

# SAFARI-1 SAFETY REASSESSMENT OUTCOME AND MODIFICATIONS IN LIGHT OF THE FUKUSHIMA DAICHI ACCIDENT

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## ***Abstract***

Following the Fukushima nuclear accident, a directive from South Africa's National Nuclear Regulator was received which required a safety reassessment of the SAFARI-1 research reactor.

The safety reassessment consisted of:

- Evaluation of the response of the SAFARI-1 Research Reactor when facing a set of extreme external events (EEE) and
- Verification of the preventive and mitigation measures chosen following a defence-in-depth (DiD) logic: initiating events, consequential loss of safety functions, severe accident management.

The safety reassessment process was performed in various steps. Site-specific natural external events were firstly identified. The full lists of EEEs identified that may have an impact on SAFARI-1 include earthquakes, external flooding, tornadoes and tornado missiles, high winds, sandstorms, storms and lightning, hurricanes and tropical cyclones, bush fires, explosions, toxic spills, accidents on transport routes, effects from adjacent facilities, biological hazards, and power or voltage surges.

This step was followed by the development of event trees which depict the progressive evolution of the EEE into plant damage states which could potentially lead to public exposure. These evaluations were carried out in accordance with the philosophy of DiD as proposed in the ENSREG stress test specification.

This paper will present the feasibility phase outcome, results of the safety reassessment, as well as some of the resulting modifications and the future plans to conclude the post-Fukushima activities.

## **1 Introduction**

Following the Fukushima nuclear accident, all operating nuclear plants worldwide underwent thorough scrutiny to consider their safety under extreme events. A safety review of the SAFARI-1 research reactor on Necsa's site was conducted to conform to the National Nuclear Regulator (NNR) directive on safety reassessment following EEE.

### **1.1 Overview of Reactor**

SAFARI-1 is a tank-in-pool type research reactor of similar design to the Oak Ridge Research Reactor (ORR). It has one unit operating at 20 MW thermal power. SAFARI-1 is a high neutron flux, light-water-moderated and cooled, beryllium and light water reflected research reactor designed and built as a general research tool, falling in the class of research reactors commonly known as Materials Test Reactors (MTRs).

## **1.2 Prominent Features of the Reactor**

### **1.2.1 Reactor Primary System**

The reactor primary system is fully enclosed and circulated separately from the pool system. The reactor vessel is fully submerged in the reactor pool, with the vessel top about 4 m below the pool surface and the core at about 7.5 m below the pool surface.

### **1.2.2 Pool Structure**

A prominent feature of the reactor building is the pool structure, which comprises three pools separated by removable gates; the reactor pool (where the reactor vessel is located), the spent fuel pool (SFP) and the canal pool. The reactor pool and SFP are in the reactor hall and form part of the confinement area, while the canal pool is a part of the laboratory area.

### **1.2.3 Confinement System**

The reactor building is not a containment structure. Confinement of releases is controlled by means of active ventilation systems, which maintain a negative pressure in the reactor hall with respect to the environment to ensure no outward leakage.

### **1.2.4 Heat Sink**

The heat sink, to which the heat from the reactor core, reactor vessel and SFP is transferred, consists of the reactor primary system and the pool primary system from where the heat is transferred through shell and tube type heat exchangers to the secondary system. Heat is dissipated to the atmosphere from the secondary system via forced convection wet cooling towers.

### **1.2.5 Features of SAFARI-1 Related to its Siting, Behaviour and Resistance during BDBA**

The following features of SAFARI-1 enhance its resistance during beyond design basis accidents (BDBA):

- The Necsa site is situated in a region of low seismic activity;
- The Necsa site is situated far inland and at an elevation of 1330m above sea level;
- A combination of an earthquake and flooding is irrelevant for the Necsa site;
- It can survive an extended SBO without damage to reactor fuel or spent fuel;
- The reactor shuts down on external power loss even if RPS doesn't work;
- The fission product inventory is approximately 2 orders of magnitude less than an average NPP
- The fuel geometry is such that complete drainage of the spent fuel pool or the reactor vessel can be tolerated with only limited fuel damage;
- There is a bund in the building basement that has sufficient capacity to contain the entire pool and reactor primary system water content.

## **2 Safety-Reassessment Methodology**

The safety reassessment process was performed in various steps and according to the ENSREG stress test specification. A comprehensive list of EEE were considered and screened according to site characteristics to identify a set of site-specific natural external events that may possibly strike the site as identified in the full list mentioned above.

For the set of situations proposed, a deterministic approach was used in which the sequential loss of the existing lines of defence is assumed, regardless of their probability of occurrence.

The ultimate objective was to confirm the degree of suitability of the existing measures for accident management and, finally, to identify potential applicable improvements regarding both equipment (fixed and portable) and organisation (procedures, human resources, emergency response organisation and use of off-site resources).

### **3 Results and Recommendations**

In the 50 years of SAFARI-1 operation, no seismic event or severe adverse weather phenomena have been encountered at the facility that impacted nuclear safety or the safe continued operation of the reactor. The feasibility and effectiveness of accident management measures are however regularly tested during emergency exercises.

#### **3.1.1 General Recommendations**

An early severe weather warning notification system or arrangement could be investigated which could be beneficial to alert operators of approaching adverse weather conditions. Certain actions may then be taken, amongst others:

- Ensuring communication between SAFARI-1's control room and the Necsa site Emergency Services.
- Bringing the plant to a safe state before the any EEE strikes.
- Stopping the intake ventilation systems to ensure that a negative pressure difference between the radiological areas and the outside environment is maintained during a severe event challenging the confinement.
- Execution of the plant emergency procedures to take action as required (e.g. evacuating personnel from areas affected by the unavailability of intake ventilation systems).

#### **3.1.2 Plant Modifications**

The safety reassessment indicates that the following hardware modifications could be investigated to enhance the robustness of the plant against EEE:

- Provision of an Independent Shutdown Room (ISR), e.g. an EEE-protected place from which it is possible to shut down the reactor and plant if this could not be done from the main control room.
- Additional diverse instrumentation: The incorporation of additional dedicated monitoring instrumentation may be an advantage. Instrumentation may include, but is not limited to: independent core monitoring instrumentation, radiation monitors, exhaust air monitoring and a small portable electrical power supply to operate the instrumentation.
- Increasing robustness of building: The robustness of the SAFARI-1 building can be improved by strengthening some structural components.
- Submersible pumps: It will be beneficial to have a number of submersible pumps at strategic places in the basement and process wing to pump water that has drained from a damaged pool wall back into the pool or reactor core.
- Re-flooding nozzle: The re-flooding of the reactor vessel along the existing re-flooding pathways can be fairly slow. The availability of an additional re-flooding path located in the vessel-top could be an improvement of the re-flooding pathways.
- Second shutdown system: An additional diverse shutdown capability independent of the control rods could also eliminate fuel damage in case of a large break

LOCA in the reactor primary system subtended by a failure of the normal Scram system.

- Racks in fresh fuel vault: The rack stands could be bolted to the walls and the Fuel Elements (FE) and control rods could be clamped to the shelves to increase the robustness of the vault.

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### 3.1.3 Status of the proposed plant modifications

#### 3.1.3.1. Racks in fresh fuel vault

##### *High level Requirements*

According to a Safety Reassessment [1] conducted on the SAFARI-1 reactor facility, in the event of an earthquake or other EEE that may cause severe shaking of the fuel racks in the vault, the fuel assemblies and target plate boxes can be shaken out of the cradles and deposited onto the vault floor. A mechanism or means of restraining the fuel assemblies and target plate boxes is required to secure them on the cradles. Further investigation revealed that the cradles themselves are fastened to the racks by one self-tapping screw, and this needs to be remedied.

##### *Proposed solution*

The solution is to apply to the existing cradles, and must not necessitate a redesign of either the cradles or the rack they are situated on.

The mass of each item is defined in the Loading Catalogue 0. Given the mass and the accelerations, the maximum instantaneous forces on the items in the horizontal and the vertical directions are given in Table 1

**Table 1: Maximum Instantaneous Forces on Cradle Contents**

Item	Mass (kg)	Acceleration (m/s <sup>2</sup> )		Force (N)	
		Horizontal	Vertical	Horizontal	Vertical
Fuel assembly	6.5	11.8	4.1	76.5	26.8
Target plate box	15			176.6	61.8

The horizontal force induced by the target plate box provides the greatest force, at 176.6 N.

The recommended factors for combining different loads during accident conditions were studied and defined. The load factors prescribed for self-weight, imposed loads, and seismic actions during accidental conditions are all 1.0, and therefore the forces determined above are applied in the relevant calculations without modification.

The nominated final solution, was a length of stretch cord with one end permanently fixed to the back end of the cradle, which is then wrapped around the item in a prescribed configuration, with the other end hooked into a plate at the front of the cradle.

The solution completely restricts all uncontrolled motion of the fuel assembly during the maximum instantaneous EEE acceleration suggested, and allows a controlled horizontal displacement of less than 11 mm of the target plate box, which is then returned to its original position due to the restorative force applied by the elastic cord. The solution satisfies all other requirements prescribed in the Requirements Specification [3].

The proposed solution also investigated the sources of fire loading, the probability of the occurrence of fire in the vault and how it will be mitigate. On assessing the risk of fire in the vault, and preventing the ingress of an external fire by examining and modifying the configuration of the doors from the passage as necessary, and removing possible sources of ignition in the vault.

### **3.1.3.2. Re-flooding nozzle**

#### ***High level Requirements***

The assessment report for Re-flooding Nozzle [4] indicated that system should consist of:

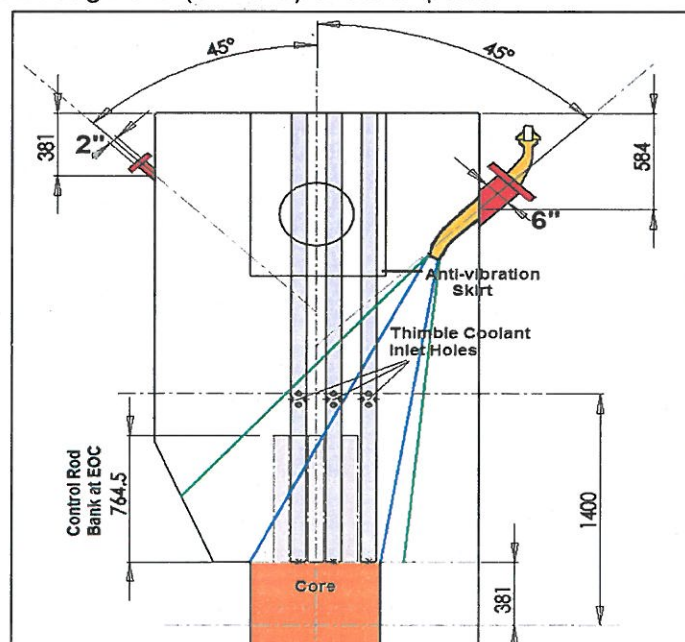
- Nozzles directed on the core (exact amounts and positioning needs to be specified);
- Elevation of the current gooseneck;
- Pipework to connect the nozzles to the pool water and to the emergency water return system and the pool;
- A means to enable (trigger) automatic opening to the nozzle in the event of loss of coolant in the reactor vessel (potentially bursting discs or floating ball valves);
- Siphon breakers in pipework to prevent drainage of pool water via gravitation from the pool to lower areas (or alternatives to prevent this).

The nozzle and siphon breaker setup will interface with the emergency water return.

#### ***Proposed Implementation concepts***

##### **Concept 1: Directing the Re-flooding Flow at an Angle**

This concept uses one of the angled experiment ports in the upper part of the vessel, sourcing water either from the pool or from the emergency water return system. The nozzle creates a droplet spray in such a fashion as to cover most of the core top structure. Figure 1 shows a schematic of the arrangement using the 6" port, but the re-flood nozzle could equally be deployed through one (or more) of the 2" ports.

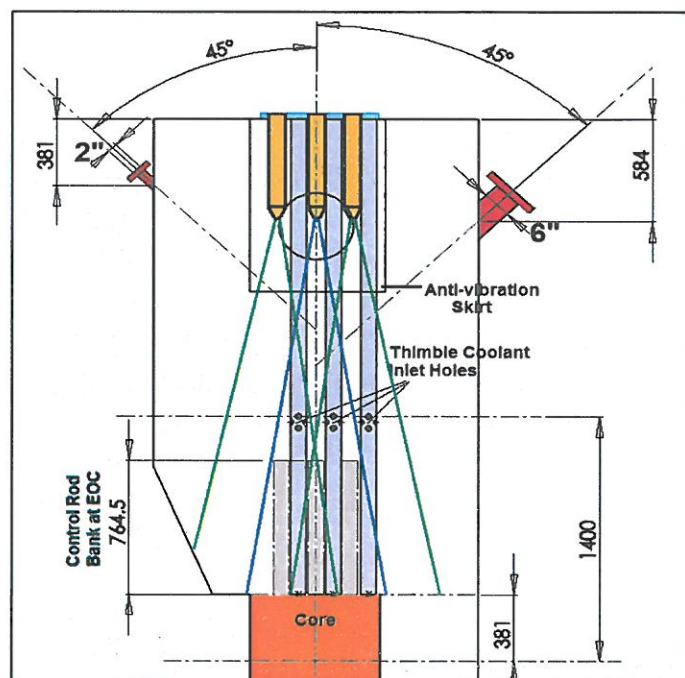


**Figure 1 : Schematic of Concept 1 using the 6" Angled Experiment Port**

From either of these ports, the spray would have to be directed at an angle with respect to the core.

### Concept 2: Directing the Re-flooding Flow Straight from Above the Core

Using penetrations through the Perspex window of the hatch cover, this concept deploys one or more spray nozzles directing their spray vertically down onto the core, between the thimble tubes. The nozzle(s) can be installed in such a way so as to provide sufficient coolant spray to the control assemblies at any extent of withdrawal. Figure 2 shows a schematic of the arrangement.



**Figure 2 : Schematic of Concept 2 using Penetrations through the Hatch Cover**

This concept improves the re-flooding nozzle spray access to the core (as compared with Concept 1); however the thimbles still obstruct "line-of-sight" with some of the fuel element positions in the core. This should not be a serious drawback, however, as it is expected that the spray flow would curve around the obstructions without any decrease in density by the time it arrives at the top of the core. This can also be tested in a simple experiment.

In summary, the main advantage of this concept is:

- It results in a more direct coverage of the core itself, including the control rod assemblies, as compared with Concept 1.

The disadvantages are the following

- The flow of cooling water into the thimbles for cooling the target plates is uncertain,
- Engineering a solution to this problem would require a re-design of the thimble sections above the core,

Space at the vessel top is severely constrained and could eliminate this concept as an option

### Concept 3: A Grid of Spray Nozzles above the Core

This is a variation of Concept 2, in which the spray is still provided from directly above the core at the reactor vessel top, but is distributed through a grid of nozzles connected to a manifold. The main idea behind this concept is to overcome the geometrical obstruction posed by the thimble tubes, as observed in concept 2 by introducing a separate spray into

each space between the thimbles. In this way each fuel assembly and control assembly is supplied with a dedicated source of cooling.

#### **Concept 4: Tapping into the Existing Emergency Spray Nozzle**

The existing emergency spray nozzle, which is supplied from a process water source in a cubicle outside the reactor building, complies with the size limitations that emerged from the analysis. Its location in the vessel and its orientation and size therefore do not differ materially from the re-flooding nozzle proposed in Concept 1. It is therefore a strong candidate for this application, provided that a means can be found to accommodate a pool water inlet and return water inlet to the supply pipe of this nozzle.

The major advantage of this concept is that it uses an existing installation that potentially requires no design changes within the reactor vessel and no new penetrations. However, its ability to provide sufficient water flow to control rods that have failed to insert and to the Molybdenum thimbles needs to be confirmed, as for Concept 1.

#### **4 Conclusion**

A number of recommendations were identified by the safety reassessment feasibility investigations, including stabilisation of fresh fuel store, emergency water return, external plugin power, re-flooding nozzle, emergency control room, independent seismic trip, second shutdown system, reactor building reinforcement and updating emergency procedures.

Most of the recommendations have been taken to the implementation phase, the work stabilisation of fresh fuel store has advanced quite rapidly and the implementation demonstrated to be successful. The verification of the Re-flooding Nozzle proposed concepts by experimental mock-up is continuing unabated.

The other recommended modifications regarding the emergency water return, external plugin power, emergency control room, independent seismic trip have work is progressing albeit at a slow rate due to resource constraints. The second shutdown system and the reactor building reinforcement implementation work have not started and there is a huge possibility that the recommendations might not be implemented given the age of the reactor. The updating of the emergency procedures is a continuous effort and the work is coordinated in conjunction with the Necsa site.

#### **5 References**

- [1] Safety Reassessment Report for the Safari-1 Reactor under Severe External Events, LD-SAFARI2011-REP-0025
- [2] Loading Catalogue Defining Design Basis for Fresh Fuel Vault Calculations, RR-REP-14/20
- [3] Requirement Specification: Securing of Fuel Assemblies and Target Plate Boxes in Cradles during and Extreme External Event, RR-SPE-0022
- [4] SAFARI-1 EEE Assessment: Re-flooding Nozzle, RR-REP-13/03