FIFTEEN YEARS OF OPERATING EXPERIENCE OF KAMINI REACTOR

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Abstract

Kamini (KAlpakkam MINI) Reactor located at Indira Gandhi Centre for Atomic Research (IGCAR), Kalpakam, India is a U-233 fuelled, low power research reactor and functions as a neutron source facility with a flux of 8.0×10^{12} $cm^{-2}s^{-1}$ at the core center. Kamini belongs to the MTR (Material Testing Reactor) type of reactors and employs Beryllium Oxide (BeO) canned in Zircoloy-2 as reflector material and plate type fuel in a reactor tank. Demineralised light water is used as moderator, biological shield and coolant. The core is cooled by natural convection of reactor tank water. Cadmium is used as the absorbing material in the safety control plates (SCP) provided for power control and shut down. This paper details the design description, facilities available for experiments and their utilization for R & D, fifteen years of operating experience of Kamini which is the only operating reactor using U-233, the recent water activity problem and the improvements made in the user facilities for meeting additional requirements.

1. INTRODUCTION

Kamini is a 30 kW, U-233 fuelled, deminerlized light water moderated special purpose research reactor located at Indira Gandhi Centre for Atomic Research (IGCAR). Beryllium Oxide (BeO) is used as reflector and cadmium as absorber material in safety control plates (SCP). The reactor was designed and built jointly by Babha Atomic Research Centre (BARC) and IGCAR. The reactor functions as a neutron source with a flux level of 8.0×10^{12} $cm^{-2}s^{-1}$ at the core center and facilitates carrying out neutron radiography of both active and non-active objects. Neutron activation analysis facilities are also available in the reactor for carrying out radiation physics research, irradiation of large samples, calibration and testing of neutron detectors.

2. BASIC DESIGN FEATURES

A judicious choice of design features; layout and control philosophy has been made using the experimental results and experience of similar reactors to provide operational flexibility and to achieve inherent safety. That is, in case of any power excursion due to inadvertent addition of reactivity, the reactor shuts down due to negative void and temperature coefficient. Kamini is a tank type reactor using U=Al plate type fuel in a light water pool. Physics of U-233 fuelled system including a full scale mock up of Kamini core has been studied extensively in PURNIMA reactor at BARC to establish the neutronic parameters and safety. Kamini is a reflector-moderated reactor where 50% of fissions are due to reflector returned neutrons. Zircoloy-2 canned BeO is used as reflector owing to its high reflection efficiency resulting in lower fuel inventory. Choice of Zircaloy-2 sheath for BeO is due to its superiority over aluminum with respect to neutron economy and structural considerations.

The inherent safety of Kamini reactor arises from the negative temperature coefficient (−0.017 $/°C) and the negative void coefficient (−0.0230 $/ml), which act as shutdown mechanisms in case of insertion of excess reactivity. A small inventory of U-233 (approximately 0.6 kg) used in a compact core of about 10 liters limits the radiological hazard potential during accidental conditions. As indicated in the safety analysis, for uncontrolled withdrawal of the safety control plate, the maximum power reached is only 115 kW, which can be easily removed by the reactor tank water with the water temperature not exceeding 70 °C without any safety consequences. The excess reactivity is provided to fully compensate for the essential operating loads namely, temperature and sample in the irradiation locations but only partial compensation is provided for xenon poisoning. This limits the excess reactivity and acts as self shutdown mechanism if the reactor is operated for more than 10 h at 30 kW_{th} power. Excess reactivity of less than 1\$ (β_{eff} = 0.0033) ensures that the reactor cannot attain prompt criticality. Reactivity compensation for burn up loss by reflector addition minimizes handling of fuel. The reactor core is cooled by natural convection. Any sudden power increase (as in an accident) results in a rapid increase of temperature in the vicinity of the core. This causes shutdown of the reactor due to high negative void and temperature coefficients of reactivity. The building housing the reactor is located at a flood safe elevation. Floor of the reactor vault is 1.5 m below the floor level of the basement area and the core top is 300 mm below the basement floor level with 3.0 m of water column above the core in the reactor tank, ensuring submergence of the core in case of gross leak in the reactor tank.

3. DESIGN DESCRIPTION

3.1. Reactor core

The fuel is in the form of flat plates of an alloy of U-233 and aluminum. These plates are assembled in an aluminum casing to form the fuel subassembly. Nine fuel subassemblies are arranged in a square lattice (Figure 1). The reflector modules are assembled around the core in a cubical arrangement for obtaining a fully reflected configuration. Additional reflector blocks (ARB) are provided for flexibility to alter the configuration in order to gain the required excess reactivity and for compensating the loss of reactivity due to fuel burn up, thus obviating the need to replace the fuel subassemblies at periodic intervals. Storage locations of ARB 2 and 3 are in the reactor tank. Three plutonium aluminum subassemblies are available as spares. These subassemblies may also be used for identification of failed fuel by substitution method. Two Safety Control Plates (SCP) made of cadmium sandwiched in aluminum are provided for reactor power control and shutdown. Gravity drop mechanism is provided for rapid shut down (scram) of the reactor. A solenoid latch prevents accidental lifting of the safety control plates from the top of the tank.

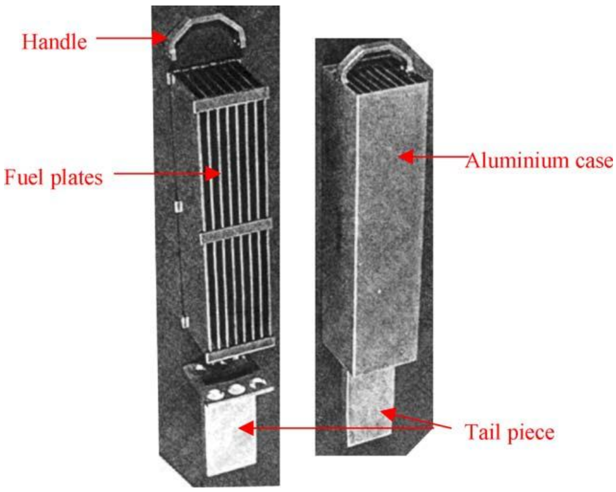

Fig.1. Fuel subassembly.

3.2. Irradiation facilities

There are three beam tubes, two irradiation locations at the core reflector boundary and one location adjacent to the core for carrying out irradiation experiments. The ratio of length to diameter for south and north beam tubes is about 160. A mechanism with a rotation facility that can index the object in front of the beam is also provided enabling neutron tomography of fuel subassembly and the pins. Both film and real time radiography are possible. A Pneumatically operated Fast sample Transfer System (PFTS) is provided for irradiation of samples to study short lived isotopes. Samples with a maximum weight of 1.7 g in special polypropylene containers can be shot into the irradiation site located adjacent to the core reflector boundary during reactor operation and retrieved immediately after irradiation. Several samples can be irradiated sequentially in this location without shutting down the reactor. Two in-tank locations on either side of the west beam tube outside the reflector blocks facilitate irradiation of samples up to 50 ml. In addition, the water cavity above the reactor core can be used for irradiation of samples located in specially designed fixtures. Two more irradiation locations outside the reflector assembly were installed recently for the calibration of neutron detectors. All essential operations such as start up of reactor, shutdown and power control, etc., are done from the control room. The control panels are provided with emergency power supply from the diesel generators. Battery backup is provided for important indications in the control room required for ascertaining safe shutdown after power failure.

4. COMMISSIONING

Commissioning of the reactor was started in 1995 after installation of the reactor tank components, coolant system piping, instrumentation and control panel. Coolant water quality and clarity were maintained by the mixed bed demineralization plant throughout the commissioning phase. After getting safety clearance for fuel loading, first criticality was achieved in October 1996. In order to ensure reproducibility and consistency of critical heights and core reactivity status, a core restraining aluminum structure namely, core cage was installed on top of the core during initial phase of operation. The core cage is a lightweight structure facilitating tight seating of fuel elements. The reactor power was raised to 5 kW_{th} and then to nominal power of 30 kW_{th} in September 1997 after completion of absolute power calibration to determine the actual neutronic power, augmentation of shielding around the beam tubes and carrying out low power physics experiments.

5. OPERATING EXPERIENCE

5.1. Physics experiments

First criticality was achieved with nine fuel subassemblies and additional adjustable reflector blocks and inverse count rate method was adopted to predict criticality. The absolute power calibration was carried out by the irradiation of uranium–aluminum wires. The axial and radial neutron flux shapes in the core and the total fission power were estimated from the measured fission product activity of the wires. Gold foils were irradiated at the pneumatic fast transfer location to establish the corresponding gold foil activity with the reactor power. Subsequently for periodic verification of power calibration, gold foil activation method has been standardized. Neutron flux levels in the radial and the axial directions were mapped by gold foil irradiation. The safety parameters of utmost importance in Kamini are the worth of the safety control plates, moderator temperature coefficient of reactivity and void coefficient of reactivity. Changes in the core reactivity of Kamini are usually estimated in terms of the changes in the position of the safety control plates. Hence calibration of the safety control plates (determination of reactivity worth per unit movement of safety control plate) is essential. Calibration of the worth was carried out in Kamini before measuring the other safety parameters.

5.2 .Reactor system performance

The reactor has been operated at various powers and durations for meeting the requirements of users. It has been demonstrated that the reactor can be operated at 30 kWt for a maximum of 10 h for special experiments. Xenon poisoning sets in after about 1 h of operation requiring SCP compensation. Water quality and clarity in the tank has been well maintained by periodic circulation through the demineraliser unit preventing corrosion of structural components, radioactivity build up and providing clear view of the core for visual inspection and handling of in-tank components. Handling of fuel and reflector needing careful judgment and dexterity in handling of tools under water have been carried out manually by maneuvering the tools from the top without instrument backup. Experience at Kamini has been incident free and smooth, affirming confidence for carrying out such critical operations safely. Performance of instrumentation and control systems has been satisfactory. Uncertainty regarding smooth transit of sample in the pneumatic fast transfer system sample injection tube was experienced in the early stages. Correction of minor eccentricity in the piping and modification of the sample capsule geometry to cylindrical shape with chamfered edges resulted in smooth injection and ejection of the sample capsule. All sample handling and irradiations have been carried out without contamination and exposure to plant personnel.

5.3 Revamping of Instrumentation systems

The neutron detectors are having drift due to leakage current and the neutronic channels and its components are obsolescent, resulting in frequent failures and large downtimes. The two computer based systems in KAMINI, mainly Process Interlock and Reactor Regulation system and Alarm Annunciation and Operator Information system are also required to be replaced due to non-availability of spare cards and component obsolescence. Hence, it is planned to revamp these systems with the state-of-the-art systems to enhance the performance of the reactor and improve the operational safety.

5.4 Investigation of high water activity in Kamini Reactor

In June, 2008, activity of reactor water sample was showing increasing trend and approaching the technical specification limit of 50 Bq/ml (sample counted after one hour delay) during continuous operation of Kamini reactor at power levels more than 15 kW_{th}. Initial investigation revealed that this is due to gaseous fission products. To find the cause for the high water activity, an experimental set up was devised and positioned over each Fuel Subassembly (FSA) and water sample was sipped for carrying out Spectral analysis. The activities of the fission gases in B1 position(Figure 2) are higher by a factor more than 10 to 20 times relative to the activities seen in A3 and A1 (Figure 3). The data also indicated that subassemblies B2, C2 & C3 appears to show activity levels few times higher than A3 or A1. The water activity of one-hour delay sample from reactor tank water reached a maximum of 131 Bq/ml after 4 h reactor operation at 20 kW. Increase in the RT water activity observed during Kamini operation was investigated. Gamma spectrometric analysis had shown the presence of mainly Fission Product Noble Gases (FPNG) and its daughters in various water samples collected from reactor tank and individual fuel assemblies during reactor operation and shut down. It has observed that there was an increase in the concentration of FPNGs for last two years but its precursors such as bromine and iodine isotopes were not detected in any of the samples. Xe-135 activity monitoring in sip water samples collected from fuel assemblies within few hours after reactor shut down is used as a simple technique to identify fission gas leaking fuel elements.

SCP-1		SCP-2
C3	B3	A3
C2	B2	A2
C1	B1	A1

Fig.2. Fuel Assembly configuration.

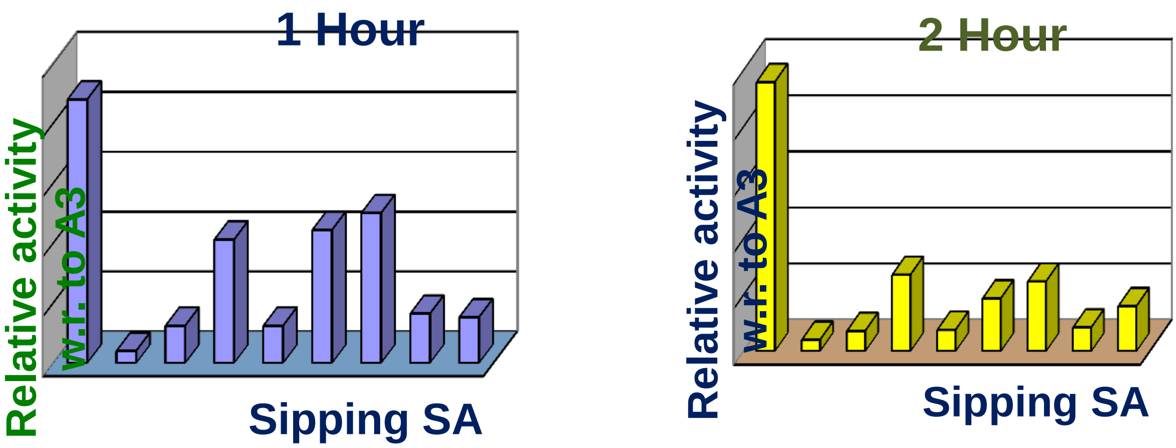

Fig.3. Comparison of Sip sample activity (Xe-135) for different SAs at 20 kW_{th}.

The discussions with the FSA designers and fabricators have confirmed that all quality checks such as glycol leak testing, radiography, and decontamination process were adopted for all SAs including Pu-Al SAs. The possibility of fixed contamination on surface and sub surface areas during fabrication could not be ruled out. It is concluded that the cause of increase in the fission gas activity in reactor water is due to the burn up seen by the U-233 lodged in the sub surface of the clad. Based on the results observed, safety clearances was obtained for restarting of Kamini reactor with new technical specification limit on reactor tank water activity at 300 Bq/ml (one hour delay) during reactor operation along with additional stipulations. Accordingly a separate area gamma monitor is installed in Kamini control room to monitor the background field. In case the background field in control room exceeds 0.01µGy.h-1 the reactor will be shutdown. Additional shielding was provided at the top surface of the ion exchange column to restrict the contact dose below 2.0 mGy/h. Spectral analysis of reactor water is carried out whenever reactor is operated to check the presence of any solid fission products and in case solid fission products are observed, reactor will be shutdown. Regular operation of the reactor resumed from April 2009 onwards after implementing the above recommendations. It is planned to replace the subassembly in position B1 by a spare Pu-Al subassembly.

6. UTILIZATION OF KAMINI REACTOR

6.1 Kamini for Space applications

Pyro devices are extensively used in the space industry. These are basically mechanical devices with a small amount of explosive. Different types of these devices are used for ignition, shearing the straps, cables and bolt cutters. Ensuring the reliability of the Pyro is a very crucial aspect in the space program. Of all the nondestructive examination (NDE) techniques, the neutron radiography is the best for this purpose. Kamini is being used extensively for the qualification of pyros for space missions of the Indian Space Research Organization (ISRO). The neutron radiography of 10,000 pyro devices from Vikram Sarabhai Space Centre (VSSC) has been completed successfully till date in Kamini.

6.1.1. Neutron irradiation of opto-electronic sensors from LEOS

There is another important activity which has been initiated with respect to assessment of performance of various critical sensors used in our satellites under neutron irradiation. Various opto-electronic devices from Laboratory of Electro-Optics Systems (LEOS), Bangalore was irradiated and their performance monitored for assessing the capabilities to withstand neutron irradiation for extended mission in the outer space. The sensors were required to be qualified in non-ionizing particle radiation up to a fluence level of 1.0×10^{10} mm^{-2} for product assurance requirement as well as to assess the degradation of the sensors from non-ionizing radiation for its estimated mission life in orbit. .

6.1.2. Neutron irradiation of MEMS based sensors and transducers for LPSC

In another campaign, three Macro Electric Mechanical System (MEMS) sensors and two MEMS transducers were received for neutron irradiation from Liquid Propulsion System Centre (LPSC), Bangalore for testing indigenously developed sensors for its use in GSAT-4 satellite. These MEMS based sensors was required to be tested up to a fluence level 7.0×10^{10} cm^{-2} for studying its performance for the designed life encountered under cosmic radiation. The performance of the transducers was monitored in real time during irradiation. The observations made during and after full irradiation also did not reveal any significant degradation of the sensors.

6.2 Utilization for R&D

6.2.1. Neutron radiography of fuel

South beam tube has been used extensively for neutron radiography because of the good length to diameter ratio, mobile shielding provision and ease of access to radiography area. In the first part of the campaign, characterization of neutron beam was carried out. Both direct and indirect imaging techniques were used. In the next phase dummy fuel pins of fast reactor and pressurized heavy water reactor were radiographed. Transfer technique was used for imaging of these fuel pins. Resolution of images was found to be satisfactory and pellet to pellet gaps and chipped pellets could be detected. Neutron radiography of fast reactor fuel pins of 25, 50 and 100 GWd burn up was carried out for characterization of fuel and pellet to pellet gap.

6.2.2. Neutron activation analysis

Irradiation of various samples has been carried out at pneumatic fast transfer system and thimble locations for activation analysis. About 1000 samples have been irradiated in Kamini till date. Typical applications of neutron activation analysis using Kamini include analysis of geological samples like ores, rocks and chemical samples from the forensic laboratories and development of method for neptunium (Np-237) estimation at microgram levels for use in reprocessing industry. Assay of iodine in leaf samples as well as rock samples for rare earths were carried out for environmental studies.

6.2.3. Shielding experiments in Kamini

Feasibility of using Kamini reactor for radiation shielding experiments has been studied. Experiments similar to those carried out at APSARA Reactor are not possible in Kamini, as the reactor spectrum is thermal. However, some experiments of general nature, such as shield material evaluation, neutron and gamma streaming etc are being done here. Testing and calibration of detectors can also be done. Shielding experiments using Ferro-boron and tungsten-boron have been successfully carried out.

6.2.4. Testing of a boron lined neutron chamber with parallel plate electrodes

A gamma compensated boron lined neutron chamber has been developed with parallel plate geometry by Babha Atomic Research Centre (BARC). Preliminary tests to estimate the neutron and gamma sensitivity and compensation characteristics of the ion chamber have been carried out at Apsara reactor. Two detectors have been tested up to a maximum neutron flux level of 1.0×10^{11} to 1.0×10^{12} nv in Kamini reactor and the results were reported to be satisfactory

7. CONCLUSION

KAMINI is a unique U-233 fuelled neutron source facility operating in India. It is providing R&D facilities for neutron radiography, activation analysis and radiation physics experiments. Fifteen years of operating experience with this facility has been satisfactory. We have been using the KAMINI reactor for neutron radiography of various pyro devices used in our entire space missions including the prestigious Chandrayaan mission. The excellent team work established between IGCAR and VSSC has matured to a level by which we are able to ensure 100% quality control as well as high reliability of the components, which are critical for our space missions. This indicates a major co-operation between IGCAR and ISRO and one more area of utilization of Kamini as a national facility.

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