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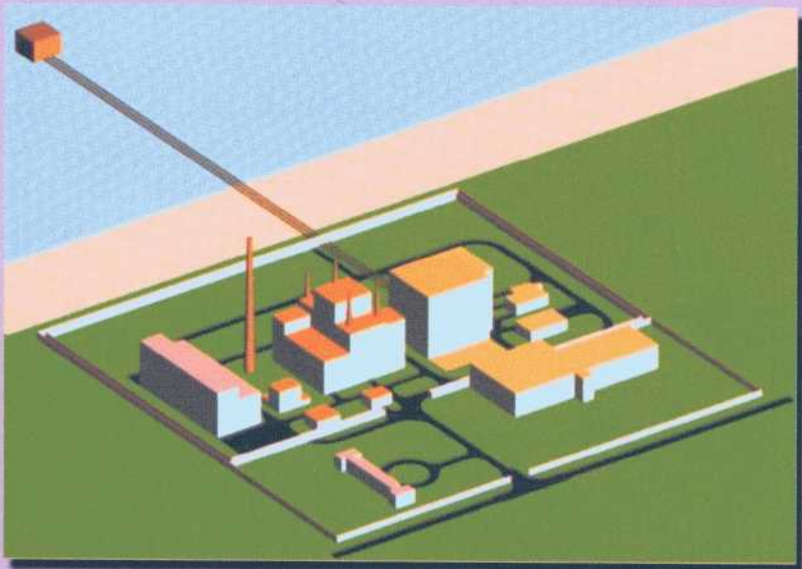
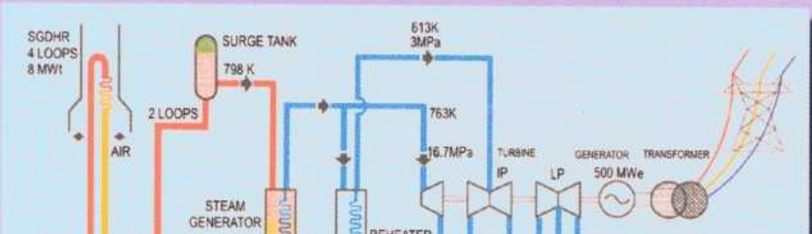
Design of PROTOTYPE FAST BREEDER REACTOR





Indira Gandhi Centre for Atomic Research
Kalpakkam - 603 102
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INDIA'S ENERGY DEMAND

The primary energy resource for electricity generation in India is coal which is adequate to meet the energy demand for about 50-70 years (500 GWe). The potential of other resources like gas, oil, wind, solar and bio-mass is very limited with their attendant problems. The only other viable energy resource is nuclear. India has a moderate uranium reserve (50,000 t) and a large thorium reserve (5,00,000 t). Nuclear energy program in India is being implemented in three stages. Natural uranium fuelled Pressurised Heavy Water Reactors (PHWR) are in operation / under construction in the first stage. The plutonium generated from PHWR will be amplified through breeding in Fast Breeder Reactors (FBR) in the second stage. This will facilitate launching of large scale Th-U233 fuel cycle in the third stage. FBR also utilize natural uranium fuel very effectively (~75 %) through breeding and thus provide a rapid energy growth potential (300 GWe for about 30 y). They also constitute a clean source of power unlike fossil fuel power stations. Several operating FBR worldwide are witness to their environment friendly performance. The use of Thorium in FBR in the third stage makes it a much larger resource (1500 billion tonnes of coal equivalent) than the combined coal, oil and gas resources. Thus FBR provides long term energy security utilizing the indigenous uranium and thorium reserves.

Indira Gandhi Centre for Atomic Research, Kalpakkam is responsible for establishment of fast breeder technology in the country. The commissioning of 40 MWt / 13 MWe Fast Breeder Test Reactor (FBTR) at Kalpakkam in 1985 marked the beginning of FBR programme in India. Synchronization of FBTR with the grid was achieved in July 1997. Considerable operating experience has been gained in the operation of sodium systems and steam water system including steam generators. This has given the confidence to commence the next phase of FBR programme, i.e., construction of Prototype Fast Breeder Reactor (PFBR).

PROTOTYPE FAST BREEDER REACTOR

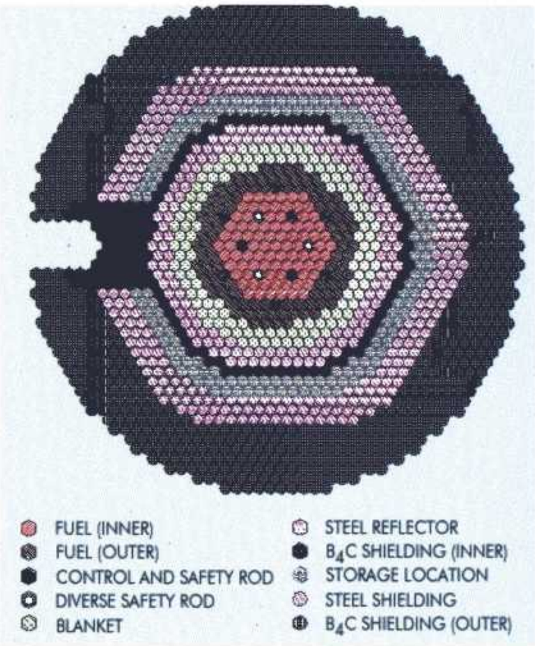
PFBR is a 500 MWe, sodium cooled, pool type, mixed oxide (MOX) fuelled reactor with two secondary loops. The reactor is located at Kalpakkam, close to the 2 x 220 MWe PHWR units of Madras Atomic Power Station (MAPS). Kalpakkam is 68 km south of Chennai on the coast of Bay of Bengal. The primary objective of PFBR is to demonstrate techno-economic viability of fast breeder reactors on an industrial scale. The main characteristics are given in Table. The reactor power is chosen to enable adoption of a standard turbine used in fossil power stations, to have a standardized design with further reduction of capital cost & construction time in future and compatibility with regional grids. Mixed carbide fuel of PuC-UC is used in FBTR due to non-availability of enriched uranium for MOX fuel option. PFBR being a commercial demonstration plant, a proven fuel cycle is essential. MOX fuel is selected on account of its proven capability of safe operation to high burnup, ease of fabrication and proven reprocessing. Pool type concept is adopted due to its inherently high thermal inertia of the large mass of sodium in the pool which eases the removal of decay heat, use of a simple vessel with no penetrations leading to high structural integrity of the vessel and no radiation damage. Two loop design has been adopted which is economical and also meets the safety requirements.

MAIN CHARACTERISTICS

Thermal power, MWt	1250
Electric output, MWe	500
Core height, mm	1000
Core Diameter, mm	1900
Fuel	PuO_2-UO_2
Fuel pin outer diameter, mm	6.6
Pins per fuel subassembly	217
Fuel clad material	20% CW D9
Primary circuit layout	Pool
Primary inlet / outlet temp, K	670 / 820
Steam temperature, K	763
Steam pressure, MPa	16.6
Reactor containment	Rectangular
Plant life, y	40
No of shutdown systems	2
No. of decay heat removal systems	2

Steam cycle selected is steam reheat with integrated steam generator (SG) instead of sodium reheat to simplify the design of SG & associated circuits, based on operating experience of other FBR and for ease of operation. Secondary sodium system and steam water systems are not required to be designed as safety grade systems, since a dedicated safety grade decay heat removal system is provided. The reactor is designed with core sodium outlet temperature of 820 K which is made possible due to use of SS 316 LN as structural material and capability to perform inelastic analysis for creep-fatigue damage assessment. Based on choice of SG material as ASTM Gr 91 (modified 9Cr-1Mo) and optimization studies, the steam parameters at TSV of 16.6 MPa and 763 K have been fixed. The overall cycle efficiency is 40% .

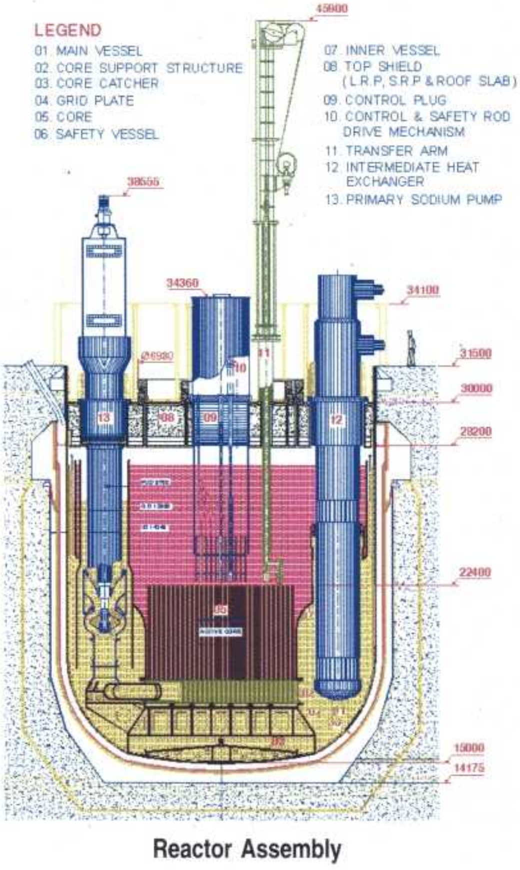
The design takes into account the lessons learnt from the operating experience of other FBR. All the reactor structures, systems and components are classified systematically depending on their safety functions and the requirements under seismic events have also been identified. The safety related and critical components are analysed in detail for all the design basis events (DBE) and it has been demonstrated that the design safety limits are met. The events with a probability of occurrence $\geq 10^{-6}$/ry are considered as DBE. The reactor is designed to meet the regulatory requirements of Atomic Energy Regulatory Board (AERB). The computer codes developed in-house have been validated and approved by the regulatory authority.



Core Configuration

REACTOR CORE

A homogenous core concept with two fissile enrichment zones of 21 / 28 % PuO_2 is adopted for power flattening. The active core where most of the nuclear heat is generated consists of 181 fuel subassemblies (FSA). Each FSA contains 217 helium bonded pins of 6.6 mm diameter with each pin having 1000 mm column of annular MOX fuel pellets and 300 mm each of upper and lower blanket columns. Considering Pu inventory, fuel fabrication cost and breeding, 6.6 mm pin diameter is decided. The clad material used is 20%CW 15Ni-14Cr-2Mo+Si+Ti (D9). The maximum linear power in fuel pin is 450 W/cm and the initial peak fuel burnup is 100 GWd/t, which is targeted to be increased to 200 GWd/t in the long run by use of improved wrapper material. Spent subassemblies are stored for one or two campaigns in internal storage with one third of active core being replaced every fuel handling campaign. Two rows of blanket subassemblies are provided. Twelve absorber rods viz., 9 control and safety rods (CSR) and 3 diverse safety rods (DSR) are arranged in two rings. Two independent and diverse shut down systems are provided for ensuring safe shut down of the reactor even when one system is not available. Both the systems are designed to shutdown the reactor in less than 1 s. In addition, axial shield in the subassemblies and radial shielding subassemblies are optimised in order to have required flux at in-vessel neutron detector locations, to limit the activation of the secondary sodium, to limit the radiation damage of grid plate and helium production in core cover plate.



Reactor Assembly

REACTOR ASSEMBLY

The entire primary sodium circuit consisting of core, primary sodium pumps, intermediate heat exchangers (IHX) and primary pipe connecting the pumps and the grid plate, is contained in a single large diameter vessel called main vessel. The vessel has no penetrations and is welded at the top to the roof slab. The main vessel is cooled by cold sodium to enhance its structural integrity. The core subassemblies are supported on the grid plate, which in turn is supported on the core support structure. A core catcher provided below the core support structure, is designed to take care of melt down of seven subassemblies and prevents the core debris from coming in contact with the main vessel. The main vessel is surrounded by the safety vessel, closely following the shape of the main vessel, with a nominal gap of 300 mm to permit robotic and ultrasonic inspection of the vessels and to keep the sodium level above the inlet windows of the IHX ensuring continued cooling of the core in case of a leak of MV. The interspace between main & safety vessel is inerted with nitrogen.

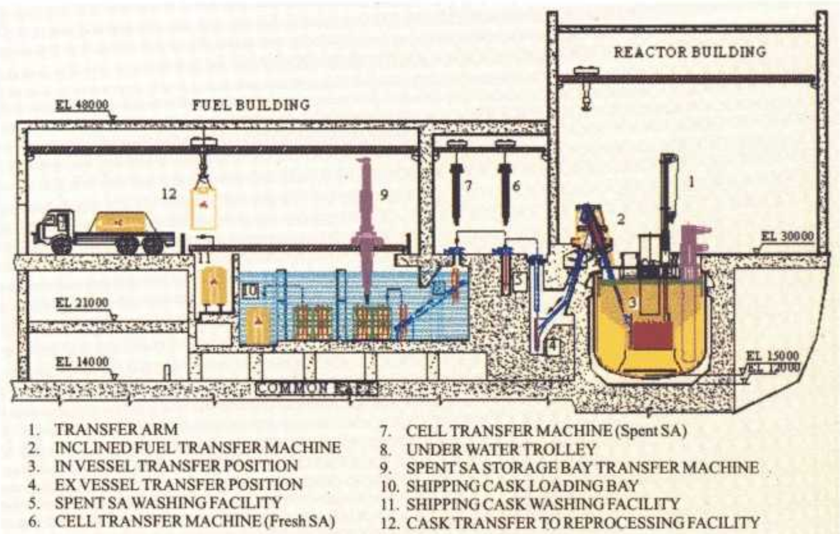
An inner vessel separates the hot and cold pools of sodium. The main vessel is closed at its top by top shield which includes roof slab, large & small rotatable plugs and control plug. The top shield is a box structure made from special carbon steel plates and is filled with heavy density concrete (ρ = 3.5 g/cm^3) which provides thermal and biological shielding in the top axial direction. The principal material of construction is SS 316 LN for the vessels and boiler quality carbon steel for top shield. Biological shielding in the radial and bottom axial direction outside the main vessel is provided by the reactor vault concrete.

MAIN HEAT TRANSPORT SYSTEMS

Liquid sodium at 670 K (397°C) is circulated by two primary sodium pumps through the core and in turn gets heated to 820 K (547°C). The hot primary sodium is radioactive and is not used directly to produce steam, but transfers the heat to secondary sodium through four IHX. The non radioactive secondary sodium is circulated through two independent secondary loops, each having a sodium pump, two IHX and four SG. The choice of 4 SG/loop is based on capital cost and operation with 3 SG in the affected loop in case of a leak in SG. The primary and secondary pumps are vertical, single stage and single suction centrifugal type, with variable speed AC drives and flywheels provided, to meet the flow coast down requirements of 8 s and 4 s respectively. An AC pony motor of 30 kW rating is additionally provided for each of the primary pumps. The SG is a once through integrated type with use of straight tubes and an expansion bend in each tube. Decay heat removal under normal conditions is done using the operation grade decay heat removal system (OGDHRS) of maximum 20 MWt capacity in the steam water system. In case of off-site power failure or non-availability of steam-water system, the decay heat is removed by passive safety grade decay heat removal (SGDHR) circuit consisting of four independent loops. Each SGDHR loop is rated for 8 MW and consists of a dip heat exchanger (DHX) immersed in the hot pool, one sodium/air heat exchanger (AHX), associated sodium piping, tanks and air dampers. Diversity is provided for DHX, AHX and dampers. The circulation of sodium and air is by natural convection.

COMPONENT HANDLING

Fuel handling is done after 185 EFPD with reactor in shutdown condition at a sodium temperature of 473 K. In-vessel handling of core subassemblies is done using two rotatable plugs and a transfer arm. For ex-vessel handling, inclined fuel transfer machine (IFTM) and cell transfer machine are used. Preheated fresh SA are transferred to the core using cell transfer machine and IFTM. The spent FSA are stored inside the main vessel for one campaign and then shifted to spent SA storage bay located in fuel building (FB) which is a demineralised water filled pool. Sodium sticking to SA is washed in spent SA washing facility. Special handling of components like pump, IHX is done using leaktight shielded flasks. The components are decontaminated in a separate facility provided within reactor containment building (RCB), before they are taken for maintenance.



Spent Fuel handling scheme

STEAM WATER SYSTEM

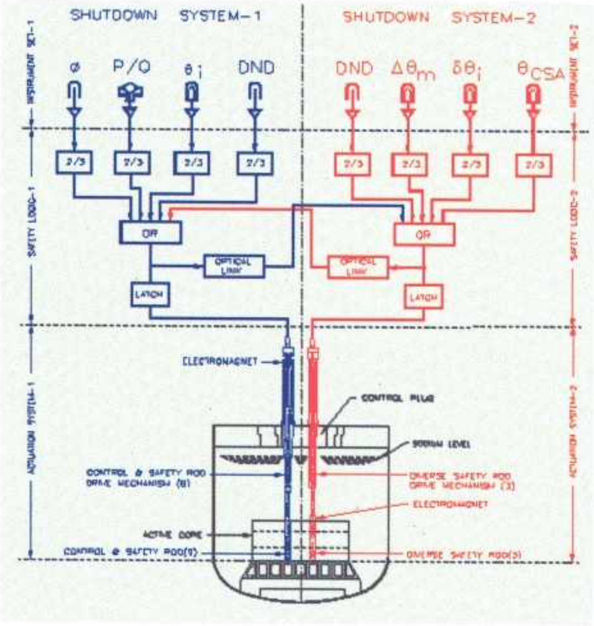
The steam water system adopts a reheat and regenerative cycle using live steam for reheating. High pressure superheated steam from the steam generators drives a turbo alternator of 500 MWe capacity. Three boiler feed pumps, two of them turbo driven, each delivering 50% of the flow and the third one motor driven with 50% capacity are provided to deliver the feedwater to the SG. Feed water heating is done in 6 stages, five in surface type feed water heaters and one in direct contact deaerator. A steam separator is provided at the common outlet of the SG for startup purpose. A turbine bypass of 60% capacity is provided. Condenser cooling is done using sea water in a once through system and the condenser tubes are made of titanium.

ELECTRICAL POWER SYSTEMS

Both off-site and on-site electrical power supply systems are provided. Power is transmitted at 220 kV. The plant is connected to the southern regional grid. A 220 kV substation with five transmission lines and double circuit ties to MAPS 220 kV bus is provided. An indoor switchyard is selected to safeguard and increase the reliability of the electrical equipment against the saline atmosphere. Standby emergency diesel generators (DG) are provided to feed the Class III power supply system. 4 DG sets, each rated to supply 50% of the total emergency power supply demand with a rating of 3 MVA are provided as on-site sources of AC power. Class I no-break 48V & 220 V DC and Class II no-break 240 V, 50 Hz, 1-phase power supplies are provided for instrumentation and control equipment.

INSTRUMENTATION & CONTROL

The reactor power is controlled manually. Burnup compensation of reactivity is very small (22 pcm/d). Six fission chambers with a sensitivity of 1 cps/nv are provided above the core, at the bottom of control plug from safety considerations. Failed fuel detection is done by monitoring of cover gas activity and delayed neutrons in the primary sodium. Three selector valves that select sodium samples from each FSA outlet, are provided for location of failed SA. Two chromel-alumel thermocouples are provided to monitor the temperature of sodium at the outlet of each FSA. Flow delivered by the sodium pumps is measured using eddy current flow meter and safety action is taken on power to flow ratio. These provisions ensure that there are at least two diverse safety parameters to shut down the reactor safely for each DBE. 10 SCRAM parameters from core monitoring systems and heat transport systems are connected to plant protection system to automatically shutdown the reactor in case any parameter crosses the limit. For SG tube leak detection, one 'Hydrogen in sodium' detector (HLD) at the outlet of each SG module and an additional HLD in the common outlet header are provided. Two 'Hydrogen in Argon' detectors are installed in the cover gas space of surge tank. Acoustic leak detectors are also installed at various locations on the outer shell of SG. Crack opening of AHX dampers and sodium flow monitoring ensures poised condition for SGDHR. SGDHR operation is automatic. Separate backup control room and fuel handling control rooms are also provided. Instrumentation directly concerned with reactor safety is designed using hardwired systems except core thermocouples, which are processed by real time computers. Non nuclear systems use state of the art distributed digital control system (DDCS) to take advantage of multiplexed signal transmission and reduced cabling leading to cost savings. Safety signals are also converted to digital form and are connected to DDCS for display in control room. Totally, about 18,000 signals are used to measure various plant parameters.



Shut Down System

PLANT LAYOUT

The plant layout is evolved on the basis of a single unit. The reactor assembly, primary sodium purification, primary argon cover gas system including its tanks & cover gas purification and decontamination facility are housed in a rectangular RCB. Each of the two steam generator buildings (SGB) houses 4 SG and associated components and piping. The RCB, SGB & FB are connected and laid on a common base raft from safety considerations of minimizing differential movement in piping and also to facilitate satisfactory working of IFTM. In addition, control building, two electrical buildings and radwaste building are also laid on the common raft and connected to form a nuclear island, to reduce the magnitude of structural response under seismic loads and length of cables. The elevation of the raft is +12 m for RCB & SGB and +14 m for the other buildings of nuclear island from functional, economic and seismic considerations (Finished floor elevation is + 30 m). A service building is provided to cater to the needs of plant services. The turbine building is located such that the turbine missile trajectory is outside the safety related buildings. The finished floor levels of all safety related structures are above the design basis flood (DBF) level estimated for 1000 y return period. The finished floor levels of non-safety related structures is based on DBF level of 100 y and these structures are located 1.5 m lower than the safety related structures from cost considerations. The diesel generators are housed in two separate safety related buildings. A 100 m tall stack is located close to the radwaste building.

SAFETY

A defense-in-depth philosophy, consisting of three levels of safety, viz., design with adequate safety margin, early detection of abnormal events to prevent accidents and mitigation of consequences of accidents, if any, is adopted. All safety related systems are designed with adequate redundancy, diversity and independence. The engineered safety features include two independent fast acting diverse shutdown systems and decay heat removal systems with passive features of natural circulation of intermediate sodium / air, along with diversity in design of DHX & AHX. Core catcher and containment are provided as defense in depth for beyond design basics events (BDBE). Selection of design features, detailed design analysis and rigorous manufacturing specifications, minimize the risk of sodium leaks from components, piping, & leaks resulting in sodium-water reaction in SG. Nevertheless, provisions have been made for early detection of sodium leaks and sodium-water reaction in SG and safety actions to minimize the consequence of the leaks. Additionally, the design also provides for in-service inspection of the main and safety vessels, secondary sodium piping and SG.

The plant is not designed for aircraft crash as the site meets the screening distance criteria of AERB of 8 km. The probability of aircraft crash is 10^{-15}/ry for the reactor site located at 47 km distance from the nearest Chennai airport. The project site is classified as zone III and there is no capable fault nearby. The plant is designed for safe shutdown earthquake (SSE) and all sodium systems irrespective of safety classification are designed for both operating basis earthquake (OBE) and SSE to avoid sodium fire. All sodium piping inside RCB are provided with double envelope with nitrogen inerting to avoid sodium fire. The structural integrity of primary containment, IHX & DHX is assured under core disruptive accident (CDA), which results in an energy release of 100 MJ, the theoretically assessed upper bound value for energy release. The use of leak before break approach is justified and provisions for leak detection and mitigation in case of a sodium fire are made systematically. A rectangular, single, non-vented, reinforced concrete containment designed for 25 kPa, is provided. The containment is designed such that the dose limits at site boundary for design basis accident is not exceeded under CDA.

R & D

R & D is carried out both in-house in the various laboratories set up at IGCAR and in collaboration with other R&D organizations and industries on reactor fuels, sodium technology, reactor engineering, reactor physics and shielding, component development, materials, non-destructive examination, structural mechanics, thermal hydraulics, instrumentation & control, reprocessing, safety etc. Facilities have been set up to test the prototype components in air, argon and sodium to validate the design of components. A large part of the R & D has already been completed.

SUMMARY

India's energy requirements are large and only nuclear energy through FBR can meet a significant part of the requirements. PFBR has been designed based on FBTR experience. The design is validated by large amount of R & D carried out in various disciplines.

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