SEVERE ACCIDENT ANALYSIS & POST ACCIDENT MANAGEMENT FOR SPENT FUEL STORAGE FACILITIES

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ABSTRACT

Spent Fuel Storage Facilities are basically away from reactor (AFR) facilities for interim storage of the spent fuel from 220MWe PHWRs awaiting for further processing. The storage of spent fuel is carried out in an underground RCC fuel pool filled with DM water. The most important requirements of safety in storage of spent fuel are viz. to maintain the temperature of pool water, to maintain the water level of fuel pool to limit radiation dose to the operators and to remove the radioactivity from the pool water. These facilities are equipped with various systems to satisfy above safety criteria.
In the wake of Fukushima accident, a safety analysis of SFSF has been carried out under external events and elaborated in this paper. The paper gives an overview of the severe accident mitigation strategy and the related measures. Complemented by specific enhancements, including higher redundancy and diversity, as well as the use of passive systems this leads to very low values of system failure frequency. Notwithstanding the very low probability, specific severe accident design measures are implemented aimed at keeping radiological consequences of a postulated severe accident low.

INTRODUCTION

Spent Fuel Storage Facility (SFSF) located at Tarapur is used to provide interim storage facility for 220 MWe PHWR spent fuel.

The spent fuel bundles are cooled for a minimum period of three years and have an average burn up of 7000 RMWD/Te to reduce the decay heat in the spent fuel before transport to storage facility. The SFSF is used for receiving, handling, storing and transfer of the spent fuel to reprocessing plant. The storage of spent fuel is carried out in an underground fuel pool filled with DM water. Refer fig.1 for flow sheet of SFSF.

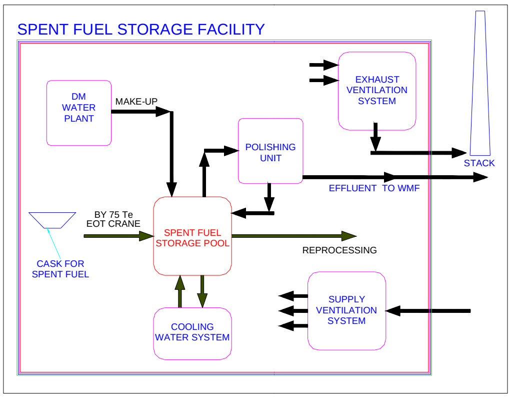

Figure 1. Flow sheet of SFSF

General Facility Description:

The SFSF has a fuel storage building which houses the fuel pool, pool water polishing plant, cask decontamination facility, 75 Te EOT crane, 10 Te EOT crane, 2 Te pool bridge, ventilation system, etc.

and a utility building which houses all auxiliary equipment and services e.g. make water DM plant, supply air fans, compressor, electrical switchgears & control room.

The fuel pool is fully underground admeasuring 35m long x 10.5m wide x 7.4m deep with a water depth of 6.5m. It is built with 1.5m thick RCC walls and floor. The peripheral walls and base raft are designed as water retaining structure. The internal walls are lined with SS plates and have liner modules embedded in the walls for leak detection and collection arrangement. Any leak from fuel pool through the SS lining will be collected through leak detection and collection modules to a pit adjacent to the fuel pool for collection, inspection and pumping. An infiltration gallery has been provided around SFSF to keep the water table low in the local vicinity of the building. The spent fuel is stored in the horizontal trays which are stacked over each other. Each stack has 30 trays and these stacks are laid in number of arrays on the pool floor.

The DM water from the fuel pool is cooled constantly so that the maximum temperature of water is less than 45°C. This is achieved by circulating the water through plate type heat exchangers (PHE). Refer fig.2 for schematic of pool water cooling system.

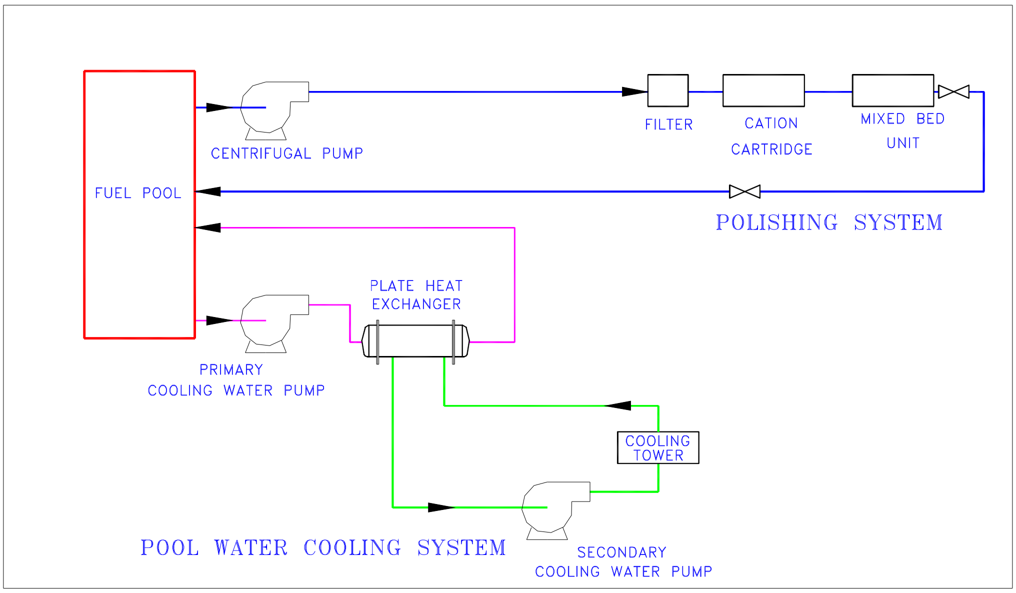

Figure 2. Schematic of pool water cooling system and polishing system

Polishing system is provided for removal of dissolved radionuclides e.g. Cs-137, Sr-90, etc. and hence activity from the pool water. A separate DM water plant provides make up water to compensate loss due to evaporation.

Ventilation system is provided for sufficient air changes to maintain air activity below permissible limits in fuel pool building, to ensure dust free atmosphere in the plant and to contain release of radioactive particulate contaminants to the atmosphere by two stage filtration (pre-filters and HEPA filters).

The electrical system of SFSF consists of Normal power system (class IV power supply) and Emergency power system (class III power supply) for ventilation system, 75Te EOT crane, infiltration pumps, cooling system and area lighting [1][3].

Safety criteria:

SFSF has been provided with engineered design features and built-in safety systems to ensure that there is no radiological exposure to the occupational workers and the environment or members of the public during the normal operation of the plant. The radiation exposures and the discharge of radioactive gases as well as particulate activity are well below the allowed limits from the facility.

In order to evaluate the impact of accidents and preparedness, following postulated accident scenarios have been considered during the operation of SFSF:

(a) Fall of stack of storage trays inside fuel pool:

Stack of storage trays is located on the pool floor with locators to avoid sliding. During a seismic event beyond design basis earthquake, the trays may fall in the pool and there is a chance that fuel bundles are subjected to impact and resulting in failure of fuel bundles. A radiological consequences analysis has been carried out and the release of activity has been estimated.

A failed fuel bundle is assumed as one that has at least one pin out of 19 nos. failed and is leaking its gap inventory. The radioactive species released as a result of clad rupture comprise fission gases and volatiles namely gaseous radionuclide (Kr-85) which will escape through the air route and cesium isotopes (Cs-134, Cs-137) which will get dissolved in water.

An estimation of volatile radio-nuclides that can escape to the environment through ventilation system to give rise to off-site consequence was done. The radio-nuclides stored in the fuel-clad gap, mainly Kr-85, would be available for release when the clad ruptures as a result of fall of the bundle. Calculation of the off-site dose to the public at 1.6 km distance (exclusion zone boundary) was calculated. Only the γ-emissions from Kr-85 were considered. For this purpose, the meteorology of the site was also taken into account.

All compounds of cesium (Cs-134, Cs-137) being highly soluble in water, the cesium activity diffusing out from the failed pins will be entirely retained by the water pool. This results into a high dose rate on the pool water surface due to the dissolved cesium isotopes. Thus, the on-site dose estimation was done on the basis of cesium isotopes. Dose rates were computed at 2m from the water surface at the centre of the pool. The released activity in the pool water will be transferred to the pool filtration system by virtue of re-circulation of the water.

The estimated release of radioactivity due to damaged fuel bundles is approx. 1.41 μSv which is negligible and there is no radiation exposure to members of the public. The situation inside pool building is manageable by following an Emergency Operating Procedures (EOP).

(b) Spent fuel shipping cask accidentally falling into the storage pool while handling:

Chances of occurrence of this event are eliminated due to built-in design safety provided in the EOT crane viz. crane has single failure proof design. The cask handling in the pool is in designated place with limited approach to avoid falling / impact of the cask on the stored fuel.

SAFETY ANALYSIS

In the wake of Fukushima accident, a safety analysis of SFSF has been carried out under external events with following postulations:

- Beyond Design Basis Earthquake (BDBE)
- Non-availability of power (Total black out)
- Flooding due to Tsunami, rain or otherwise

Beyond Design Basis Earthquake (BDBE)

The civil structures of SFSF are considered as Seismic Category-I structure and designed for Operating Basis Earthquake (OBE) condition as specified in ANSI/ANS 2.19 -1981 "Guidelines for Establishing Site-Related Parameters for Site Selection and Design of an Independent Spent Fuel Storage Installation (Water pool Type)". For stability of structures, a design check analysis using ground motion with peak ground acceleration (PGA) of 0.2g has been carried out (equivalent of SSE).

Analysis for DBE (OBE):

The SFSF has been analysed in two steps. In first step, complete structure was analyzed with unified three-dimensional model of the structure including superstructure and raft. The raft and relevant part of superstructure, which affects out of plane stiffness of raft, were modeled in second step. [6]

Complete three-dimensional Finite Element model of SFSF Fuel Pool is used for the analysis. (Refer Fig.3 & Fig.4) Soil is represented by tension-compression springs. Analysis is done for all basic loads like dead load, live load, etc. including earthquake loading and hydrodynamic effect. Response spectrum analysis is done for OBE condition as per site specific response spectra for site. Resultant responses have been used for design of walls and superstructure.

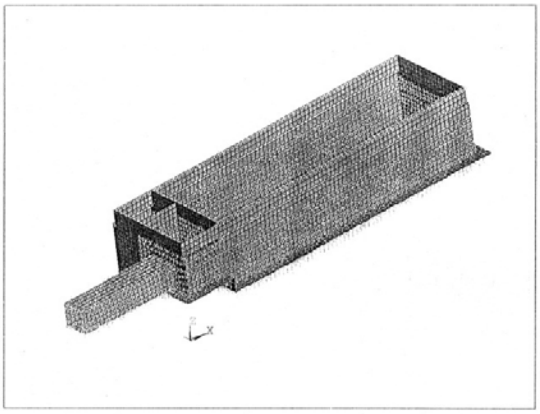

Figure 3. 3-D FEM model of fuel pool

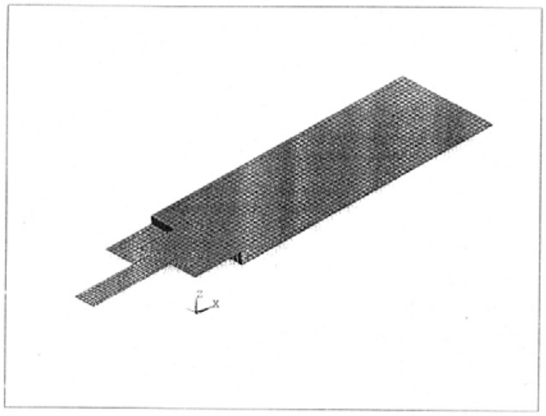

Figure 4. 3-D FEM model of raft

The structures were designed for reinforcement and crackwidth. Bearing pressure checks and stability checks were performed to check overturning, sliding and floatation for load combinations and the structure was found to be safe.

Analysis for BDBA (SSE):

A design check for consequence of SSE level of earthquake for SFSF was carried out. The methodology adopted for the analysis was same as adopted for OBE analysis. Here the design for strength was performed to satisfy design requirements for flexure and shear and the design for crackwidth is performed with elements results for unfactored combinations. The crackwidth was calculated as per ACI-224 [4].

Fuel pool has been found to be safe for the reinforcement provided as well as crackwidth for SSE condition. The factor of safety (FOS) on crackwidth (permissible / actual) varies from 2.5 to 25. Bearing pressure check, stability checks for overturning, sliding and floatation for load combinations are satisfactory. It was found that there is no remarkable change in the FOS for stability in OBE and SSE conditions.

The results of the analysis proved that the structures get qualified for SSE level of earthquake, which were designed for OBE level of earthquake. The analysis for higher level of earthquakes is being carried out for checking up of margins available.

Consequence Analysis for Higher Level of Earthquake & Post Accident Management:

In the postulated event of loss of pool integrity, e.g. damage to RCC pool raft due to higher level of earthquake, there may be a break in containment of fuel pool. Pool water may start leaking into surrounding soil and water level in the pool would start falling down. The analysis indicates that the radiation levels will rise in the area and the area will be unapproachable. A consequence analysis for such a scenario has been carried out. Following three stage post accident management plan would be followed during such a scenario [5] :

(a) Action for maintaining the pool water level:

There is three tier safety provided depending on leak rate. For low leak rates, the DM water supply from overhead tank is available. For larger leak rates, supply from overhead domestic water tank is connected to the pool.

In case of further higher leak rates, the water level will be maintained by taking domestic water from fire hydrant to maintain the pool water level. The fire water ring has been hooked up to fire water system. These pumps will feed the raw water at 5000 lpm and the available quantity of water in the water storage tank is more than required.

(b) Removal of fuel bundles:

Pool water level indication with low & high level alarm annunciation has been provided in the control room. It is monitored continuously and make up DM water is added to maintain the water level. Normally make up water requirement is very less (around 2000 lit/day) to take care of evaporation losses. An analysis regarding environmental impact due to breach of integrity of fuel storage pool indicated that in the event of a highly unlikely escape of one pool volume of radioactive water to the environment, the resulting dose to the critical group of population is negligible. Hence plant authorities have time for removal of spent fuel bundles. Following alternatives will be followed to remove spent fuel pool bundles:

- Reprocessing the spent fuel at enhanced capacity: Full capacity utilization of the reprocessing plants will be made and water level will be maintained by continuously adding water.
- Shipment of fuel bundles: The spent fuel bundles from fuel pool will be shipped to various fuel storage facilities.

(c) Action for rectification:

Fuel pool will be dried and decontaminated. Rectification work will be taken up after consulting experts from Civil & Mechanical Engineering and plant health physicist. A hydro test will be conducted before reuse of the pool.

Sloshing

The sloshing height for DBE was calculated which is well below the freeboard available for fuel pool (900mm) and thus the water level remains within fuel pool.

An estimation of level of earthquake to reach the sloshing height upto 900mm was also done and it was found that about 7.1 Richter scale earthquake is required (0.25g PGA) for sloshing height of 900mm. In this case, water will enter inside exhaust duct through the ventilation grills provided in the pool freeboard area reducing water shielding over stored fuel. Assuming triangular profile of water sloshing and the quantity of water which is above ventilation grills only will enter into ventilation duct, it is estimated that the pool water level will reduce by approx 700mm, which has no significant effect on increase of radiation levels at pool bridge level. Some of the water filled in ventilation duct which is above grills level will come back into the pool. This amounts to approx 500mm effective reduction in the water level.

Stack of fuel trays

Spent fuel bundles are stored in horizontal fuel trays and the 30 trays are kept one above another to form one stack of fuel trays. FEM analysis & shake table tests on a 50 Te shake table have been conducted to prove stability of stacking of 30 trays for an earthquake of 0.2g PGA [2].

In the event of higher level of earthquake resulting in fall of all the stack of fuel trays in the pool, a radiological consequence analysis was also carried out and it indicates that the situation will be manageable, for which an emergency action plan has been prepared to mitigate this situation.

Non-availability of power (Total black out)

The decay heat of spent fuel bundles stored in fuel pool is dissipated into the pool water. In order to maintain pool water temperature within permissible limits, a pool water cooling system has been provided. Pool water cooling system has been designed for SSE level of earthquake (0.2g PGA).

Pool water cooling system pumps have been provided with Class III power supply (DG set) if Class IV Normal power supply fails. In the event of failure of Class III power supply (DG sets) which are housed in a non-seismically qualified building, an additional portable DG set has been provided for cooling system which is readily available closed to the building. These are located on ground level and can be hooked to the cooling system within two hours.

In the event of non-availability of pool water cooling system because of power failure or failure of piping, an analysis for rise in pool water temperature has been carried out for rated capacity of the fuel storage. The following phenomenon is likely to take place:

- The fuel pool will continue to receive decay heat from spent fuel bundles stored in the pool.
- Heat loss from the pool to the surrounding gets affected due to surface evaporation : Though there is no air curtain over pool water surface, there will be certain amount of heat loss associated with surface evaporation due to internal circulation of air inside building. Empirical equation has been used for estimating heat loss due to surface evaporation
- Heat loss from fuel pool to ambient air due to convection and radiation: Air temperature inside pool building starts rising up because of failure of ventilation system. This results in fall in temperature potential between pool water and its ambient, decreasing rate of heat loss from fuel pool.
- On the other hand, rise in ambient air (air inside pool building) temperature will cause increased dissipation of heat through walls and roof of the building to the outside environment.

The total heat loss (surface evaporation, convection and radiation) and rate of evaporation for different temperatures have been estimated and plotted in Fig. 5 and Fig. 6 respectively.

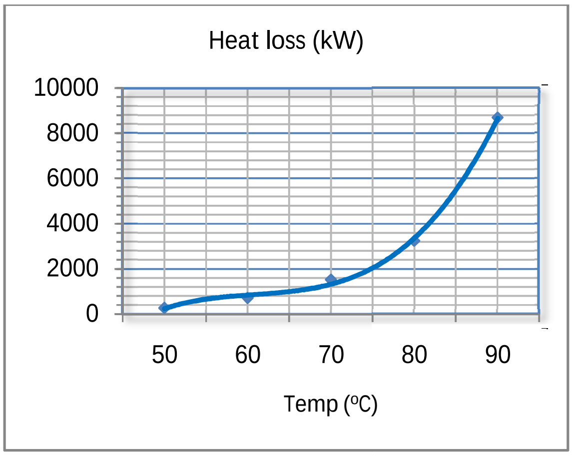

Figure 5. Heat loss Vs pool water temperature

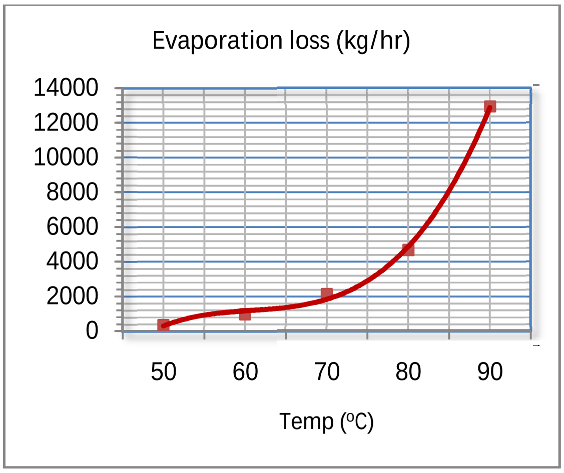

Figure 6. Evaporation loss Vs pool water temperature

The time taken to reach equilibrium condition i.e. reaching pool water temperature to 63°C was arrived by assuming that the decay heat is utilized by water mass in the pool as latent heat and it takes 37 hours to reach the equilibrium condition.

Thus it can be concluded that the pool water temperature will increase up to 63°C within 37 hours and will be maintained provided water equivalent to water loss due to evaporation.

Uncovering of spent fuel

The time available for restoration of the cooling system was arrived at as stated further. The rate of loss of water shielding was arrived based on the evaporation rate, assuming there is no addition of water to pool. It requires 42 days to uncover the stored fuel, if pool water cooling system is not restored and leading to metal water reaction. Thus sufficient time period is available to restore pool water cooling system.

Flooding due to Tsunami, rain or otherwise

Tarapur being a coastal site, a remote possibility of Tsunami exists. The Design Basis Flood Level (DBFL) for Tarapur is 32 RL. The finished floor level (FFL) of the facility is 35.1 RL. Hence, there is already margin of 3.1m for flooding.

During heavy rainfall (approx.1000mm) at Tarapur site in Jul, 2006, there were no signs of flooding near the facility. The performance of drainage system was as intended. Site studies for evaluation of Design Basis Flood Level (DBFL) shows that there is a margin for normal flooding and flooding due to Tsunami with respect to finished floor level (FFL).

In the event of severe flooding beyond design basis, water may enter fuel pool. The consequence analysis for this condition has been carried out which indicates it is a safe situation, as cooling of the pool water is not hampered. For any flooding more than the margin available, water will enter into fuel pool. As electrical sub-station, DG sets, pool water cooling system pumps and heat exchangers are housed at floor level (FFL) and batteries are at 1m from FFL, these systems will be affected. The area lighting also will be affected. Since control room and UPS are at floor-1 (6m above FFL), some of the important parameters like pool water level and temperature will be available for at least 2 hrs from power failure. But no catastrophe will take place since water acts as cooling medium. Only minor contamination (upto 500 μμCi/ml level) will take place in the flooded area

Following two major recommendations from the safety review of storage faculties are being implemented:

(a) A hook up line should be laid from outside the building to fuel pool with valve outside the building. The external water supply source (fire tender, portable water tanks, etc.) can be hooked to this pipe for maintaining the pool water level.
(b) Passive and remote instrumentation should be employed for measurement of pool water level, pool water temperature and radiation levels in the pool area.

CONCLUSION

SFSF design involves a complete and balanced set of components and systems for severe accident mitigation. The impact of the remaining uncertainties is eliminated by a robust design of the components. Sever accident analysis post-Fukushima accident was carried out for SFSF for different conditions. Analysis of the civil structure of SFSF including fuel pool indicates that a sufficient margin is available. It is further recommended to carry out a detailed analysis for the structures to check for margin.

The safety assessment of SFSF with regard to decay heat removal of the fuel indicates that there is no immediate concern as sufficient time period is available to restore pool water cooling system. Moreover, other provisions exist for maintaining the water level in fuel pool and removing the decay heat of the fuel. External water hook up provision for maintaining the required water level in the fuel pool has been provided irrespective of any other design provision. The make-up flow rate able to be commensurate with the water loss due to evaporation.

The existing monitoring of pool water level, temperature and radiation filed may not be adequate during a beyond design basis earthquake. Accordingly, suitable passive monitoring / indicating facility should be provided which will be capable of monitoring the above parameters.

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