Lessons and Strategies from PFBR to Future Fast Breeder Reactors

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Abstract

BHAVINI, a public sector unit under Department of Atomic Energy, is responsible for construction, commissioning and operation of fast reactors in India. Prototype Fast Breeder Reactor (PFBR) which is in advanced stage of commissioning is the forerunner for the second stage of India's three stage nuclear programme. PFBR is a 1250 MWt (500 MWe), MOX fuelled, sodium cooled, pool type fast reactor. It is a first of its kind reactor with total indigenous technology. Starting from civil construction, manufacturing of over-dimensional & precision machined components, installation, integration, till commissioning and operation of all the mechanical, electrical and control & instrumentation systems, there were many challenges and surprises which have been addressed one by one in a systematic manner. The experiences gained during various phases of PFBR project have enriched the scientists and technologists to fine tune the specific aspects in design, sizing of layout, manufacturing & transportation methodologies, sequence of installation and commissioning of the plant and equipment. It is clear that special attention is needed for achieving leak-tightness, making provisions for pre-service and in-service inspections, appropriate routing of power & instrumentation cables and protecting nuclear & process instrumentations. The project management for the future fast breeder reactors, twin units of 2 x 600 MWe will be well established based on the feedback from PFBR. Concept of twin units will be beneficial for both economy and time schedule. The site assembly shop can cater the need for fabrication of individual components of reactor assembly meeting the stringent tolerance limits and their integration at more conducive environment, so that handling and erection of the assembly will be cost effective and time beneficial. Advance planning is required for achieving leak-tightness of integrated assemblies. The well planned sequence of layout of sodium and associated piping, their interfaces with the equipment, provision of redundant heaters, thermocouples, and leak detectors will play key role in project schedule.

This paper details out the experiences gained and lessons learnt from PFBR and the strategies to be adopted for future fast reactors towards safety, economy and time schedule.

Key Words: PFBR, FBR, sodium, BHAVINI

1. Introduction

India's three stage nuclear programme mandates commercial operation of fast breeder reactors at its second stage. In this direction, the country started fast breeder reactor (FBR) programme by constructing a 40 MWt / 13.5 MWe loop type Fast Breeder Test Reactor (FBTR) at Kalpakkam, which is in operation since 1985. This was followed by the design and development of a 500 MWe capacity Prototype Fast Breeder Reactor (PFBR). The construction, commissioning and operation of PFBR has been undertaken by Bharatiya Nabhikiya Vidyut Nigam Limited (BHAVINI), A Government of India Enterprise. Total construction activities and erection of the systems & components have been completed. Commissioning of the individual and integrated systems in nuclear island and balance of plant are in advanced stage of completion. Beyond PFBR, it is planned to construct commercially viable FBRs in the form of twin units. The experiences gained during construction, erection and commissioning of PFBR and the lessons learnt have given vital knowledge and confidence to jumpstart from prototype reactor to commercial FBRs.

2. Description

PFBR is a 500 MWe (1250 MWt) power, (U-Pu) O_2 fuelled, sodium cooled, pool type fast reactor. The plant layout has been developed on the basis of a single unit. The layout has been made taking into consideration of safety requirements, distance for flow of energy, constructability, maintainability, security and economics. The reactor containment building (RCB) is rectangular in shape. The RCB, fuel building (FB) and two steam generator buildings (SGB) are connected and laid on a common raft from safety considerations. In addition, control building, two electrical buildings and rad-waste building are also laid on the common raft and connected to form a nuclear island consisting of nine buildings to reduce the magnitude of structural response under seismic loads. A service building is provided to cater to the needs of plant services. The turbine building is located such that the missile trajectory is outside the safety related buildings and the stack. Four diesel generators provided for Class III emergency power requirements are housed in two separate buildings. The stack, 100 m tall, is located close to the rad-waste building. There is single point entry in the radiation zones. The condenser pump house is located offshore. The switchyard is oriented to suit the power evacuation scheme, based on 220 kV transmission system. The overall view of PFBR is shown in Fig. 1 and flow sheet in Fig. 2.

Fig. 1: Overall View of PFBR

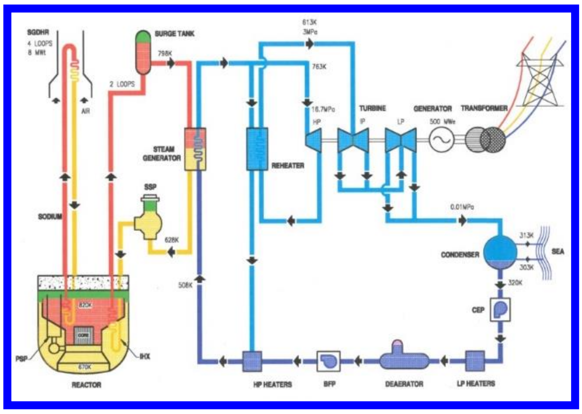

Fig.2: Flow Sheet of PFBR

2.1 Nuclear Steam Supply System (NSSS)

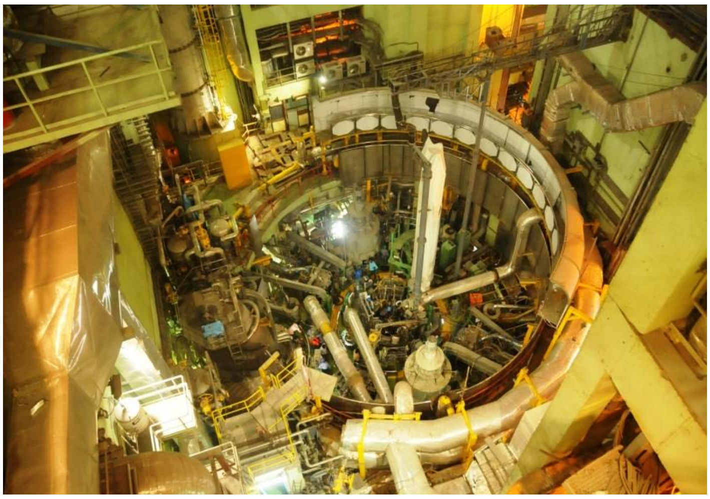

Fig.3 Top view of Reactor Assembly

NSSS consists of reactor assembly at its heart generating thermal energy from nuclear fission reaction at reactor core. The reactor assembly comprises main vessel along with its internals, top shield along with the components supported on it and safety vessel surrounding the main vessel. Heat energy from the core is transferred from the primary sodium loop (contained in the main vessel) to the tertiary steam-water circuit through an intermediate secondary sodium loop. The primary sodium has free surface blanketed with argon. Top view of Reactor Assembly is shown in Fig. 3.

The steam generator is a once through integrated, vertical, counter current shell and tube heat exchanger with provision of expansion bend in each tube. Each SG is provided with tube leak detection system. Rupture discs are provided at the inlet and outlet of each SG to limit the pressure in the IHX from large sodium water reaction. Variable speed AC drives are provided for the two primary and two secondary sodium pumps. Mineral insulated stainless steel sheathed heating elements with extruded cold end are used for preheating the sodium systems. The primary sodium side is preheated using nitrogen gas system. SG tube side preheating is by hot water in the tubes together with electrical heaters on the shell side. Typical sodium circuits are shown in Fig. 4.

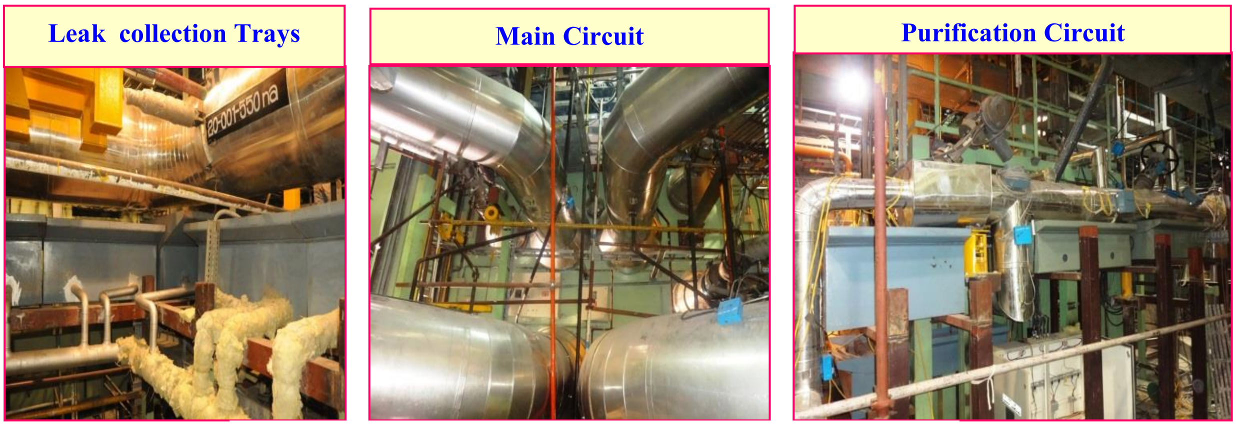

Fig.4 Typical view of Secondary Sodium Circuit

In case of off-site power failure or non-availability of steam-water system, the decay heat is removed by safety grade decay heat removal (SGDHR) circuit consisting of four loops. Each of these loops consists of one sodium/sodium heat exchanger (DHX) immersed in the hot pool, one sodium/air heat exchanger (AHX) located at elevated level, associated sodium piping, tanks and air dampers. The intermediate sodium and air flow are by natural circulation. Each loop can remove 8 MWt when hot pool temperature is 803 K.

The core subassemblies (fuel absorber, blanket, reflector and shielding SA) are handled in shutdown condition of reactor at a sodium temperature of 473 K, using two rotatable plugs and a transfer arm machine for in-vessel handling and inclined fuel transfer machine (IFTM) for ex-vessel handling.

RCB is designed to provide a leak-tight boundary that contains the release of radioactive core fission products from fuel and withstands the pressure resulting from burning of sodium leaked in case of core disruptive accident (CDA), so that dose limits are not exceeded. Single containment, rectangular, non-vented and reinforced concrete construction are the main design features of the containment. During normal operation, the containment is kept under negative pressure. All ventilation ducts opening to the containment atmosphere are automatically isolated by dampers in the event of CDA.

Special instruments are used to monitor neutron flux, sodium process conditions, radiation levels and reactor safety actions. The instrumentation for sodium level, flow, leak detection from capacities and pipelines and for detection of water/steam leak in the steam generators are also very specific to fast reactors. About 30,000 signals are involved in measuring various plant parameters. Where safety is of prime concern, each measurement is triplicated and 2/3 voting logic is employed for initiating safety actions. Diverse instruments are provided for protecting the reactor from any single abnormal event. Redundant sensors are used to improve plant availability. With large amount of instrumentation sensors being deployed, the advantages of digital computer based systems are also leveraged effectively adopting a hybrid of analog and digital technologies depending on its safety class. Distributed Digital Control System on a large scale basis has been deployed. Three level architecture has been adopted for the process control and instrumentation viz., field level, Local Control Center level and Main Control Room.

2.2 Balance of Plant

The steam-water system adopts the standard turbine that is used in fossil fired thermal power stations of the same rating. The turbine is of tandem compound design with separate HP, IP and LP cylinders. Turbine generator assembly view is shown in Fig. 5. To remove the heat rejected from the steam cycle in the condenser, a once-through condenser cooling water system is employed using sea water. The generator is directly coupled to the turbine.

Fig. 5: Turbine Generator

Electrical Power System is a source of power for the reactor coolant pumps and other auxiliaries during normal conditions and for the protection & engineered safety systems during normal & accident conditions. Both off-site and on-site electrical power supply systems are provided. An indoor switchyard is provided to increase the reliability of the electrical equipment against the saline atmosphere.

The plant is equipped with the auxiliary systems for nitrogen supply, argon supply, service water, biological shield cooling, fire-water and sodium-fire protection.

3. Experiences during Construction

Reactor components were successfully manufactured and installed at PFBR site. Various industries were involved in the manufacture of the components of reactor assembly. The major components of reactor assemblies can be categorized based on their functions and configurations as shown in the following table.

Category	Components
Large size thin shell structures	Main vessel Safety vessel Inner vessel Thermal baffle
Large size box type structures	Top shield (Roof slab, rotatable plugs) Core support structure
Large dia. precision machined components	Grid plate Control plug
Long thin slender components	Absorber rod drive mechanisms
Long drawn tubular components	Core subassemblies
Coolant circulation & Heat Transport components	Primary sodium pumps Intermediate Heat Exchangers

The complexities and challenges in manufacture, handling and erection are specific to characteristic features of these categories. Owing to first of its kind, several challenges / issues were faced during manufacture of these components. The issues were discussed and solved by the taskforces comprising of designers, construction team and quality assurance team along with the concerned industries. They were broadly categorized into four groups:

1. Deviations in chemical composition and mechanical properties of raw materials
2. Constrains and difficulties related to forming and machining processes
3. Welding electrodes, qualification of welding process, quality of production welds and distortion control
4. Respecting the dimensional and geometrical tolerances.

Systematic approach was followed in resolving each of the above issues. It was observed that the deviations need to be tackled w.r.t. its implications on safety intended functions and life / availability of the components. Certain design changes were also necessitated based on the feedback from the industries.

The rich experience gained is a valuable input for design improvements in future FBRs. It will ease the manufacturing process and help in proper planning and meeting the project schedule.

Handling and transportation of gigantic and slender components such as main vessel, safety vessel, grid plate, steam generators, IHX, AHX, tanks, posed many challenges at site. Each one is unique in its design & configuration and hence component specific procedure suitable for safe handling and erection at site is a must. Therefore many new and innovative methods, procedures and tools were evolved and implemented at site. The experiences during manufacture, handling and erection of large sized reactor components are elaborated separately [2, 3]. The methodologies adopted during manufacture, testing and qualification of shielded flasks to be used for handling the large sized components such as pump, IHX, etc. within the constrained space over reactor top are presented in [4].

The interfaces between the top shield and the components that will be erected at later date and the airlocks of the handling flasks were checked to ensure that there would be no surprises during actual requirement.

Challenges during construction of sodium piping systems are discussed in [5]. The experiences during construction & commissioning of Electrical power generation and evacuation systems are detailed in [6].

4. Commissioning Activities

All the auxiliary systems have been commissioned and are in operation. This includes the electrical systems, emergency diesel generators, additional diesel generators (due to post Fukushima upgradation), cooling water systems, ventilation system, compressed air system etc. Commissioning of primary & secondary sodium circuits is in progress as per the programme approved by the regulatory body. Initial Test programme (ITP) has been formulated with the concurrence of the regulatory body and is being followed during each stage of commissioning. Training & qualification of personnel in sodium system operation and sodium fire-fighting have been done. The fuel handling equipment, i.e., Inclined Fuel Transfer Machine (IFTM – to facilitate movement of fuel from reactor vessel to outside the vessel and vice versa) and Transfer Arm (for in-vessel handling of core subassemblies) have been commissioned along with the rotatable plugs and handling of dummy subassemblies (with and without bowing) has been demonstrated. Absorber rod drive mechanisms along dummy absorber rods have been testes as per ITP. Leak-tightness of the integrated reactor assembly along with inter-seal argon supply has been ensured. Signals from the field instrumentations are available at control room.

Integrated leak rate testing and proof testing of Reactor Containment Building have been completed, involving all the relevant agencies and utilizing large number of man-power in a systematic pre-planned manner.

5. Experiences & Lessons Learnt from PFBR to Future FBR

5.1 Civil Construction

- Post Tsunami (26th Dec 2004), design of PFBR has been given a complete relook on all the aspects and several modifications were taken up. Several design safety features were added to the plant to make the plant safer for an expected Tsunami. Shore protection which otherwise was looked at the security perspective view has gained additional importance. The agents for mitigation of impact of Tsunami waves are vegetation, artificial bund, RCC protection wall etc. In the case of future FBRs, before start of excavation for main plant, tsunami bund and wall shall be constructed, so that PFBR like situation, in case of tsunami, will not arise.
- The RCB walls should have corridor for accessibility at both inside and outside. Soffit of the roof shall be made accessible by providing permanent platforms. They should be free from structural supports and have optimum penetrations with minimum size of openings. Vertical construction joints should be avoided in the walls. Minimum embedded parts (EP) should be provided on the wall and there should be no post construction drilling for providing anchors of various supports. If required, supports should be taken from the floor.
- The finished floor level (FFL) of main plant was raised by 2.5 m, whereas the site assembly shop which is basically a facility for fabrication and integration of major large size components such as main vessel, safety vessel, inner vessel, roof slab etc. remained 2.5 m below the FFL of main plant. This has caused problem in shipment of major fabricated items. Hence in future plants, the FFL of main plant and site assembly shop will remain same.
- The openings and doors in the buildings should be sufficient enough to facilitate trouble-free movement of equipment during construction and operation. Their sizes should commensurate with the size of the equipment housed, as well as the equipment which needs to be replaced or drawn out for maintenance during reactor operation. Few openings were required to be modified post construction of civil building. This will be envisaged in civil design lay out of future FBR.
- As-built foundation and support arrangements details from civil construction have to be scrupulously passed on to the component manufacturers during fabrication of component to facilitate proper alignment and erection at site. Moreover, instead of foundation anchor bolts, Embedded Parts (EP) are to be encouraged for supporting the components to have extra space in vertical direction during erection and to avoid problems related to misaligned foundation bolts.
- Finish level flooring has to be carried out after ensuring sufficient number of construction EPs including mechanical anchor fasteners are installed at site.

- In SGDHR enclosure, out of four walls, only the wall at containment side is reinforced for load bearing. This has caused transfer of pipe loads, cable tray loads, supports of leak collection trays etc. only over one side and created congestion in the layout and hence maintenance of the system difficult.
- The design should be such that all concrete works shall be completed around reactor vault area before starting erection of nuclear components.
- As far as possible, open top construction should be avoided for safety reasons.
- Excavations for main plant buildings and construction upto ground level should be taken up simultaneously to avoid slope stability issues and long period dewatering.

5.2 Plant Layout

- In many of the auxiliary systems the size of equipment is substantial and they are to be accommodated in a relatively smaller spaces / rooms. This had resulted in reduction of working space around the equipment. The civil building drawing is to be finalized considering the size of the standardized equipment rather than a least dimension of a particular manufacturer / brand. Due consideration for approach during maintenance and working space around the equipment has to be made while designing the layout.
- Large movement of materials at job site might cause unexpected damages. When the materials are delivered at job site, they have to be unloaded and arranged close to the designated erection point and near to the lifting position adjacent to the erection area. This will facilitate effective sorting and delivery during erection.
- Considering the number of equipment, pipelines and cables mounted on the top shield, it is imperative that operable / maintainable layout of equipment over top shield is very much essential.
- Steam generator buildings are to be provided with suitable handling arrangements like crane / full travel hoist to facilitate erection of surge tanks, expansion tanks, steam generators and large diameter piping more conveniently.
- Platforms and access ways are to be part of initial design itself to respect seismic criteria and to have ergonomic layout.
- Virtual proto-type of the entire plant is to be made available during design stage itself to optimize the layout and to avoid interface / interference issues.

5.3 NSSS

- The manufacturing schedule for the components shall match with the construction schedule to reduce long storage and preservation of the components at site till the availability of erection work front and also to avoid delay in erection due to non-availability of the components. During fabrication and integration of reactor assembly components inside the site assembly shop, in parallel reactor vault and safety vessel should be made ready. This will reduce the project time.
- The large sized components from manufacturer’s shop are to be transported through barge, else they have to be manufactured at site itself to reduce the constraints in transportation. Subassemblies of the large sized components can be transported from the manufacturer’s shop without difficulties.

- Stand pipes for IHXs and pumps on inner vessel are to be located and welded after integration of roof slab with main vessel.
- In-situ machining of roof slab penetrations will reduce the requirement of annular gap between the component and penetration and hence, requirement of complementary shielding can be substantially reduced.
- Leak search and achieving leak-tightness of reactor assembly were highly challenging due to the presence of heavy complementary shielding and other site related constraints. Hence, the complementary shielding over the components is to be installed just prior to pre-heating.
- Piping shall be erected and measured with global co-ordinate systems in addition to isometric and plot plan to have better clarity and dimensional accuracy and also to facilitate easy as-built analysis and qualification of the system.
- Pipe-in-pipe concept for secondary piping will totally avoid the requirement of leak collection trays and supports which occupy huge space and cause permanent hindrance for erection of bottom mounted supports and also general maintenance activities.
- External works such as fixing of heaters, thermocouples and leak detectors on the large dimensional sodium tanks and components are to be carried out at site, instead of manufacturer shop, so that transportation time and cost will be reduced, as the components can be transported at comfortable position / orientation.
- Optimization is needed with respect to pipe sizing, snubbers and supports.
- Pipes exposed to open atmosphere such as in SGDHR system are to be insulated at the earliest to avoid corrosion.
- Sequential heating is to be ensured for sodium pipelines by providing all the heaters powered in parallel.
- All the cells have shielding doors and sealing criterion is specified for these doors. Shielding and sealing are to be segregated to achieve both the function without much difficulty.
- In addition to SS lined floor, wall and ceiling in FTC are also to be SS lined to improve leak-tightness.
- Cell Transfer Machine is to be floor mounted to facilitate easy maintenance.
- Sensors in under water trolley are to be approachable for ease of maintenance.
- In all the cells, power and signal cables are to be routed through Electrical Penetration Assemblies (EPA).
- De-mineralized water plant has to be commissioned in advance at construction phase itself to cater to the needs of hydro testing of the site fabricated components.

5.4 Control & Instrumentation System

- In view of large number of leak detectors and thermocouples mounted all along the sodium pipe lines, special effort has to be put for physical protection of field instrumentation against damage. In order to avoid huge quantity of cabling work involved in connecting the signals to data acquisition system for monitoring and control purpose, it is preferable to use wireless sensors connected to network, wherever possible.

- Since rectification works in wire type leak detectors necessitate complete removal of insulation and other associated heaters and thermocouples from the pipe lines, spurious actuation of leak signals has to be avoided by appropriate protection methodology around the pipe line.

- Since relay based panels for safety auxiliary systems occupy more space and hence difficulty in maintenance, PLC based systems which are qualified for safety applications in nuclear plants have to be considered.

- Layout of Local Control Centre rooms should have adequate space for trouble shooting.

- Each fuel subassembly temperature may be monitored by three thermocouples instead of two thermocouples forming three channels. This will take care of single failure criteria and improved plant availability.

5.5 Auxiliary Systems

- The Induced Draft Cooling Tower (IDCT) is located on the terrace of Service Water Pump House. This cooling tower needs to be qualified for wind speed of 306 km/h. Due to its height, difficulties were faced to meet the requirement. This has hampered meeting the design holdup of water in the sump. Hence for future FBRs, the IDCT will be at ground level. The water pumps of cooling towers are to be housed in an enclosed structure.
- In fuel building, liquid nitrogen plant which works on sterling cycle, brings down the temperature of nitrogen to the range of -196^{o}C. The chillers have outdoor condensing unit. The location of the nitrogen plant is at the middle of several peripheral rooms. The outdoor unit has to be kept in the plant vicinity itself, otherwise it will increase the load on the ventilation system. In the future reactor, the layout has to be such that the liquid nitrogen plant is in the periphery to facilitate the outdoor unit.
- The crane capacity at the site assembly shop was determined by the weight of the equipment being fabricated. However, it has to be derived based on the maximum anticipated weight (with sufficient margins) of the components, including the components which may be stored temporarily.
- Centrifugal blowers are deployed in top shield cooling circuit. The same blowers are used for recirculation of nitrogen in pre-heating circuit of reactor assembly, since the preheating circuit is essentially a one-time requirement prior to sodium filling. During pre-heating, no cooling arrangement is available for top shield which has many penetrations with elastomeric seals. Hence cautious sequence of operation is followed, so that temperature of the top shield does not exceed the limit. It would be easy to control and maintain the temperature of main vessel internals and the top shield as per requirements, if independent blowers are used for pre-heating circuit and top shield cooling circuit. This will be considered in the future FBR design.

5.6 Electrical Systems

- The SF_6 bus duct connecting Gas Insulated Switchyard to common gantry (installed at outdoor which is air insulated) should not be exposed to direct sea to avoid corrosion of structures / bus duct. The gantry structure for each outgoing double circuit lines should have physical independency.
- Adequate measures have to be taken to avoid electro-magnetic interferences on the variable speed drive system panels pertaining to primary and secondary sodium pumps.

- The Deluge valve station room for Mulsifier system protection of Generator Transformer / Unit Auxiliary Transformer / Station Unit Transformer is to be located away from the transformer and to have a covered roof top.
- To avoid fire inventory in the electrical panel room, cable tray routing should not pass through the electrical equipment room. Wherever unavoidable, elevations of cable tray should be well above the panel height.
- The fire doors provided for the electrical equipment room should be of double compartment type with a provision to dismantle top portion to facilitate shifting of panels into the room.
- Ventilation ducts of adequate capacity for inlet supply air and exhaust air should be provided for all the electrical rooms to avoid increase of ambient temperature and thereby to protect the PLC based Switchgear interface panels and Heater Isolation transformers.
- Independent verification and validation of the programmable / computer based system panels has to be completed at factory itself.

6. Conclusion

The experiences gained during construction, erection and commissioning of PFBR systems / components are quite enriching and have taught many valuables lessons towards safe, economic and timely construction and commissioning of future FBRs. Cautious steps are being taken towards sodium filling, fuel loading and approaching first criticality.

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