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KAMINI REACTOR COMMISSIONING AND OPERATING EXPERIENCE, RESEARCH FACILITIES AND THEIR UTILIZATION

R.R. RAMANARAYANAN, V. ANANDKUMAR, P. MOHANAKRISHNAN,
C.P. PILLAI, P.V. KUMAR, R.P. KAPOOR

Indira Gandhi Centre For Atomic Research,
Kalpakkam, India

Abstract

Kamini is a ^{233}U fuelled, 30 kWt low power research reactor located in the post irradiation examination facility of Radio Metallurgy Laboratory (RML), Indira Gandhi Centre For Atomic Research (IGCAR), Kalpakkam, India. This is being utilised as a neutron source facility for carrying out neutron radiography of irradiated fast reactor fuel, activation analysis and calibration of radiation instruments. Design, construction and commissioning of the reactor was jointly carried out by Bhabha Atomic Research Centre (BARC) and IGCAR. This versatile research tool is also available for use by research institutions and universities.

1. INTRODUCTION

Kamini is a ^{233}U fuelled, light water cooled/moderated and beryllium oxide (BeO) reflected low power research reactor. Presently it is the only operating research reactor with this fuel and therefore, it also serves as a facility to study the physics characteristics of ^{233}U fuelled reactor systems. Kamini has highly desirable safety features like negative temperature coefficient and void coefficients of reactivity. Other special characteristics of this reactor are very low inventory of fuel (approximately 0.6 kg) with small core volume (10 L) providing a flux of 1.0 E12 n/cm^2/s which is achieved by using highly efficient reflector material, BeO. Two cadmium safety control plates (SCP) are used for start up, control and shutdown of the reactor. Core cooling is achieved by natural convection. Experimental facilities available include three neutron beam tubes, pneumatic fast transfer system (PFTS) and irradiation thimbles for carrying out a variety of research by neutron irradiation. The reactor attained first criticality on 29 Oct 1996 and reactor power was raised to its nominal power of 30 kWt on 17 Sep 1997. The reactor is presently being used for various irradiation experiments.

2. DESCRIPTION OF REACTOR

The reactor system consists of the reactor tank with internals, core-reflector assembly, and top structure (Fig. 1). Salient features are given in Table I.

TABLE I. SALIENT FEATURES OF KAMINI

Type of reactor system	Tank type
Power	30 kWt
Fuel	^{233}U (20 weight %)-Al alloy plates cladded with aluminium
No. of fuel subassemblies	9
No. of plates per subassembly	8
Reflector	200 mm thick BeO encased in Zircaloy
Moderator/Coolant/shield material	Demineralized light water
Absorber material	Cadmium sandwiched in aluminium
Design flux levels	
Core	1.0 E12 n/cm^2/s
Beam tubes	1.0 E 06 to 1.0 E 07 n/cm^2/s
PFTS location	1.0 E 12 n/cm^2/s

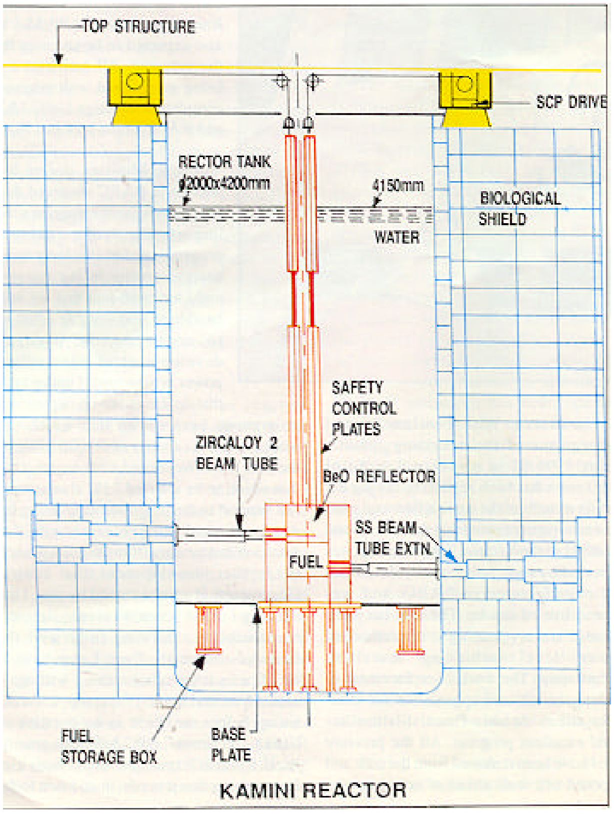
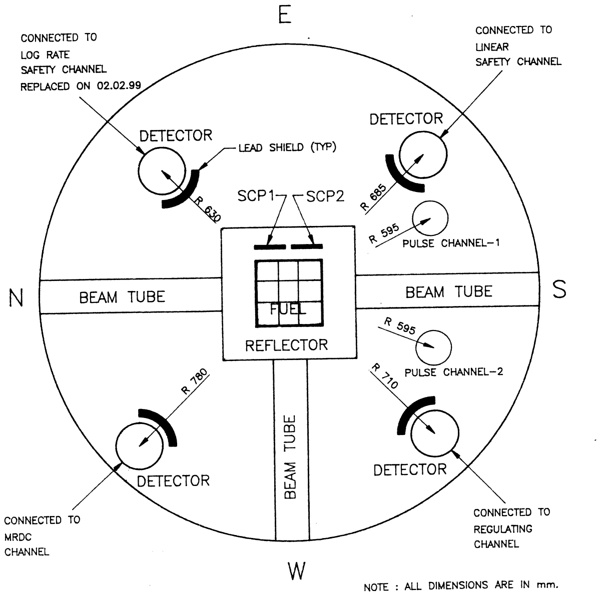


FIG. 1. *Kamini reactor.*

Fuel subassemblies are arranged in a square matrix of 3 × 3 (Figs 2 and 3) with each side of reactor core being 20 cm in length and 27.5 cm height. BeO reflector blocks are arranged all around the core in a cubical fashion. The top and the bottom reflectors are made in a grid structure to allow coolant water to flow thorough the passages. Adjustable reflector blocks (ARB) are also provided to add reactivity for long term burnup compensation.



SCP 1	SCP 2

N⇐

3	USA 4	USA 7	USA 8
2	USA 2	USA 1	USA 9
1	USA 6	USA 5	USA 3
	C	B	A

FIG. 2. *Detector arrangement.*

FIG. 3. *Core configuration.*

The entire core reflector assembly is contained in a stainless steel tank of 4.2 m height and 2 m diameter holding 13 kL of demineralized light water. The reactor tank is located in an annular catcher vessel of 400 mm height provided with instrumentation for detection of water leak. The top steel structure of reactor consists of channels for supporting components. Biological shield of the reactor is made of a combination of different types of interlocking concrete and lead bricks.

Start up and regulation of the reactor is done by adjusting the positions of two safety control plates located at core reflector interface. These plates are provided with gravity drop mechanism for rapid shutdown of the reactor.

Though the core cooling is achieved by natural convection, a heat exchanger system is provided for cooling the tank water to maintain the water inlet temperature at a steady value during prolonged operation. An on-line demineralizer plant (DM) maintains the water quality (pH = 6.5 to 7.0, conductivity <3 μ mho/cm, chloride <400 ppb) to keep the corrosion levels very low. Waste disposal system is provided for collection and disposal of radioactive effluents.

Neutron detectors consisting of two boron lined proportional counters and four boron lined uncompensated ion chambers are arranged in the tank around the core reflector assembly, as shown in Fig. 2, for monitoring reactor power and initiating safety action in case of abnormality.

All reactor operations are carried out from a central control panel in manual mode. The controls are configured as a hybrid system consisting of hardwired systems and microprocessor based data acquisition system.

3. COMMISSIONING EXPERIENCE

Commissioning of the reactor was started in 1995 and after obtaining clearances at various stages from safety authorities, reactor power was raised to its nominal power of 30 kWt. Salient events during this period were as follows:

- Installation of all reactor tank components, control panel and piping related to water systems.
- Commissioning of water systems viz., primary heat exchanger, on-line DM system and waste disposal system.
- Installation and assembly of reflectors providing required gaps for beam tubes and pneumatic fast transfer tube.
- Addition of water in the reactor tank and water circulation.
- Clearance from safety authorities for operation up to 100 W.
- Fuel loading and first criticality on 29 Oct. 1996.
- Operation of reactor at 0.5 W for physics experiments viz., Void coefficient measurement, absolute power calibration using uranium wires and absorber worth measurement. Calibration of detectors based on power calibration.
- Finalisation of detector locations.
- Neutron flux measurements by foil irradiation at beam tube end and irradiation locations.
- Erection and augmentation of shielding consisting of paraffin, lead and concrete around all beam tubes based on radiation survey at low power.
- Complete draining of reactor tank for certain in-tank jobs and refilling of reactor tank
- Raising of reactor power to 5 kWt after obtaining clearance from safety authorities. Demonstration of satisfactory operation of systems at high power.
- After further shielding augmentation, raising of reactor power to 30 kWt on 17 Sep 1997.
- Commissioning of secondary coolant system.
- Redesign and installation of shielding around south beam tube for neutron radiography work.

4. OPERATING EXPERIENCE

4.1. Reactor operation

During 30 kWt operation, it was observed that functioning of neutronic channels, performance of reactor regulation and shutdown system and water system are satisfactory and radiation levels are within permissible limits. The temperature at core outlet is found to fluctuate indicating setting up of natural convection. Power fluctuations of 1 to 1.5 kWt which are easily controlled by operator, have been observed during steady power operation. Xenon poisoning is found to set in after 1 h of operation requiring compensation by control rod withdrawal. The reactor has been operated at various power levels and for various durations with DM and primary circuits in operation for experiments involving irradiation for activation analysis, neutron radiography and physics studies.

The main operating parameters and operation statistics are given in Table II.

TABLE II. REACTOR OPERATION PARAMETERS

Parameters	Value
Maximum reactor power	30 kWt
Longest run at 30 kWt	7 h
Maximum temperature at core outlet	45° C
Global water temperature rise during longest run	7° C
DM water flow	2 kL/h
Primary water flow	5 kL/h
No. of start ups for various experiments	263

4.2. Physics experiments

4.2.1. Void coefficient experiment

Void coefficient was measured by comparing critical heights after introducing an aluminium box containing a void area in the core and later puncturing the box to clear the void. From the volume of air the reactivity worth/unit volume was estimated.

4.2.2. Reactor kinetics

An experiment was conducted at low power by withdrawing SCP continuously to add reactivity in a ramp fashion to study the power evolution. Data obtained from experiment indicated that beta value matched well with the theoretical assumption

4.2.3. Temperature coefficient experiment

During long operation, the tank water and core inlet temperature increases and Xenon also builds up introducing negative reactivity. To separate the reactivity effect due to temperature alone, this experiment was conducted. Immersion heaters were installed in reactor tank water and kept on for 7 h with reactor power maintained at 10 W. From the water temperature rise and SCP withdrawal, the average moderator temperature coefficient was estimated to be –5.6 pcm/°C. Using this, Xenon reactivity effect during reactor operation has been estimated and found to be 0.9 mk for 7 h operation.

4.2.4. Flux mapping and power calibration

Flux levels in radial and axial directions were mapped by gold foil irradiation. Typical flux distribution in the axial direction is shown in Fig. 4.

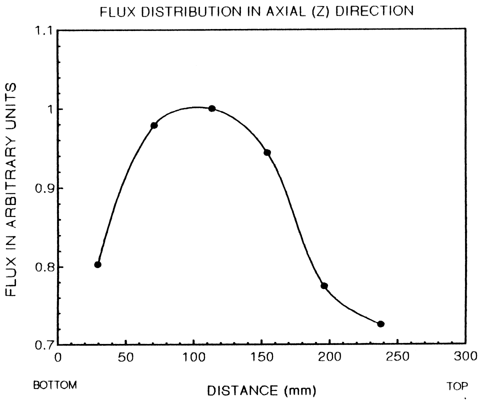


FIG. 4. Axial flux distribution.

First power calibration was performed using uranium-aluminium wires. From the fission product activity of the wires, the core flux and the total fission power were estimated. Subsequently, the reactor power was also derived from the flux levels obtained by irradiation of gold foils inside the core. Both these estimations matched reasonably well. For periodic verification of power calibration, the activity of gold foil irradiated in the PFTS location has been standardised.

Table III gives the physics characteristics and measured values of physics parameters.

TABLE III. PHYSICS PARAMETERS

Parameters	Value
Excess reactivity	2.5 mK
Effective delayed neutron fraction (β)	3.3 mK
Control rod worth	25 mK
Void coefficient	-0.076 mK/mL
Cadmium worth in PFTS location	-0.12 mK/cm^2
Average moderator temperature coefficient	-0.056 mK/^{o}C

4.3. Modifications based on operation experience

During initial phases of operation, it was observed that critical heights were not reproducible whenever fuel elements are handled and put back. After detailed investigations and trials, an aluminium core cage (Fig. 5) was installed on top of the core to ensure that fuel elements are tightly seated and restrained from any minor displacement in position. With this modification reproducibility in critical heights was achieved.

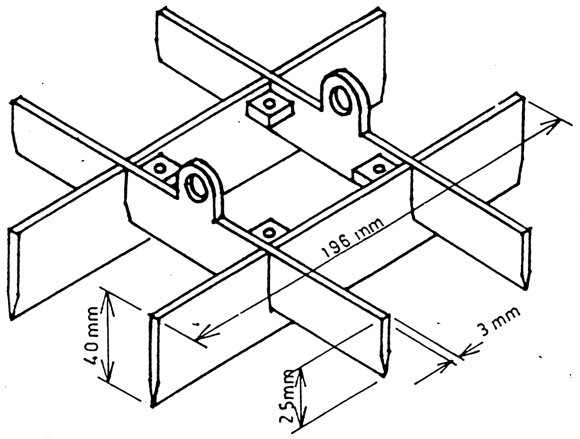


FIG. 5. Core cage.

During primary pump start-up for tank water circulation, bubbles were seen at the top of the core. This was overcome by diverting the pump discharge line to terminate at the tank periphery from its earlier location directly below the core to avoid bubble passage through core during starting of the primary pump. As the core cooling is by natural convection this modification did not have any adverse effect.

Problems related to neutron detector failures due to moisture ingress were overcome by replacing mineral insulated cable with moisture resistant polyethylene cables. Log P trip setting was raised to 130% from 110% to improve the operating margin after clearance from safety authorities. Noise pickup problems were rectified by replacing defective electronic components. It was observed that after the introduction of 50 mm thick lead shield in front of ion chambers to reduce the gamma effect, neutron flux increased at the detector location by 38% necessitating recalibration of neutronic channels. The change in flux was due to lower attenuation of lead shield compared to an equivalent thickness of water shield.

During extended operation, it was observed that water activity was exceeding the technical specification limit of 20 Bq/ml due to the presence of short lived fission gases (measured immediately). Detailed investigations indicated that this was due to fuel surface contamination during the plate rolling process in fabrication. The technical specification limit was subsequently revised to 50 Bq/ml, to be measured after 1 h delay to allow for the decay of short lived fission gases. Presently, the observed water activity during operation is well within technical specification limit.

5. RESEARCH FACILITIES AND THEIR UTILIZATION

5.1. Irradiation facilities

One of the uses of this reactor is for carrying out neutron radiography of irradiated fuel, control rods and non-active samples of fuel and material composites. Two neutron beam tubes with beam shutters are available for this purpose for extraction of collimated neutron beams employing cadmium lined collimators. The south side neutron beam tube terminates in a radiography rig which is earmarked for neutron radiography of irradiated fuel received from Fast Breeder Test Reactor (FBTR). Provision also exists for varying aperture size by means of an aperture control plate. A beam tube with shutter and a pit for setting up experimental equipment is available on the west side for carrying out radiation physics experiments.

Activation analysis is another area for which this reactor will be used extensively. Two aluminium tubes of 50 mm inside diameter with motorised drive facility for lowering samples are located outside the reflector for long duration irradiation. A pneumatic fast transfer facility enables irradiation of samples at the core periphery above the west beam tube for experiments involving study of short lived activity.

The measured fluxes at some of the irradiation locations at 30 kWt power are given in Table IV.

TABLE IV. MEASURED FLUXES AT IRRADIATION LOCATIONS

Location	Total flux $n/cm^2/s$	Flux above 0.4eV $n/cm^2/s$
West beam tube outer end	2.33 E 08	0.98 E 08
North beam tube outer end	7.2 E 07	4.47 E 07
South beam tube outer end	1.85 E 08	1.39 E 08
PFTS location	2.3 E 12	–
South thimble location	3.0 E 11	–

5.2. Neutron radiography

In the first part of campaign, characterisation of neutron beam on the west side was carried out. This beam tube had a L/D ratio of about 50. The objects examined were the beam purity indicator, sensitivity indicator and the beam purity indicator (fuel). Both direct and indirect imaging techniques were attempted. For the direct method, a gadolinium screen of thickness about 25 μm was used along with a combination of Agfa D2 ultra fine grain film and fine grain Fuji 80 film. For the indirect method, both Indium (125 μm thick) and Dysprosium (100 μm thick) screens were used. The cassettes with the converter screens and object were placed in the beam path and irradiated for 15 min for the indirect method. Analysis of the beam purity indicator indicated that the gamma background is quite high and epithermal content of beam is higher than the thermal content. Analysis of the sensitivity indicator pointed to an achievable resolution of 250 μm [1, 2].

In the next phase dummy fuel pins of FBTR (dia -5.1 mm) and pressurised heavy water reactor (dia-17 mm) were radiographed. Transfer technique was used for imaging of these fuel pins. A number of experiments were conducted at power levels of 5, 15 and 30 kWt and upto an exposure time of 30 min. The images were subsequently processed using image analysis techniques such as contrast stretching and spatial filtering to improve the overall image quality. Resolution of images was found satisfactory and pellet to pellet gaps and chipped pellets could be detected. Figures 6 and 7 show the edge enhanced images indicating the pellet to pellet gap and cracked pellet.

Radiography of irradiated fuel is being planned in the near future.

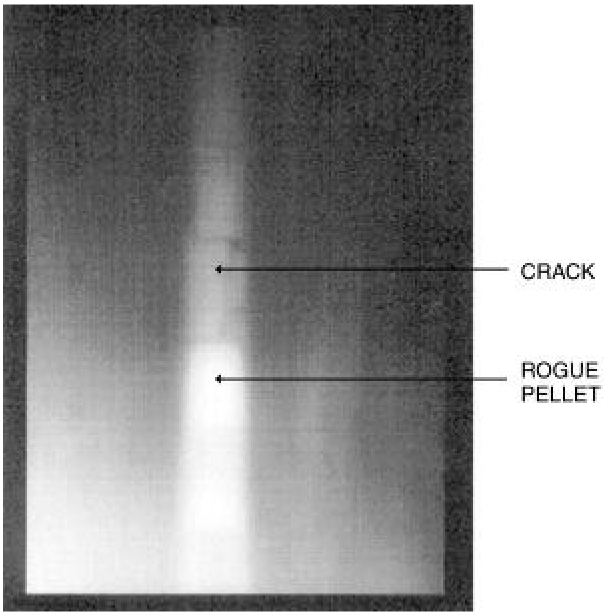


FIG. 6. *Edge enhanced image of FBTR fuel pin showing cracked and rogue pellets.*

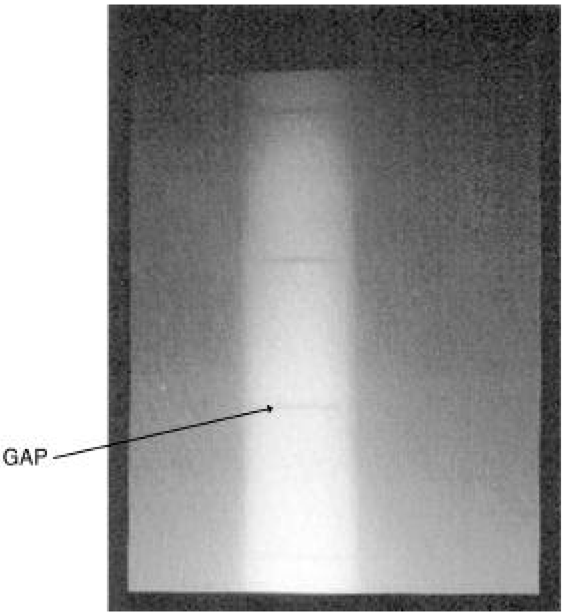


FIG. 7. *Image of PHWR fuel pin showing pellet to pellet gap.*

5.3. Activation analysis

Samples of gold with and without cadmium cover were irradiated at pneumatic fast transfer location to obtain the flux and epithermal to thermal ratio. The latter parameter was also determined by irradiation of Zirconium foil. Both experiments indicated that the thermal/epithermal ratio (‘f’ factor) was around 28.

After conducting trials for the above standardisation, a number of samples were irradiated. Two typical results are given below:

1. Samples were received from Forensic sciences laboratory for comparison by trace element profiling. Samples were irradiated and cobalt concentration showed that, of the four samples, three had a common origin while the fourth had a different origin.

2. Samples of lake sediments have been analysed for elements like mercury which are of importance from ecological point of view.

   Other samples irradiated are polymer for metallic impurities, human hair samples, etc.

6. CONCLUSION

Operation of this reactor has given valuable experience in ^{233}U fuelled reactor system and results from activation analysis and neutron radiography have given the confidence that reactor fulfils its main objective viz., providing a powerful neutron source facility.

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