RADIATION PROTECTION: ROLE OF DESIGN IN 500 MWE PROTOTYPE FAST BREEDER REACTOR (PFBR)

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ABSTRACT
The ionizing radiation exposure to the occupational worker and radioactive release to the environment are very low in fast breeder reactors compared to the permissible limits prescribed by the regulatory authority. Radiation protection procedures have been developed with a view to minimise the occupational risk for the working environment and controlling the release of radioactivity to the external environment too. The threshold value of release of radioactivity to the environment and the general public will be of lesser magnitude compared to the occupational exposure that is permitted by Atomic Energy Regulatory Board (AERB) for a plant worker. The paper brings out the details of sources of radio activity in PFBR during operation phase, zoning and shielding concepts, dosimetry and the radiation protection procedures that will be followed in PFBR.

Key words: Occupational Exposure, Occupational Risk, Ionizing Radiation, Zoning and Shielding Concept, Dosimetry
1. INTRODUCTION

The 500 MWe Prototype Fast Breeder Reactor (PFBR) which is presently under construction at Kalpakkam is a pool type reactor that uses Uranium Oxide (UO$_2$) and Plutonium Oxide (PuO$_2$) as MOX fuel and Sodium as coolant. Argon is used as cover gas. The layout of the reactor building is divided into Nuclear Island Connected Building (NICB) and the Power Island (PI). The Reactor Containment Building (RCB) is rectangular in shape. The RCB, Fuel Building (FB) and two Steam Generator Buildings (SGB), two Electrical Buildings (EB), Radioactive Waste Building (RWB) and Control Building (CB) are connected and laid on a common raft. The buildings are laid on the common raft to reduce the magnitude of structural response under seismic loads. This also provides economic advantage. The power Island consists of Turbine Building and associated buildings.

The Prototype Fast Breeder Reactor (PFBR) uses the large size components with stringent quality requirements which have been never experienced in the past in our country. The manufacture of the equipment was taken up at Kalpakkam in the Site Assembly Shop (SAS) of PFBR which is closely located to NICB. This has helped in avoiding the risk of damage during transport of equipment, associated time delay, quality check at every stage of manufacturing etc.,

For discharge of gaseous effluents from the plant around 100m high stack is constructed. The stack is located near to the Rad Waste Building (RWB) to reduce lengths of exhaust ducts.

2. RADIOLOGICAL SAFETY ASPECTS CONSIDERED DURING DESIGN OF PFBR

The fundamental safety objective in the design and operation of Nuclear Power Plant (NPP) is protection of occupational workers, members of the public and environment from undue radiological hazard. In order to achieve this objective, a lot of measures such as adequate radiation shielding, suitable plant layout ensuring stringent access control and appropriate radiation protection procedures for radiological surveillance are provided.

As per ALARA (As Low As Reasonably Achievable) principle, efforts have been made to minimize radiation exposure wherever possible by appropriate design and shielding. It has been noted that in earlier fast breeder reactors maximum radiation exposure occurred during repair and maintenance activities.

It is indicated that the activation of cobalt based alloys used as hard facing material resulted in high dose rates during handling, maintenance and decommissioning of vintage nuclear reactors. The systematic study has been carried out to assess the possibility of replacing cobalt based alloy-stellite as hard facing materials in Prototype Fast Breeder Reactor. Colmonoy has been used as hard facing material in PFBR to avoid menace due to Cobalt-60 (Co-60) activity.

It has also been observed that significant collective dose arise due to surveillance activities during reactor operation. The radiation level on the top shield is generally higher than the radiation level elsewhere in Reactor Containment Building.
(RCB). A platform is designed above the top shield to enable most of the maintenance to be completed in low active zone. The area between the platform and top shield which has higher activity has very limited access for maintenance activities. The radiation level on the roof slab platform which is the accessible area for normal surveillance, has much lower radiation level. This will also lead to significant reduction in radiation exposure during surveillance activities.

The separation of the area into active buildings and non active buildings by dividing them into zones of radioactivity levels help in implementation of suitable access control and radiation protection measures. The spread of contamination due to personal or equipment movement is controlled by providing rubber areas* and double rubber areas** in inter-zonal areas. The personal protective equipment wear like gloves, shoe-covers, head caps etc., which are considered as the solid radioactive waste (discussed in detail under Radioactive waste management heading) generated while being used in the zones of high activity will act as a source of contamination spread if not properly disposed off.

3. ACTIVE AND NON ACTIVE BUILDINGS IN PFBR

Based on the levels of radioactivity present, the buildings are separated as active and non-active buildings. The classification of the buildings in PFBR is listed below.

<table>
<thead>
<tr>
<th>Active Buildings</th>
<th>Non active buildings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor Containment Building (RCB)</td>
<td>Control Building</td>
</tr>
<tr>
<td>Fuel Building (FB)</td>
<td>Electrical Building 1&amp;2</td>
</tr>
<tr>
<td>Steam Generator Buildings 1&amp;2</td>
<td>Service Building</td>
</tr>
<tr>
<td>Rad Waste Building (RWB)</td>
<td>Turbine Building</td>
</tr>
<tr>
<td>Personnel change room and Shower room</td>
<td></td>
</tr>
<tr>
<td>Stack</td>
<td></td>
</tr>
<tr>
<td>Active Chemical Control Lab (ACCL)</td>
<td></td>
</tr>
<tr>
<td>Liquid Waste Management Plant</td>
<td></td>
</tr>
</tbody>
</table>

4. ACCESS CONTROL

The strict monitoring over the access control greatly helps in avoiding the spread of contamination. The personal airlock and material airlock in Reactor Containment Building (RCB) are so provided to maintain the control over access and movement of men and equipment. The air pressure in the low active zone is maintained higher than the pressure in high active zones. This is kept to enable the air flow only from low active to high active zone.

Further to active and non-active buildings, the areas in the nuclear island connected buildings are separated into supervised areas and controlled areas. Supervised areas have free access. In these areas too, the occupational radiation protection conditions need to be kept under review, even though the specific occupational protection measures and safety provisions are not normally needed. The external radiation field in these areas shall not exceed 1 µSv/h (micro-Sievert per hour) and potential of escalation of radiation field and spread of air and surface contamination is judged to be reasonably low. In controlled areas, the personnel
access is limited and controlled. In these areas, the ambient radiation level exceeds than those set for supervised areas. Generally, all rooms beyond personnel change rooms are considered as controlled areas.

For the active areas at PFBR, the access control is derived as per the design values specified. It is proposed that the design radiation level in normal full time occupancy areas shall not exceed 1µSv/h. The air changes in full occupancy areas shall not exceed 1/10th of the Derived Air Concentration (DAC). The maximum radiation level in accessible areas is limited to 25µSv/h. This is ensured by the design of ventilation system. The airflow will be from low active zone to high active zone and the exhaustion of air from the Reactor Containment Building (RCB) is done through filters to meet the stipulated discharge limits to environment through stack.

5. ZONING CONCEPT

The zone classification of the plant areas shall be in the ascending order of potential of contamination. In PFBR the following is the details of various zones identified for different buildings.

Table 2 Zoning classification adopted in PFBR

<table>
<thead>
<tr>
<th>Zone 1</th>
<th>Zone 2</th>
<th>Zone 3</th>
<th>Zone 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>No radioactive materials and will be free of contamination at all times.</td>
<td>This zone will also not contain any radioactive materials / equipment and is unlikely to become contaminated during normal operation. However it may be infrequent subjected to some low level contamination.</td>
<td>areas meant for servicing of active equipments and materials which are a potential sources of contamination. Periodic decontamination is envisaged for these areas</td>
<td>open sources of contamination</td>
</tr>
</tbody>
</table>

6. SOURCES OF RADIOACTIVITY IN PRIMARY COOLANT (SODIUM) ACTIVITY IN PFBR

- The sources of activity in primary coolant are:
- Sodium-24 (Na-24) produced by the reaction \{Na-23 (n,\gamma) Na-24\} in the core region.
- Na-22 produced by the reaction Na-23 produced by the reaction \{Na-23 (n,2n) Na-22 \}
- Active Corrosion particles and fission products.

Activity of Sodium-24

The saturation activity of the Sodium-24 in primary sodium is estimated to be 592MBq/ml. This activity is reached within two days of reactor operation and decays with a half life of 15 hours. Bulk shielding is provided against Sodium-24 activity as it is a gamma emitter. Due to its shorter half-life, Sodium-24 portion of the coolant ceases to be radioactive within a few days after removal from the reactor.
Activity of Sodium-22

The saturation activity of Na-22 in primary sodium is attained in ten years of reactor operation and is estimated to be 28 kBq/cm³. This activity builds slowly with reactor operation since T\textsubscript{1/2} = 2.6 years, but poses problem for maintenance on the primary sodium circuit. Sodium-22 is a positron emitter.

6.1. Corrosion and Fission Products

The radioactive corrosion products formed in the primary sodium are: Chromium-51, Manganese-54, (Iron) Fe-59, Cobalt-58 and Cobalt-60. The specific activity in the coolant for important corrosion products are estimated based on the design values. About 90% of Mn-54 is deposited on Intermediate Heat Exchanger (IHX) and this poses an exposure problem during handling requires elaborate shielding arrangement.

6.2. Sources of activity in Cover Gas Circuit

Argon is used as the cover gas in the fast breeder reactor. The reactor is operated with limited gas leakers. Four fuel pin failure operation is considered for design. The cover gas during normal operation may contain fission gas activities due to four fuel pin failures. Hence, even during normal operation, activity in cover gas is mainly due to release of fission gases from the pins. The Argon-41 activity in cover gas is due to the activation of potassium present as impurity in sodium. During normal operation, the following gaseous activities are released to the cover gas from sodium.

- Potassium 41 undergoes n,p reaction produces Argon 41. (half life of is 1.8 hours) K\textsuperscript{41}(n,p)Ar\textsuperscript{41}
- Sodium 23 undergoes n,p reaction produces Sodium 24 (half life is 37 sec) Na\textsuperscript{23}(n,p)Na\textsuperscript{24}
- Calcium 40 undergoes n,α reaction produces Argon 37 (half life is 35 days) Ca\textsuperscript{40}(n,α)Ar\textsuperscript{37}

6.3. Shielding against sources of activity during reactor operation and maintenance

The Prototype Fast Breeder Reactor, being very compact pool type reactor with invessel fuel storage, it is necessary to have effective shielding around the core for controlling the

1. Fission power at storage locations
2. Activation of secondary sodium in Intermediate Heat Exchanger (IHX)
3. Neutron damage in the structural material and
4. Activation of pump and IHX from maintenance point of view

The invessel shielding is such that the required neutron flux is ensured for the neutron detectors, placed in control plug near the lattice plate. To achieve the design dose rate, the invessel shielding around the core is provided in such a way to minimise the activation of IHX and pumps due to neutron irradiation, damage to core cover plate etc.,.

The sources of radiation arising on top shield and reactor vault are considered through bulk shielding.

- The neutron flux incident on the top shield
- The neutron flux incident on the reactor vault concrete
Fission product gammas from the core get attenuated in the shields and sodium before reaching the reactor vault or top shield. The prompt gammas from the core is negligible.

The gamma flux due to Na-24, at the bottom of top shield and at the inner surface of reactor vault.

7. HEALTH PHYSICS LABORATORY INSTRUMENTS USED IN PFBR

Radiological surveillance in all zones is required to find the background radiation level. To meet this requirement different types of radiation measuring instruments are procured, installed and calibrated. To measure the radiation levels in zone 1 and office areas, Micro-R (Roentgen) Survey meter will be used and in other zone areas teletector will be used for surveillance.

The list of Health Physics lab instruments in PFBR and the frequency of surveillance is as follows.

Table 3 Frequency for Surveillance for the Health Physics lab Instruments used in PFBR

<table>
<thead>
<tr>
<th>S. No</th>
<th>Monitor</th>
<th>Source used for calibration</th>
<th>Frequency of Check</th>
<th>Frequency of Test</th>
<th>Frequency of Calibration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Survey meters (in use)</td>
<td>Cs 137</td>
<td>Daily (II shift)</td>
<td>----</td>
<td>Once in 3 months (General shift)</td>
</tr>
<tr>
<td>2</td>
<td>Survey meters (spares)</td>
<td>Cs 137</td>
<td>Monthly (General Shift)</td>
<td>----</td>
<td>Once in 6 months (General shift)</td>
</tr>
<tr>
<td>3</td>
<td>Teletectors (in use)</td>
<td>Cs 137</td>
<td>Daily (II shift)</td>
<td>----</td>
<td>Once in 6 months (General shift)</td>
</tr>
<tr>
<td>4</td>
<td>Teletectors (spares)</td>
<td>Cs 137</td>
<td>Monthly (General Shift)</td>
<td>----</td>
<td>Once in 6 months (General shift)</td>
</tr>
<tr>
<td>5</td>
<td>Rem counter</td>
<td>Am-Be</td>
<td>Daily (II shift)</td>
<td>----</td>
<td>Once in 6 months (General shift)</td>
</tr>
<tr>
<td>6</td>
<td>α counting system in use</td>
<td>Pu-239</td>
<td>Daily (each shift)</td>
<td>----</td>
<td>Once in a month (General shift)</td>
</tr>
<tr>
<td>7</td>
<td>α counting system (spares)</td>
<td>Pu-239</td>
<td>Monthly (General Shift)</td>
<td>----</td>
<td>Once in 6 months (General shift)</td>
</tr>
<tr>
<td>8</td>
<td>β counting system in use</td>
<td>Sr90-Y 90</td>
<td>Daily (each shift)</td>
<td>----</td>
<td>Once in a month (General shift)</td>
</tr>
<tr>
<td>9</td>
<td>β counting system (spares)</td>
<td>Sr90-Y 90</td>
<td>Monthly (General Shift)</td>
<td>----</td>
<td>Once in 6 months (General shift)</td>
</tr>
<tr>
<td>10</td>
<td>Gamma counting system (Single Channel Analyser)</td>
<td>Na-22 (disc source)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Gamma counting systems (Multi Channel Analyser)</td>
<td>Na-22 (disc source)</td>
<td>Daily (each shift)</td>
<td>Weekly (III Shift)</td>
<td>Once in a month (General shift)</td>
</tr>
</tbody>
</table>

To identify the presence of contamination, Alscin (Alpha Scintillation Counter), survey meter cum contamination monitors are used. To measure the air activity in controlled areas, air sampler is used. The samples are analyzed using the filter paper in alpha counting and beta counting system and the respective activity is estimated. Analysis of stack gaseous release samples and biological shield cooling system water
samples will be done in HPGe (High Purity Germanium detector) to identify the radionuclide concerned and activity present in it. Before the disposal of radioactive liquid waste, liquid samples are analyzed to identify the category.

8. ACCESS CONTROL
The strict monitoring over the access control greatly helps in avoiding the spread of contamination. Further to active and non-active buildings, the areas in the nuclear island connected building are separated into supervised areas and controlled areas. Supervised areas have free access. In these areas, the occupational radiation protection conditions need to be kept under review, even though the specific occupational protection measures and safety provisions are not normally needed. The external radiation field in these areas shall not exceed 1 µSv/h and potential of escalation of radiation field and spread of air and surface contamination is judged to be reasonably low. In controlled areas, the personnel access is limited and controlled. In these areas, the ambient radiation level exceeds than those set for supervised areas. As a general idea, all rooms beyond personnel change rooms are considered as controlled areas.

For the active areas at PFBR, the access control is derived as per the design values arrived at. It is proposed that the design radiation level in normal full time occupancy areas shall not exceed 1µSv/h. The air changes in full occupancy areas shall not exceed 1/10th of the Derived Air Concentration (DAC). The maximum radiation level in accessible areas is limited to 25µSv/h. This is ensured by the design of ventilation system. The airflow will be from low active zone to high active zone and the exhaustion is done through filters to meet the stipulated discharge limits to environment through stack.

9. RADIOACTIVE WASTE MANAGEMENT SYSTEM IN PFBR
In general, anything that has no further use is termed “waste”. Radioactive waste can be divided into two groups as hazardous and non-hazardous. Non-hazardous waste has no environmental concern. The disposal is through normal means and it is recyclable and reusable. Hazardous wastes require stringent control over handling, storage and disposal in order to prevent undesirable effects on man and the environment. Presence of radioactive material poses unique problems in dealing with waste management. The hazardous radioactive waste is given utmost attention for its storage and disposal because the reduction in the hazard potential is not possible in short span by physical, chemical other than natural decay process. Radioactive arises in three forms viz., solid, liquid and gas. The disposal radioactive wastes is based on three principles: 1. Delay and Decay 2. Dilute and Disperse and 3. Concentrate and Contain.

The waste in any form is categorized based on the strength of the radioactivity present in its initial form.

As PFBR is situated in the area where multi units are already operational, the dose release to the environment has the apportioned value of total 100 µSv/y; out of which 90 µSv/y is for release by air route and 10 µSv/y is for liquid route generated by PFBR. Liquid, gaseous and solid radioactive wastes are generated during operation and maintenance of the plant.

Segregation of radioactive solid waste in PFBR is categorized as below:
Table 4: Categorisation of Solid waste in PFBR

<table>
<thead>
<tr>
<th>Category</th>
<th>Radiation dose (D) on the surface of waste package</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>R/h</td>
<td>mGy/h</td>
<td></td>
</tr>
<tr>
<td>I</td>
<td>D &lt; 0.2</td>
<td>D &lt; 2 Beta-gamma emitters</td>
</tr>
<tr>
<td>II</td>
<td>0.2 &lt; D &lt; 2</td>
<td>2 &lt; D &lt; 20 Beta-gamma emitters</td>
</tr>
<tr>
<td>III</td>
<td>2 &lt; D</td>
<td>20 &lt; D Beta-gamma emitters</td>
</tr>
<tr>
<td>IV</td>
<td>Alpha bearing waste</td>
<td>Alpha emitters dominant activity in Ci/m3 or Bq/m3</td>
</tr>
</tbody>
</table>

Category I wastes are segregated as
1. combustible
2. compressible
3. amenable to melt densification (Polythene) and
4. non-treatable.

Discarded contaminated clothing reading < 0.2 mGy/h (combustible waste) will be separately packed in cloth bag / cardboard box and sent to CWMF. Other wastes are segregated as type b, c or d and packed in double Polyethylene (PE) bags, then sealed & taped suitably and then transported to CWMF. Category II and Category III waste are handled in shielded containers such that surface dose outside the containers is less than 2 mGy/h. All the ventilation filters are packed in double PE bags and placed inside the original cardboard cartons and sent to CWMF for further processing. Higher surface dose cotton waste are packed in double PE packets and sent to CWMF. Other items like glassware, tools, equipment etc. are placed inside MS container /standard drum and sent to CWMF. Waste will be packed in drums and placed in shielded casks if surface dose exceeds 2mGy/h and sent to CWMF.

The liquid waste generated in PFBR is categorized into 3 categories, viz., Category I, Category II and Category III depending upon their activity. The following table shows the segregation of liquid waste based upon their activity.

Table 5 Categorisation of Liquid waste in PFBR

<table>
<thead>
<tr>
<th>RADIOACTIVE LIQUID WASTE CATEGORIES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Category</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>I</td>
</tr>
<tr>
<td>II</td>
</tr>
<tr>
<td>III</td>
</tr>
<tr>
<td>IV</td>
</tr>
<tr>
<td>V</td>
</tr>
</tbody>
</table>
Category I, Category II and category III B wastes are collected in intermediate storage tanks, at Rad Waste Building (RWB). Category IIA wastes are routed to intermediate storage tanks in Fuel Building (FB). From RWB, the category I and II effluents are discharged to sea through Centralised Waste Management Facility (CWMF) control post, after dilution with the condenser cooling water. Category III effluents are sent to CWMF by tankers for final treatment and disposal. Category IV liquid effluent is generated during special operations like equipment decontamination. After converting the waste to Category-III, they will be sent to CWMF for further treatment.

10. LIQUID WASTE IN PFBR ARISES CATEGORY WISE

Category I: Showers, wash basins, effluents from active laundry, effluents from spent subassembly storage bay cooling and purification system, Change rooms in maintenance building, washing of spent fuel cask during fuel handling campaign

Category II: Effluents from Biological Shield Cooling (BSC), effluents from small material decontamination facility, Active chemistry control lab, small decontamination facility in Maintenance Building

Category III A: Decontamination facility – rinsing after sodium cleaning, Spent Subassembly Washing Facility (SSWF)

Category III B: Decontamination facility – rinsing after decontamination process

Category IV A: Decontamination facility – sodium cleaning – (Maximum activity is indicated which corresponds to washing of Intermediate Heat Exchanger (IHX))

Category IV B: Decontamination facility-chemical decontamination (maximum activity is indicated which corresponds to washing of Intermediate Heat Exchanger (IHX). Drains from primary sodium pump oil circuit is categorized under organic liquid effluent.

The gaseous effluents releasing from RCB is discharged through 97.6m height stack which is closely located to RWB. The stack location is provided close to RWB in order to reduce the length of exhaust duct length. The gaseous effluents will pass through the filters in the tunnel and discharged from the stack.

Active Argon and fission gases released from Primary Argon Cover Gas Circuit, Cover Gas Purification System, Fission Gas Detection Circuit, Leak of cover gas with fission product gases if any, into Reactor Containment Building and various cells etc., will produce the gaseous effluent.

![Figure 1 Stack monitoring system](http://www.iaeme.com/IJARET/index.asp)
The sampling air line drawn at the height of 2/3 of total height of Ventilation stack is connected to the detectors in the stack monitoring room. The sampling air will pass through the particulate activity detector, Iodine activity detector and Fission Product Noble Gases (FPNG) and Argon Activity detector. The FPNG and the Argon activity indicates the gross gamma activity released during the operation of the reactor. The integral flow release, FPNG

Concentration, high activity and faulty alarm channels are connected to the Main Control Room. The apportioned discharge limits through air route for PFBR is 90 µSv/y. This necessitates that the stack discharges shall be regulated so that the dose to the general public from all the radionuclides through all the pathways of exposure do not exceed the limit specified.

The Stack monitoring system which provides the release of activity to environment is installed and commissioned successfully in PFBR.

11. DOSIMETRY AND RADIOLOGICAL PROTECTION IN PFBR

The main aspect of radioactivity is that it is non sensory. It is hugely relied upon the instruments to detect the presence of radioactivity, contamination and the associated dose received by the radiation worker. The instruments of higher sensitivity and efficiency are used for radiological surveillance depending on the radiation background radiation levels. Use of lead aprons, shielding the high active equipment, shielding of area, distance, airchanges etc., are some of the means of reducing the occupational exposure.

12. PERSONAL DOSIMETRY SYSTEM IN PFBR

Dosimetry is maintained in every nuclear power plant to assess the dose measurement and the dose limits as low as reasonably achievable (ALARA). In general practice, Thermo Luminescent Dosimeter (TLD), Direct Reading Dosimeter (DRD) and Alarming Dosimeter are used as the personal dosimeter devices.

12.1. Establishment of TLD Card Processing Laboratory

To maintain control and record the dose received by the occupational workers, TLD cards are issued to all radiation workers. TLD card processing laboratory will be accredited by Bhabha Atomic Research Centre (BARC), Mumbai. The accreditation process of TLD card processing laboratory of PFBR is in process.

National Occupational Dose Registry System (NODRS) serves as the centralized dose registry system of the country. The Registry is responsible for maintaining and updating of computerized occupational radiation dose data inventory system of all radiation workers in the country. This is the specific and important feature followed in our country which largely helps to avoid over exposure to any occupational worker, wherever he goes and works inside the country. In PFBR, National Occupational Dose Registry System (NODRS) connectivity from BARC is being established in PFBR. The TLD laboratory is furnished with sufficient numbers of Semi automatic TLD badge readers, annealing oven for annealing of TLD cards and Nitrogen generator. Construction of personal monitoring calibration facility is located close to the TLD card processing laboratory wherein the TLD cards will be calibrated using Caesium-137 source.
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13. CONCLUSIONS
The prototype fast breeder reactor being the first of its kind in our country. This plant has specific radiological features pertinent to fast breeder reactors, compared to the existing pressurized heavy water reactor, pressurized water reactors and boiling water reactors. All the radiological procedures, required instruments and personnel dosimetry systems are in place and equipped with all mandatory requirements well before First Approach to Criticality of PFBR.

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