly. On receiving the scram signal, the EM is deenergised and the DSR alone, unlike in CSRDM, is released to fall under gravity.

There are two mechanisms for handling fuel. These are called transfer arm and Inclined fuel transfer machine. Transfer arm handles sub assembly between core positions and invessel transfer positions. All subassemblies are handled vertically under sodium at a depth of about 8 m below the supporting roof slab. Inclined fuel transfer machine is used to transfer sub assembly from reactor assembly to the fuel transfer cell (FTC). All the mechanisms will be tested in air, argon and sodium to validate the design.

Materials Development for Prototype Fast Breeder Reactor

3000 t of stainless steel, 570 t of modified 9Cr-1Mo steel is needed for NSSS of PFBR. These material are required in various forms and shapes, such as plates, tubes, forgings, hollow bars, castings, welding electrodes and filler wires. Plates are required in lengths of 8 m, width 3.5 m to reduce the number of weld joints on the vessels. Tubes for SG are required in a single length of 23 m to minimize the number of welds.

Development of indigenous suppliers of raw materials was taken up. Clad tubes in D9 material with 20% cold work; 23m long steam generator tubes in modified 9 Cr – 1 Mo material: 8m long SS 316 LN tubes of 19mm OD x 0.8mm wall thickness; SG tube sheet forgings in modified 9 Cr – 1 Mo material, SS 316 LN tube sheet forgings required for IHX, Modified 9 Cr – 1 Mo electrodes and filler wires have been developed successfully. Indigenous development of 2 m wide, 8 m long and 30 mm thick plates in SS 316 LN, modified 9 Cr – 1 Mo and CS is in progress along with SS316 LN welding electrodes and 16-8-2 welding filler wires.

Manufacturing Technology Development of PFBR Components

Manufacturing technology development of major nuclear steam supply system components as mentioned above is taken up through the Indian industry. Manufacturing development of fuel, blanket and absorber rod subassemblies, main vessel sector, inner vessel sector, steam generator, control and safety rod drive mechanism, diverse safety rod drive mechanism, Intermediate heat exchanger tube to tube sheet weld has been completed successfully for PFBR. These components meeting stringent manufacturing inspections and testing requirements have been delivered to site. Transfer Arm and roof slab sector are in advanced stage of manufacture. CSRDM and DSRDM and transfer arm will be tested in sodium at 550^{o}C at IGCAR to validate the design.

Future Plan

Construction of PFBR is planned to be taken up in the beginning of 2002 with a construction period of 7 years. After PFBR it is proposed to construct 4 more FBR's of 500 MWe each by the year 2020. It is also proposed to carry out design and development of 1000 MWe FBR

Conclusion

- Indigenous manufacture of PFBR components is a challenging task. Large diameter thin walled stainless steel vessels having large diameter to thickness ratio are to be manufactured with stringent requirements of profile and weld acceptance criteria involving shop manufacture of sectors and their integration at site workshop before final installation. Manufacture of steam generator requires development of high integrity tube to tubesheet welds. Manufacture of CSRDM, DSRDM, Transfer Arm, IFTM requires machining of hollow bars and other parts to very close tolerances.
- Manufacturing technology development for critical nuclear steam supply system components has been carried out successfully through the Indian industries. Suppliers of raw materials have also been developed indigenously. These activities have given sufficient confidence to produce the materials and manufacture the components indigenously for PFBR.
- Techno-economic demonstration of PFBR on industrial scale at the earliest time is a high priority task for DAE and the plant is scheduled for construction in beginning of 2002 to be followed by 4 more breeder reactors of 500 MWe each. Design and development of 1000 MWe fast breeder reactor is also proposed to be taken-up.

Born on April 9, 1942, Mr. S.B. Bhoje did his Bachelor of Mechanical Engineering from the University of Poona in 1965. He joined the 9th Batch of BARC Training School in that year in August. He joined, as Scientific Officer, the Fast Reactor Section of Reactor Engineering Division of BARC for the designing of an experimental fast reactor. During 1969-70 he was deputed to the Centre d' Etudes Nucleare Cadarache, France as a member of the team, under Indo-French collaboration, to design a 40 MW (Thermal) Fast Breeder Test Reactor (FBTR) adopting the design of Rapsodie Fortissimo Reactor. In the year 1970 he became section head of Reactor Assembly of FBTR design group of RED, BARC. Later, he was transferred to Reactor Research Centre, now called Indira Gandhi Centre of Atomic Research Centre (IGCAR), the new R&D wing of the Department of Atomic Energy set-up for the development of FBR technology in India. He continued to head the Reactor Assembly of FBTR design group until 1984. Mr. Bhoje was appointed Member Secretary of 500 MWe Proto-type Fast Breeder Reactor (PFBR) working group appointed by the Government of India for the preparation of preliminary design and feasibility reports. In 1985, Mr. Bhoje became head of the Nuclear Systems Division (NSD) for the conceptual and detailed designing of nuclear systems of the PFBR. In addition to his responsibilities of NSD, Mr. Bhoje, in 1989 was appointed as Head of Reactor Operation Division and Station Superintendent of FBTR to commission it and raise the power with steam generators. He was appointed as Director of the Reactor Group of IGCAR in 1992 with the responsibility of operation of FBTR, and design and detailed engineering PFBR. In August 2000 he became 'Distinguished Scientist' and Director of IGCAR and General Services Organisation on November 1, 2000.

Mr. Bhoje is a member of the International Working Group on Fast Reactor (IWGFR) of IAEA since 1987. He is a Fellow of the Indian National Academy of Engineering and recipient of Vasvik Award for 1992 in the field of mechanical engineering and sciences. He has over 150 papers to his credit on FBRs and related subjects.