**Over three decades of radiological protection experience at Fast Breeder Test Reactor (FBTR)**

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**Abstract**

The Fast Breeder Test Reactor (FBTR) at Kalpakkam is the flagship unit in the second stage of the three-stage nuclear program of Department of Atomic Energy in India. Health physics services commenced at FBTR in April 1985 and the reactor attained first criticality in October 1985. FBTR is a unique reactor utilizing (U,Pu)C as the fuel. Presently, FBTR has been operated up to a maximum power of 32 MWt and the fuel has attained a maximum burnup of 165 GWd/t. Health Physics experience gained from the operation of reactor for 35 years is outlined. These include area monitoring, stack monitoring, annual discharge of activity released vis-à-vis technical specification limits, personnel monitoring that include man-rem expenditure, waste disposal etc. Installation, calibration and usefulness of special monitors, unique to LMFBRs, such as gas flow ion chambers in primary cover gas circuit for detection of gaseous fission products due to clad failures, fume activity monitors in the ventilation ducts to indicate sodium leak / fire, sodium aerosol detection monitors in the primary double envelop sampling line and gas activity monitors are highlighted. Fuel clad failure incident of short time release with wet rupture and clad failure with gas leaker of slow release due to dry rupture are presented. Reactor vessel cover gas activity sampling and analysis was helpful in the identification of failed fuel assemblies. Towards controlling external exposures to occupational workers during maintenance work, initial baseline studies were conducted to assess the deposition of radioactive corrosion and activation products and dose rates in the primary sodium pipelines and various components of FBTR, which are housed in the shielded cells. The environmental release of radioactive material from FBTR is negligible.

1.INTRODUCTION

Fast Breeder Test Reactor (FBTR) at IGCAR, Kalpakkam is a research reactor with an installed capacity of 40 MWt. The reactor serves as a test bed for irradiation of fuels and materials and provides experience in large scale handling of sodium and reactor operation [1]. The fuel used is (Pu,U)C and coolant is sodium. The basic design of the reactor block, primary loop and reactor instrumentation is similar to French reactor Rapsodie, whereas steam-water circuit and turbo generator (TG) were indigenously designed and commissioned. Steam Generator was put into service at a power level of 10.2 MWt in December 1993. In July 1997, Turbo-Generator was synchronized to grid. First criticality was achieved in 18th October 1985 with a mixed carbide core of 22 fuel subassemblies (FSAs). The core size has been progressively enlarged and the power level has also been progressively increased and reached a maximum power of 32 MWt in October 2018 in the 27th irradiation campaign. The 29th irradiation campaign carried out with 56 FSAs in core was successfully completed in February 2020.

In the last three decades, there were a few incidences of radiological importance occurred in the plant. A sodium leak in the primary coolant system in April 2002 was detected by leak detectors as well as by the particulate air activity monitors [2]. The first fuel clad failure incident resulting in a wet rupture occurred in February 2011 and was detected by DND detectors in the primary sodium circuit. The first clad failure incident resulting in a dry rupture occurred in November 2018 and was detected by ion chambers in reactor vessel cover gas (RVCG) circuit. In both occasions, the failed FSA was successfully indentified and removed from the core. The health physics experience gained during three decades of FBTR operation, the radiological status of the plant and radiological measurements carried out during incidences are presented.

##### 2. RADIATION AND AIR ACTIVITY MONITORING SYSTEM

The Radiation and Air Activity Monitoring System (RAAMS) consists of 12 particulate activity monitors, 13 area gamma monitors, 13 gas activity monitors and one discharge flask high range gamma monitor. Continuous monitoring of Reactor Containment Building (RCB) atmosphere for particulate and gas activity by particulate activity monitors (RPIs) and gas activity monitors (RGZs) respectively is unique for FBTR.

FBTR experience shows that for gas activity monitor to be sensitive and dependable, differential ion-chambers (DIC) type monitor is essential. Special purpose radiation monitors were introduced in FBTR for primary sodium leak detection, fuel clad failure detection and decay heat measurement. Four numbers of sodium fume activity monitors were installed in the ventilation ducts, to detect the leak of active primary sodium from the pipelines and the components such as sodium pump, intermediate heat exchanger (IHX) and overflow tank in the shielded concrete cells (B cells). The detectors were located in the duct away from the entry position to B cell and provided with lead shielding around the detector to obtain better signal to noise ratio. The gamma energy threshold was kept at 1 MeV to detect mainly 24Na gammas. A gas activity monitor to detect active sodium aerosols in the double envelope (filled with nitrogen gas) of reactor vessel and a particulate activity monitor for detecting primary sodium leak in purification system were introduced. During reactor operation, the increase in activity as registered by the monitor in double envelope could be correlated to 41Ar produced from trace amount of 40Ar impurity present in the nitrogen gas.

RVCG is monitored continuously using two gas flow ionization chambers known as Clad Rapture Detection (CRD) monitors namely, Rgz371 and Rgz372 for the early detection of fuel pin failures. Two monitors are located in the exhaust duct of the RCB after the filter bank and one monitor in the combined duct of RCB and active building (AB) to measure the activity released from FBTR. The gas activity monitor Rgz492 and particulate activity monitor Rpi490 measure the gaseous activity and the iodine activity releases respectively from FBTR complex. It was observed that whenever the CRD compressor was operated at a higher flow rate (100 cc/s), increase in the gas flow monitors in the CRD system readings followed by in-duct monitors due to detection of short lived (28 s) 23Ne. The anomaly was resolved by adjusting the flow rate of compressor and thereby introducing necessary time delay to ensure decay of 23Ne. Since the readings of stack monitors are showing activities near to background values due to large dilution of exhaust air of FBTR, stack release is estimated based on in-duct monitor reading. Grab gas samples are taken regularly from the exhaust of RCB ventilation system after HEPA filter bank to identify the radionuclides present in the exhaust air and to verify the sensitivity of the exhaust activity monitors. A high range gamma monitor (range upto 106 R/h) based on ion chamber has been installed in RCB after Chernobyl reactor accident to measure the radiation level in RCB in the event of an accident. The monitor is calibrated and installed such that it can roughly estimate the peak reactor power reached in case of design based accidents. The discharge flask is provided with a high range gamma monitor to prevent inadvertent removal of under cooled fuel SA. The alarm threshold for the monitor is set at 400 W. Computer based data screening, management and storage system has been introduced for RAAMS in early 90s. The readings of most of the installed radiation monitors are fed to a dedicated industrial PC and data is automatically stored for every shift and on user request. It has capabilities to retrieve data and analyze for the preceding 9-h (at 3 min interval) and one-hour (at 1 min interval). Besides the industrial PC, readings of select monitors installed in potentially active zones are displayed in control room panel with facility for alarm annunciation. Health physics unit has taken active role in the calibration, fixing of alarm thresholds and in preparing surveillance procedures for all the installed monitors [3, 4].

### 3. HEALTH PHYSICS ACTIVITIES – WORK PLACE MONITORING

Health physics unit (HPU) carries out radiological measurements in round the clock shifts as mandated in Plant Technical Specifications document. Besides the mandated work place monitoring, personnel monitoring and effluent monitoring, gamma spectrometry of various active samples using HPGe detector are also performed from early 90s which is unique to an operational health physics unit. During reactor operation, in controlled areas like top of pile, personnel entry is permitted with personnel protective equipment.

**3.1 Radiation survey**

All the accessible areas of RCB and AB (fuel assembly shop, decontamination hall, RCB exhaust filter room, and effluent tank area) are periodically monitored using installed (Rrg) and portable radiation survey meters. The supervised areas of the plant are surveyed to ensure that the radiation level is within 1 μSv/h. The measured gamma background radiation levels in different elevations of RCB and outside B1 cell are shown in Fig.1. The background radiation level at ‘0’ m and -2.81 m elevations are due to activity in sodium lines of B cells, cover gas circuit lines and minor cover gas leakages. The background radiation level at -10.5 m elevation is primarily due to radiation streaming from B cells through penetrations. The background radiation level at -14.5 m elevation remains the same over a period of time. The neutron field above top of pile area is 25 μSv/h.

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*Fig.1. Gamma radiation level during reactor operation in Reactor Containment Building (RCB)*

**3.2 Air monitoring**

Air activity in RCB and AB is periodically monitored using installed particulate and gas activity monitors. Particulate air activity is also monitored using portable air sampler and the activity in the filter paper is estimated using counting systems. The gas activity is also monitored by taking grab samples in PVC bottles and counting the same in gamma spectrometer [5]. The trend of particulate air activity in ‘0’ m elevation of RCB is shown in Fig. 2. The particulate activity from 1985 to 2006 excepting after the sodium leak incident in 2002 was about 25 Bq/m3. The activity is attributable to natural radionuclides. After the sodium leak incident, the particulate air activity was 175 Bq/m3 and 24Na was detected. A special U-Ni alloy based SA was irradiated in the core at different positions for checking the response of delayed neutron detection system of east and west loops. Perforations were made on SS clad of the pins for the release of delayed neutron precursors such as 87Br and 137I to the coolant. During the operation of the reactor with the special SA, the particulate air activity increased in RCB indicated a maximum value of 6322 Bq/m3 [6]. The special SA was discharged after the experiments. A metallic cocoon was installed above top of pile with an exhaust blower connected to RCB ventilation system to reduce the air activity inside RCB. With cocoon in place, the particulate air activity was observed to be between 150 and 450 Bq/m3 for reactor power of 19 MWt. The gamma spectrometry of the filter papers revealed the presence of the presence of 138Cs (t1/2=32 min) and 88Rb (t1/2=18 min), which are the daughter products of Fission Product Noble Gases (FPNGs) 138Xe (t1/2=14 min) and 88Kr (t1/2= 2.84 h) respectively. The DAC value for 88Rb and 138Cs is 2.976E+05 Bq/m3 and 1.812E+05 Bq/m3 respectively.

The first clad rupture incident occurred in February 2011 and reactor underwent SCRAM on DND signals. RCB ‘0’ m elevation particulate air activity increased from 300 Bq/m3 to 16460 Bq/m3 and air activity after 12 h was 5000 Bq/m3. From 2012 to 2016, the particulate air activity was 900 to 1200 Bq/m3. Additional supplementary blowers were installed after identifying the leak paths around top of pile based on composite (β and βγ) radiation survey [7]. The replacement of liquid metal (Tin and Bismuth alloy) seal in 2016 that provides isolation between RVCG and RCB atmosphere and change in cooling procedure of the seals helped in reducing the particulate activity to 250 Bq/m3 in 2017. During 2018, reactor was operated with a gas leaker FSA in core and the particulate activity increased to 1050 Bq/m3. The specific activity of gas samples obtained from RCB atmosphere was 0.037 MBq/m3 in 2000 and 41Ar alone was detected in the samples. In 2018, the specific activity of gas sample was 0.81 MBq/m3 and the gamma spectrometry revealed the presence of 41Ar, 133Xe and 135Xe.

**3.2. Contamination survey**

Contamination surveys have been carried out periodically in RCB and AB areas. During reactor operation, about 1 to 2 Bq/ cm2 was observed on the RCB ‘0’ m elevation floor whenever the particulate air activity is more than 500 Bq/m3. The gamma spectrometry of the swipe samples revealed the presence of 138Cs and 88Rb. During fuel handling operations in 2019, 137Cs was observed in the swipe samples due to some traces of primary sodium deposits. Primary sodium sample is periodically taken and analysed for activity. The specific activity of 137Cs was 281 Bq/g and 19240 Bq/g in December 2017 and December 2019 respectively. The increase is due to reactor operation with a gas leaker FSA.



*Fig. 2. Beta particulate air activity at 0 m elevation of RCB during reactor operation*

4. FBTR FUEL and blanket handling OPERATIONS

In FBTR, (Pu,U)C FSAs in varying compositions have been assembled and loaded into the core. The measured gamma and neutron dose rates on the surface of FSAs were 1.1-1.8 mGy/h and 0.4-0.8 mSv/h respectively. 208 numbers of thoria blanket subassemblies (TBSAs) were loaded in the reactor between 2014 and 2016. The maximum gamma dose rate on the surface of the assemblies was 0.6 mGy/h. Augmentation of shielding during straightness measurements of TBSAs resulted in reduction of personnel exposure by a factor of 12. No floor, personnel or air contamination was observed during assembling operations.

5. Decontamination of major components

During the three decades of operation of FBTR, decontamination of several components such as lower part of Control Rod Drive Mechanism (CRDM), micro filters, sodium centrifugal pumps, guide tube, core coordinate measuring device etc., were carried out. Decontamination of the damaged CRDM was carried out to reuse part of the mechanism having lesser radioactivity and dispose the rest having higher activity. Intense gamma field of 500 mGy/h was measured on the surface, which is essentially due to 60Co due to activation of stellited portion. The outer surface of the CRDM was cleaned to remove the 60Co contaminated sodium deposits by steam-nitrogen process. The liquid waste generated indicated the presence of 60Co with maximum activity of 2 MBq/m3. Electro decontamination was done to remove the active surface layer of lesser active portion of the CRDM that was meant for reuse. Decontamination of the guide tube was successfully carried out in the decontamination pit and the liquid effluent had shown activity due to the isotopes 203Hg (776 Bq/m3), 22Na (2616 Bq/m3) and 60Co (1702 Bq/m3). Sodium sampling canal plug was decontaminated using alcohol to remove the deposited primary sodium over the plug.

6. Gamma Spectrometry Measurements of Primary Sodium Lines

The ambient gamma radiation levels in the B cells after draining primary sodium from pipelines was 40 μGy/h. Spectral investigation studies revealed that deposited activity in the primary sodium pipelines consists of 54Mn (93%), 22Na (2.5%), 60Co (2%), 58Co(1.5%), 124Sb(trace), and 65Zn(trace) isotopes. Presence of 58Co and 54Mn in the lines confirm the transport of corrosion and core material activation products to the primary sodium pipelines [8].

7. Radiological significant incidences

**7.1 Primary sodium leak incident**

In 2002, sodium leak occurred in the primary sodium purification system when the reactor was in operation at 17.4 MWt. The purification system excepting the filter (cold trap) is housed in a cabin inside a concrete cell. Purification cabin provides physical isolation to the system and maintained under nitrogen atmosphere. During the incident, Rpi monitors of RCB showed increasing trend of air activity coinciding with the first alarm annunciation by wire type leak detector located in the cabin. The release of sodium aerosols into the RCB atmosphere had come down after six hours following shutdown. The maximum air activity during the incident was 0.1 DAC of 24Na [9]. About 75 kg of leaked active sodium was safely removed from the cabin. The cabin was decontaminated with alcohol. The dose expenditure incurred during the decontamination operation was 2.25 P-mSv. The purification system was normalized after replacing the defective valve. The active solid sodium removed from the purification cabin was converted to sodium hydroxide in decontamination pit by admitting stream in nitrogen atmosphere. Caustic aqueous sodium hydroxide was converted into a neutral solution of sodium metahexa phosphate in reaction with ortho-phosphoric acid (H3PO4). A dedicated Rpi monitor located near the decontamination pit did not indicate any increase in particulate activity during the operation [10]. The off-gas system from the decontamination vessel and the associated active-building area were allowed to pass through the HEPA filters located in the downstream of active-building filter bank to remove the particulates. Radiation field and air activity levels in the decontamination hall were continuously monitored. Personnel protective equipment was used and no personnel or area contamination occurred during the operation. The liquid effluents generated in the decontamination vessel were transferred to the low-level liquid effluent waste storage tank, adequately diluted, transferred to the FBTR delay tank and latter pumped to Centralised Waste Management Facility (CWMF). In 2015, primary sodium leak occurred for the second time from a bellow seal valve in the purification system. The activity was promptly detected by the dedicated Rpi monitor, installed based on the experience of first leak incident, in the incipient stage itself and the quantum of sodium leak was only 2 g.

**7.2 First fuel clad failure incident: Wet rupture**

In 2011, when reactor was operating at 18 MWt, it underwent scram on Delayed Neutron Detector (DND) west signals [11, 12]. The CRD monitors in RVCG circuit also showed large increase in activity. RCB exhaust activity monitor, Rgz490A showed more than 12 times of the baseline value. RVCG and RCB exhaust samples collected after the scram confirmed the presence of large amount of FPNGs along with 41Ar. Transferable contamination was observed in the RCB floor, table top etc. from the settling of 88Rb and 138Cs isotopes. RCB particulate activity remained above 15000 Bq/m3 for 5 h and above 5000 Bq/m3 for 12 h after incident. Maximum RCB activity was less than 1/10th of DAC values. A rubber station was installed on the entrance of RCB and entry was permitted with protective clothing and respirators. However, area gamma monitors in RCB showed a very small increase of 1.5 uSv/h after the incident and it has not reached the alarm threshold. Stack exhaust air samples were collected and gamma spectrometric analysis of the samples showed essentially 133Xe and 135Xe. Total stack gaseous activity release after the incident was 485 GBq. No particulate activity release through stack was detected. No personnel contamination was detected. Failed fuel localization samples (Kr and Xe samples) were collected and gamma spectrometry was performed. From the 88Kr/85Kr or 87Kr/85Kr ratios, it was inferred that the failed fuel pin attained a high burn-up (>100 GWd/t). Reactor was operated for short periods at 10 % power level and failed FSA was successfully identified and removed from core.

**7.3 First fuel clad failure incident: Dry rupture**

In 2018, during reactor operation at 32 MWt, RVCG activity monitored by Rgz371 and Rgz372 showed a sudden increase and grab gas sample from the circuit showed increase in FPNG activity. However, no increase in delayed neutron detector (DND) system was observed in any of the east and west channels indicating that only a dry rupture of the fuel clad had taken place [13,14] and reactor continued its operation. FPNG release as puffs was observed for three more times with a time interval of 48 to 72 hours. Higher activity of FPNGs was also observed in the samples taken from East & West IHX plenum region and Failed Fuel Localization System (FFLS) meant for RCVG sampling. The gamma spectrometry of RVCG samples revealed the presence of long lived 85Kr and the ratio of specific activity of 87Kr/85Kr and 88Kr/85Kr give the estimate of burn up of failed FSA. From the analysis of samples and reactor operation history, suspected FSAs were shortlisted. The shuffling of suspected FSAs and reactor power operation at 20 MWt to identify the gas leaker FSA was done in two stages. The analysis of RVCG gas samples during the second test reactor operation identified the FSA (Burn up 107 GWd/t) as the gas leaker. This was reconfirmed by operating the reactor once again at 25 MWt and monitoring the stack release. The stack release during this period was around 3.7E10 Bq which is lower than the normal stack release with a healthy core.

8. RADIOACTIVE WASTE DISPOSAL

Generation of solid waste in FBTR, so far, is very minimal. Intermediate level (Category-III) solid wastes were disposed only once during 1994 and consisted of cut portions of damaged CRDM. The surface dose rate on the waste bag was 500 mGy/h and it was due to 60Co. Category-II wastes were disposed only twice so far [ i) SS cut pieces of CRDM with a maximum surface dose rate of 0.5 mGy/h due to 60Co; ii) activation of defective cables used for neutron detectors, containing 447 MBq of 110mAg]. The potentially active wastes are mostly the HEPA filters removed from RCB and AB exhausts. For the last two decades, low level (Category B1) solid waste comprising of cotton waste, polythene sheets, used PVC bottles, surgical gloves, PVC wrappers and absorbent sheets were only generated.

Low level (Category B1) liquid effluent from personnel decontamination facilities and condensates from air handling units located in potentially active areas are stored in separate SS tanks and transferred to a delay tank of 150 m3 capacity and finally pumped to CWMF for disposal. Category B2 liquid effluent generated from minor leakages from BSC circuit, decontamination of components, sodium cleaning operations, liquid waste generated during passivation of guide tube, etc. are stored in SS tanks and disposed directly to CWMF through pipelines. Samples from the sediment accumulated in the SS storage tanks showed the presence of 60Co (980 kBq/kg), 137Cs (750 kBq/kg), 54Mn (250 kBq/kg), 134Cs (1300 kBq/kg) and 125Sb (300 kBq/kg). Radioactive sodium removed from primary purification cabin in 2002 was treated and disposed to CWMF as liquid waste containing cumulative activity of 188 MBq of 22Na.

Radioactive gaseous wastes of FBTR are diluted, filtered and released to the environment through a 65 m tall stack. The major and only radioactive component expected to be present in the gaseous effluent of FBTR under normal operating conditions prior to reactor operation without clad failure incidences was 41Ar. Following clad failure incidences, gas samples taken from the RCB ventilation duct revealed the presence of 41Ar and 135Xe. Under failed fuel-pin conditions, provision exists in the design to store the radioactive gaseous isotopes in four storage tanks for controlled release of activity. Each tank is of 4 m3 volume and can be pressurized up to 5 bars. The gaseous activity released through FBTR stack is shown in Fig 3. The releases are negligibly low compared to the technical specification limit of 3376 TBq per annum for 41Ar and FPNGs. The activity released in the year 2000 was 4.75 TBq. Subsequently higher releases were observed in the year 2011, 2016 and 2019 due to clad failure incident, Continuous operation for 134 days at 27.3 MWt and operation of the reactor with gas leaker respectively. During reactor operation at 32 MWt with a gas leaker in core, the mean daily release was 0.7 TBq. Assuming the reactor is operated continuously for a year with a gas leaker FSA the release would have been 256 TBq only. The dose to the public would be 0.004 mSv against the apportioned value of 0.05 mSv. There had been no release of 131I due to reactor operation, for which the technical specifications limit for discharge is 185 GBq per day (0.01 mSv/y), the installed iodine monitor observed small release during the in-situ testing of iodine filters of the ventilation system. Estimation of 90Sr and other particulate fission products are done by commissioning a dedicated Rpi monitor and gas sample is taken from stack exhaust air. The release of 90Sr is below the detection limit all the time.

9. PERSONNEL MONITORING

About 350 personnel are provided with personnel monitoring devices (PMD). All these occupational workers undergo routine wholebody monitoring annually and periodic medical examination. There had been no significant case of internal exposure. The blind test procedure of PMD was introduced in the year 2014 at FBTR. It is a quality assurance program to be conducted by the plant/user facility in association with the Health Physicist of the concerned facility, to check the performance of the monitoring laboratory during routine processing of PMDs for dose assessment. The performance of the tests conducted till date is highly satisfactory.

The man-rem expenditure for FBTR has been consistently low. Since the regular operation of reactor at high power level was mainly started after 1990, the collective from 1990 to 2019 is shown in Fig. 4. The collective dose in the year 2003 was 9.9 P-mSv and major work carried out was sodium removal and cleaning operation in purification cabin. The collective dose incurred during the loading of Thoria SAs in the reactor in 2015 was 8.1 P-mSv [15]. The maximum collective dose of 18.8 P-mSv was incurred in the year 2016 and the major operations are inspection work in the primary sodium cells, fresh fuel assembly operations and replacement of valves in purification cabin after the second primary sodium leak incident. The total collective dose from 1990 to 2019 was 153 P-mSv.

Integrated exposure control software is used to process personal dose data to retrieve information at various time intervals and to restrict exposures within the stipulated limits [16]. The personnel exposure data management at IGCAR was computerized in 1990’s and utility of system was enhanced manifolds in 2000 to integrate information of personnel, devices and exposures for occupational workers and retrieve monthly, quarterly, annual, any five-year-period and life-time exposure histories and generate personal and plant specific information with ease.



*Fig. 3.**Gaseous activity 41Ar and FPNGs discharged through FBTR stack*



*Fig. 4. Trend of collective exposure for FBTR personnel*

10. CONCLUSIONS

Health Physics Unit, FBTR acquired expertise in tackling unique situations such as sampling and estimation of activity in the double envelope, annunciation of frequent alarms from the installed monitors due to leakage of reactor vessel cover gas and subsequent increase in ambient radiation levels etc. In case of the sodium leak in the primary sodium system, it is proved beyond doubt that the radiation monitors respond faster compared to sodium leak detectors of different types. Time and motion studies adopted to estimate the dose expenditure to be incurred for handling various fuel elements helped in the reduction of collective dose. The radiation level in B cells is contributed by 22Na and 137Cs in primary sodium pipelines and capacities. With continued reactor operation, the activity build up is expected in the primary sodium and deposition on the pipelines. External exposure during any inspection or maintenance work in B cells is likely to consume considerable exposure in future. Adequate radiation protection measures coupled with effective surveillance by the health physicists have made it possible to have low personnel exposures and ensured compliance to regulatory requirements.

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