AGEING MANAGEMENT AND REFURBISHMENT OF RESEARCH REACTOR CIRUS

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ABSTRACT

Cirus, a 40 MWt, tank type reactor utilizing heavy water as moderator, graphite as reflector, demineralized light water as primary coolant and natural uranium metal as fuel; had been in operation since 1960. After about three decade of operation, the reactor exhibited signs of ageing. A detailed programme of ageing studies was initiated to assess useful life of various components / systems. Subsequently the reactor was shut down during 1997 for execution of refurbishment program. After completion of refurbishment, the reactor was brought back in operation with significant increase in availability and safety margins. Several safety upgrades were incorporated in light of current safety requirements. A desalination plant utilizing low temperature waste heat was integrated with the reactor. It was commissioned and operated successfully. The reactor had been permanently shut down during December, 2010. The reactor core had been unloaded and preparatory work for decommissioning are on hand.

1. Introduction: Cirus, a 40 MWt, tank type reactor utilizing heavy water as moderator, graphite as reflector, demineralized light water as primary coolant and natural uranium metal as fuel; had been in operation since 1960.

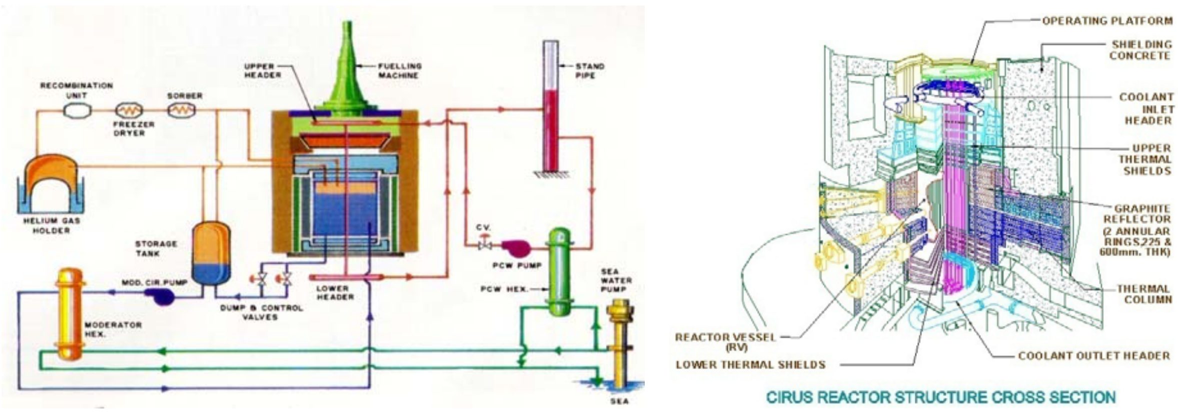
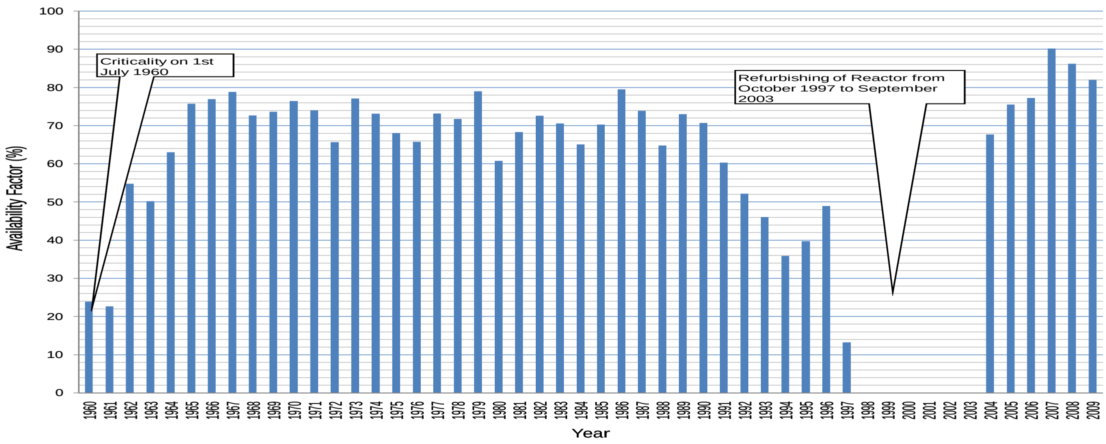


Fig 1. Simplified flow circuits of Cirus Reactor

Since the late 80's, Cirus started showing signs of ageing necessitating extra efforts for maintenance and the reactor availability factor started declining gradually. Detailed ageing studies were undertaken during 1990-95 and SSCs which required replacement / upgradation for trouble free operation of reactor for next 10-15 years were identified. Reactor was shut down in 1997 for refurbishment work and re-started in 2003. Post refurbishment, reactor operation was excellent with an availability factor of > 80%. Reactor was shut down permanently on 31st December 2010, core has been unloaded and preparatory works for decommissioning have been initiated.



Tab 1: Cirus Availability Factor during 1960 - 2010

2. Preparatory work for refurbishment

2.1 **Unloading of Core and Measures to Control Tritium Hazards**: Repair of the central shaft of Ball Tank (emergency DM water storage tank for core cooling) to rectify the seepage started during the 70’s was one of the important jobs identified for execution during the refurbishment. Core unloading was carried out to permit repair of Ball Tank, working on non-isolatable sections of main coolant system and other planned refurbishing work in core region. Execution of major refurbishing jobs on pumps, heat exchangers, valves and pipelines required draining of coolant from the system. System components and pipe segments were maintained to minimize corrosion. To prepare Heavy water & Helium system for various refurbishing jobs, entire heavy water system inventory was transferred to storage tank #1 and it was provided with separate helium venting arrangement to isolate it completely from rest of the system. Residual heavy water from loops and instruments was drained and the whole system was dried by moisture recovery system to bring down tritium content in cover gas and permit replacement of system piping without tritium hazard.

2.2 **Assessment of In-core components**

Reactor vessel: The reactor vessel (RV) is a vertical cylindrical aluminium tank. It consists of a ¼” thick shell attached to 3” thick tube sheets at either end. The RV has 192 lattice tubes of 2¼” ID & $^{1}/_{16}$” thickness, 6 tubes of 4” ID & $^{3}/_{32}$” thickness and one tube of 5¾” ID & $^{1}/_{8}$” thickness. Leakage from two 2¼” tubes developed in 1971 and in 1994 and they were plugged. To check the condition of RV tubes, all 2¼” dia tubes were examined with in-house developed dual frequency eddy current test (ECT) probe. The results indicated that most of the tubes were in healthy condition. Remote visual examination of six tubes, which indicated some flaws, was carried out using borescope. Also, helium sniffing was carried out in these six positions. No leak was detected.

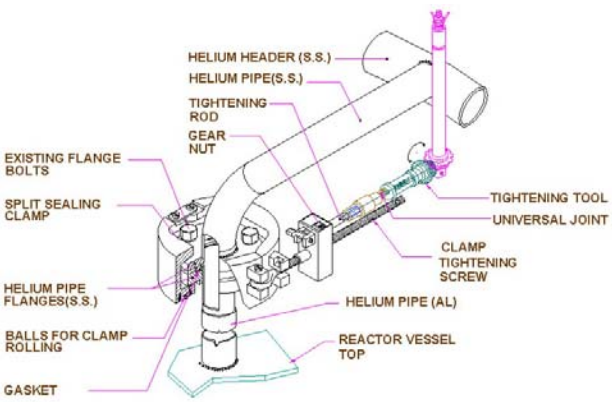
Remote visual inspection of the reactor vessel shell outer surface was carried out through experimental neutron beam holes using a micro video camera and was found to be without any defect. A plasticine impression was taken on modeling clay at one location, where a crack like depression was seen. The depth of depression was found to be insignificant. In order to assess the extent of radiation damage suffered by the reactor vessel material, metallurgical studies were conducted on a sample piece of 1S aluminium tube, which was removed from an experimental position after 14 years of service. Neutron fluence seen by this sample piece was of the same order as the neutron fluence seen by the reactor vessel shell (i.e. 1.6 x 10^{22} n/cm^2). The studies indicated the tendency of saturation in tensile properties for the fluence seen by the material. The uniform elongation after neutron fluence of 2.7 x 10^{21} n/cm^2 is reduced to 3.7%. However, a local ductility of 42% reduction in area is retained[(2)]. The swelling in RV at end of life was assessed to be negligible.

The expansion bellow between RV and top tube sheet had experienced a fast neutron fluence of 1x10^{22} n/cm^2 and had been subjected to thermal stresses due to temperature cycles. A finite element analysis to assess the thermal cyclic stresses suffered and the balance useful life of the bellow indicated that the stresses in the bellow were well below the yield point of the bellow material.

From these assessments it was concluded that the reactor vessel can be continued in operation.

Graphite reflector: The graphite reflector consists of two co-axial cylindrical structures of 330 cm height placed around the reactor vessel and separated by an annular gap of 2½", between the inner and outer structures. For cooling of graphite, ventilation air is passed through the annular gap. When graphite is irradiated, crystal lattice defects are produced due to displacement of atoms from their normal position in the lattice leading to stored Wigner energy. When irradiated graphite temperature is raised by external heating or by the heat generated due to irradiation, the displaced atoms can get back to their vacant positions in the lattice, thus causing release of stored energy. During irradiation when stored energy is getting accumulated, concurrent annealing of graphite also occurs. A few years prior to the shutdown in 1997 for refurbishment work, reactor was operated at 20 MW. It was thought that this could have increased the Wigner energy in the graphite due to decreased concurrent annealing during this period. Before taking up refurbishment outage for life extension of Cirus, it was considered necessary to assess the extent of Wigner energy in the graphite and to assess the pattern of energy release to rule out incredibly large spontaneous temperature rise due to heating of graphite during reactor operation at rated power.

For measurement of Wigner Energy release by Differential Scanning Calorimetry, sampling was carried out on a graphite plug subjected to maximum neutron fluence and consequently the worst conditions of stored energy. The sampling tools and the procedure were designed to restrict the temperature rise, at the sampling site, not more than 1°C during cutting operation. Thermal safety analysis of the irradiated graphite reflector was carried out for design basis events including the case of no ventilation airflow after reactor trip. Theoretical outputs were verified by operating the reactor at 36.5 MW and it was observed that the thermal conductivity of the graphite remained practically unaffected during the brief high power run, which otherwise would have shown improvement, had there been any significant release of stored energy. Based on review of observations, planned annealing of graphite reflector was considered not necessary. However improved measures were implemented to monitor graphite temperature by installing a Data Acquisition System (DAS).



3.0 Major Refurbishment Works:

3.1 **Rectification of helium leak from the Tongue & Groove joints above reactor vessel:** There are 8 nos. of 2" diameter aluminium pipes rolled into top tube sheet of the reactor vessel used for recirculation of moderator cover gas (helium). These pipes come up vertically to the 8” gap between the upper thermal shields and the top biological shields. There they are joined to SS 304 pipelines of the helium system through special flange joints called Tongue and Groove (T & G) joints having Buna-N gaskets as sealing medium. Helium loss rate from the cover gas system had increased gradually till the time the reactor was shut down in 1997. By carrying out various checks, it was concluded that one or more of the T & G flange joints could be leaking. Since there was no easy access to carry out repairs, remote repair was planned. Suitable split sealing clamp was designed & developed and a full-scale mock up facility was created to qualify the procedures. The clamps were fabricated and installed remotely to tighten the T & G flange joints. Measure were taken to not to subject the pipelines to excessive stress at any stage of work execution.

3.2 **Repair of Ball Tank central shaft:** Ball Tank; a spherical tank, stores DM water to provide core cooling when primary coolant pumps are not operating. It has a cylindrical opening running along its height called central shaft. The central shaft developed leakage (20-50 lph) near its base. As a part of ageing studies, NDE checks like rebound hammer test, ultrasonic pulse velocity checks, corrosion activity & corrosion rate test, carbonation test etc. were carried out on bottom skirt area, top spherical portion and shaft bottom area to assess the health of the concrete structure. The condition of concrete was found to be good. After core unloading, Ball Tank was emptied completely and visually inspected. A circumferential crack was seen on wet side about 1 m above the bottom of the shaft and cupola joint. Cracks were also observed above water surface region. A detailed plan was prepared to repair the leakage from wet side. Forced clean ventilation was provided inside the Tank. The Tank was decontaminated. Repair work was carried out by chipping of plaster, fixing wire mesh and cementing by polymer modified cement mortar up to 2-meter height on wet side of central shaft. Reinforcement bars were seen in good condition. Pressure grouting of epoxy was also carried out from both wet and dry sides. Seven layer epoxy treatment was given to the entire inner surface. The joint of central shaft with cupola at bottom was found to be having stresses more than permissible during its seismic evaluation. 3 mm thick carbon steel liner plates up to full height on wet side and up to 1.5 meter height on dry side of central shaft were installed to meet the seismic requirements.

3.3 **Primary Cooling Water (PCW) Pipelines:** PCW system pipelines are made of carbon steel (A53 grade A) except the embedded pipe sections which are made of SS 304. A major chunk of pipe lines run subsoil about 4 m below ground level and are joined together by mechanical couplings called Dresser Coupling (DC) having elastomer seals. These couplings have features to accommodate thermal expansion of pipe sections as well as minor misalignment between the pipe sections. Outer surfaces of pipelines were provided with asphalt coating for weathering protection. One DC joint on core outlet line housed in an underground concrete pit developed leak during the 80's. As the leak rate was well within the make-up capacity of the system and leaky water was not going into sub-soil, DC replacement was postponed during refurbishment outage as the job involved core unloading. During refurbishment all underground pipe lines were pressure tested. The test pressure was limited to 110% of maximum operating pressure as per the guidelines of ANSI B-31.4. Leakage was observed from one more DC joint. In view of failure of two nos of DCs, all underground lines were exposed by excavation and elastomer seals were replaced. Old weathering protection was removed, external surface of pipelines was inspected and repaired by metal filling wherever required. Some smaller diameter pipelines which were subjected to varying internal environment condition were replaced as their thickness had reduced due to corrosion. For leakage detection in future by acoustic emission method, wave guides were welded to pipelines. Bore holes were installed near pipelines for checking of activity of sub-soil water near them.

To check the microstructure of pipe material, one meter long piece of pipe removed from core outlet was examined by metallurgical experts. It was in good condition with no sign of preferential attack. 2-3 mm thick layer of hematite was seen on internal surfaces. Estimated corrosion rate based on the observations was 0.035 mpy against a nominal expected value of 0.1 mpy under such conditions.

DCs exposed.

UG lines after weathering protection

3.4 **Repair of leaks from the Aluminium thermal shields:** The thermal shields, made of aluminium and steel, provided above and below the reactor vessel are in the form of circular water boxes with appropriate lattice openings for installing fuel and other assemblies. Upper Aluminium thermal shield has two lines each for water entry and outer outlet. Water is recirculated through heat exchangers to remove heat and strict chemistry control is maintained to minimise corrosion. Leakage from one of the inlet lines developed in inaccessible location where it joins the thermal shield due to failure of weld joint. A hollow metal plug was fabricated and expanded at the leaky location to arrest the leakage and at the same time maintain water flow.

3.5 **Safety Up-gradation**: Cirus, being a reactor of vintage design, did not have some of the safety provisions incorporated in modern research reactors. Feasible safety upgrades were implemented during refurbishment. A new Iodine removal system comprising of activated charcoal filters followed by a bank of HEPA filters was installed in place of less efficient old system of an alkali scrubber followed by a bank of silver-coated copper wire mesh filters and a bank of HEPA filters. Seismic analysis of major civil structures and safety systems such as reactor structure, containment, Ball Tank, Dump tanks, stack, battery banks, emergency core cooling pipe lines was carried out. Most of the structures were meeting the required safety norms. Corrective actions were taken wherever required. Physical separation of vital safety equipment to avoid common cause failures, a new failed fuel detection system of higher reliability, installation of cable fire barriers, a modern fire detection and alarm system etc were also implemented.

3.6 **Other Jobs:** Radiation mapping of in-core components, assessment of healthiness of core components such as cast iron thermal shields, biological shields, pile ventilation ducts, master plate, revolving floor by visual inspection through a camera, replacement of leaky or corroded portions of pipe lines of various systems, replacement of heat exchangers and pumps, cleaning, repair and testing of underground liquid waste storage tanks, overhauling/replacement of transformers, overhauling of diesel generators, replacement of breakers, servicing of shut-off rods drive mechanism, replacement of pneumatic transmitters with electronic transmitters, replacement / servicing of first isolation valves, renovation of heavy water leak detection system, replacement of fuel channel inlet and outlet valves, refurbishment of DM water plant, replacement / repair of conditioned air supply plant, replacement of pipelines / pumps of other auxiliary systems were some of the major jobs carried out during refurbishment.

4.0 Desalination: A 30-T/day capacity desalination plant working on low temperature vacuum evaporation technology was coupled to primary coolant circuit of the reactor during refurbishment to demonstrate utilization of low temperature waste heat of nuclear reactors for seawater desalination. The plant could be operated at its rated capacity to augment the demineralized water inventory of primary coolant system after processing it through ion exchanger resin. Water jet ejectors are used to create vacuum and pump out concentrated seawater from the evaporator. Scale formation is practically eliminated because of the low boiling temperature and brine density. This unit is eco-friendly, since it does not require chemical pretreatment of the feed seawater. Apart from the electric energy required for motive pump of ejectors, no other power or fuel is necessary, except for waste heat at around 65˚C to heat seawater to 41˚C.

5.0 Re-Commissioning: One full charge of dummy fuel rods containing aluminium tube in place of fuel section were installed in core. Iron flakes which were released from pipelines were observed to be trapped in dummy fuel rods during PCW recirculation. A strainer with feature for on line cleaning was installed at the core inlet. After satisfactory operation with dummy fuel, full charge of fresh fuel was loaded in the reactor. Isotopic purity of heavy water was upgraded to gain extra reactivity. After ensuring the performance of all systems to be normal and review by regulatory authorities, the reactor was made critical. Reactor power was raised in steps to rated power after review and clearance from safety authorities at every stage.

6.0 Conclusion: The ageing studies and refurbishment works extended the operational life of Cirus by many years in addition to enhanced safety. Refurbishment was carried out in a very economic way, about 7% of estimated cost of a new similar reactor. The work gave an insight into various ageing processes for reactor systems, structures and components. This experience will be useful in the life management of similar facilities.

References:

1. Cirus – 50 glorious years; Rakesh Ranjan, N. Ramesh, DVH Rao et.al
2. Refurbishment and safety up-gradation of research reactor Cirus; DVH Rao, S.K. Marik et.al.