PRA (Probabilistic Risk Assessment) for Spent Fuel Decommissioning of the Fugen Nuclear Power Station

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Abstract

Fugen Nuclear Power Station will be permanently shutdown in 2003 and immediate fuel unloading and fuel transportation is necessary. The spent fuel pool should be stored safely because the spent fuels are kept in the spent fuel pool. Loss of cooling in the spent fuel pool can lead to a serious condition. This paper is to calculate the risk of the spent fuel pool especially probability calculation of consequence during decommissioning. In this case, fuel uncovery is as end state. Calculation is based on NUREG-1738. Analysis has been done for 4 initiating events that are loss of cooling, internal fire, loss of offsite power (LOPA) and loss of inventory. Initiating event frequency is adopted from Fugen condition and NUREG. More, calculation data is taken from the living PSA of Fugen and NUREG. Results of analysis showed that the spent fuel pool of Fugen is safe enough because the fuel uncovery probability is 4.438E-08 per year. Moreover, the spent fuel pool cooling system of the Fugen NPS has high reliability because the failure probability is 7.435E-04 per year and will become 2.794E-06 per year if RHR (residual heat removal) system is included. Therefore, RHR system can be considered in the accident management during decommissioning. On the other hand, the maintenance cost increases by keeping the RHR system during decommissioning.
Keywords : PRA, Spent Fuel Pool, Decommissioning

1. Introduction

Fugen is a heavy-water-moderated, boiling light water cooled, pressure tube type prototype reactor with electric output of 165 MWe. Fugen got a final license of commercial operation in March 1979. since then , Fugen has been operating more than 23 years and achieved 21 TWh of power generation 130,000 hours of total operation time and 64% as an average load factor [1]. In this period, It has operated safely and reliably.

After the permanent shutdown in 2003, immediate fuel unloading and fuel transportation is necessary. This activity needs about several years because of capacity of the Tokai reprocessing plant. During this period, the plant especially the spent fuel pool should be stored safely because the spent fuels are kept in the spent fuel pool. Loss of cooling in this system or incident can lead to a serious condition, therefore it is necessary to analyze risk of the spent fuel pool during decommissioning.

The spent fuel assemblies are retained in the spent fuel pool (SFP) and submerged in water to cool the remaining decay heat and to shield the radioactive assemblies. Therefore, the most severe accident postulated of SFPs is loss of water from pool. In this case, decay heat for the fuel clad heats up and Zr clad will reach the point of rapid oxidation in air. More, Zr react with air or steam and this reaction is exothermic. The energy released from exothermic reaction and combined with the fuel decay heat, can cause the reaction to become self-sustaining and ignite the Zirconium. The increase in heat from the oxidation reaction can also raise the temperature in adjacent fuel assemblies and propagate the oxidation reaction. The zirconium fire would result in a significant release of the spent fuel fission products which would be dispersed from the reactor site in the thermal plume from the zirconium fire.

Purpose of this paper is to calculate probability or frequency of consequence during decommissioning of Fugen.

2. Layout of Fugen System and Spent Fuel Pool Cooling System

The cooling system is to remove the heat generated in the core by boiling and to send the steam to turbine [2]. The coolant flows into the lower header from the outlet of the recirculation pumps through 2 check valves and enters into the pressure tubes from the bottom. The heat from the fuels causes coolant to boil in the core, forming a two-phase flow of saturated steam and water, this then goes into the steam drums through the reactor outlet pipes. The two-phase flow entering the steam drums is separated into the saturated steam and water, the steam is then sent to turbine, while saturated water is mixed with the feed water and returned via the recirculation pumps through the downcomer and manifolds. Layout of Fugen is shown in Figure 1.

The reactor cooling system consists of 224 pressure tubes which are divided into two independent loops, each loop consists of a steam drum, 2 recirculation pumps, a manifold, a lower header and piping connecting these components. Four downcomers from the steam drum are combined into 2 before connected to each recirculation pump. In each loop, coolant (light water) is supplied into 112 inlet pipes in the reactor inlet header and flows into each pressure tube and then flows into the steam drum through 112 outlet pipes.

The spent fuel pool system is designed to make subcriticality condition of fuel, therefore design criteria is as follows. Temperature of pool water is kept between 20 ^{0} C and 70^0 C. Also, condition of fuel assembly is arrangement, so that k_{eff} is less than 0.85. More, pool water temperature is adjusted less than 66 ^{0} C to make safety margin.

The block diagram of spent fuel pool cooling system is shown in Figure 2. Suction is taken from the spent fuel storage pool via recirculation pumps of pool cooling (A, B and C) and is passed through the heat exchanger (A, B and C). After cool down, the coolant goes through filter system or by-pass and is returned to the discharge line. Coolant flow in shell side of heat exchanger, therefore temperature outlet of heat exchanger is kept on less than 52^0 C.

RHR (Residual Heat Removal) system is used for the abnormal condition of the SFP (Spent Fuel Pool). First condition, if amount of fuel is taken from core quickly with large decay heat after shut down when reactor troubles. Second condition, if recirculation pump of pool cooling is loss of function after loss of normal power.

2. Analysis Method

2.1. Event Tree for Initiating Event

Analysis has been done based on NUREG-1738 [3]. Analysis used event tree analysis and fault tree analysis. An event tree is a quantifiable logical network that begins with an initiating event or condition and progresses through a series of branches (usually binary) that represent expected system or operator performance that either succeeds or fails and arrives at either a success or failed condition at the end of the tree. There are 4 internal initiating events that lead to fuel uncovery (endstate). The other way, a fault tree is a logic diagram that is used to determine the logical combination of failure or condition causes that will produce an undesired event.

In this case, to calculate risk of spent fuel pool especially probability calculation used 4 initiating events that are loss of cooling, internal fire, loss of power and loss of inventory. Event trees for each initiating event are developed as in Figure 3.

Initiating Event for Loss of Cooling (IE-LOC) includes conditioning arising from loss of coolant system flow because of the failure of the operating pumps or valves, from piping failures, from an ineffective heat sink (e.g., loss of heat exchanger). In this condition, there are 5 expected (mitigating) systems/operator performance to end state as follows: Control Room Alarms (LOC-CRA), Other Indications of Loss of Cooling (LOC-IND), Operator Recovery of Cooling System (LOC-OCS), Operator Recovery Using Onsite Sources (e.g : fire water system) (LOC-OFD), Operator Recovery Using Offsite Sources (LOC-OFB).

Initiating event for Internal Fire (IE-FIR) is to assume fires of sufficient magnitude, therefor if not suppressed, would cause a loss of cooling to the spent fuel pool. Cause of loss of cooling is from damage of spent fuel pool cooling system or the offsite power feeder system. In this condition, there are 5 expected (mitigating) systems/operator performance to end state as follows: Control Room Alarms (FIR-CRA), Other Indications of Loss of Cooling due to Fire (FIR-IND), SFPC System Survive – Fire Suppression (FIR-OSP), Operator Recovery Using Onsite Sourcess (FIR-OMK), Operator Recovery Using Offsite Sources (FIR-OFD).

Initiating event for Loss of Offsite Power from Plant-centered and Grid-related (IE-LOPA) is to represent loss of spent fuel pool cooling resulting from losses of offsite power from plant centered and grid-related. These events include : hardware failures, design deficiencies, human error (in maintenance and switching), localized weather-induced faults (e.g. lightning) etc. In this condition, there are 4 expected systems/operator performance to end state,as follows : Offsite Power Recovery (LOPA-OPR), Cooling System Restart and Rerun (LOPA-OCS-REV), Operator Recovery Using Makeup Systems (LOPA-OMK), Operator Recovery Using Offsite Sources (LOPA-OFD).

Initiating event for Loss of Inventory (IE-LOI) includes loss of coolant inventory from events such as those resulting from configuration control errors, siphoning, piping failures, and gate and seal failures. In this condition, there are 7 expected systems/operator performance to end state, that are loss exceeds normal makeup capacity (LOI-NLL), Control Room Alarms (LOI-CRA), Other Indications of Inventory Loss (LOI-IND), operator isolates leak and initiates SFP make-up (LOI-OIS), operator initiates SFP Makeup System (LOI-OIL), operator initiates make-up using fire pumps (LOI-OMK), recovery from offsite sources (LOI-OFD)

2.2. Frequency of initiating event and mitigating system

Initiating event frequency for loss of cooling system is calculated based on failure of the spent fuel pool cooling system of Fugen, therefor fault tree of SFP cooling system is arranged which top event is Spent Fuel Pool Cooling System Fail. Fire and loss of inventory initiating event frequency are adopted from NUREG. LOPA (Loss of Offsite Power) frequency is adopted from level 1 PSA of Fugen. Frequency or failure probability for each mitigating system is determined based on fault tree analysis.

3. Calculation and Result

Component failure data is adopted from living PSA of Fugen (http://ftessn13.fugen.t-hq.jnc.go.jp:8010) [4]. Some data, especially human error data used NUREG data that is generic data. Also, generic data from the level PSA 1 of Fugen is used to calculate failure probability of the spent fuel pool system. Calculation is carried out by using Saphire Window ver. 6.14. The result of calculation is shown in Table 1.

Table 1. The result calculation for fuel uncovery frequency

Initiating Event	Frequency, per year		End State (Fuel Uncovery) Frequency, per year	
	RHR not included, per year	RHR included, per year	RHR not included, per year	RHR included, per year
1. Loss of Cooling	7.435E-04	2.794E-06	3.494E-10	1.537E-12
2. Fire	3.000E-03	3.000E-03	3.999E-08	3.999E-08
3. LOPA	1.200E-03	1.200E-03	1.341E-09	1.341E-09
4. Loss of Inventory	1.000E-03	1.000E-03	2.695E-09	2.695E-09
TOTAL			4.438E-08	4.403E-08

4. Discussion

Based on event tree analysis, there are 11 sequences for loss of cooling initiating event, that are 3 sequences for fuel uncovery condition and 8 sequences is safely. First worst condition, operators know that iniating event occurred but operators fail to recovery of cooling system or to run fire pumps. Moreover, operators fail to recovery using offsite sources. Frequency of this condition is 3.486E-10 per year. Second worst condition, if control room alarm fail after iniating event occurred, but operators know iniating event from other indicationts. The following sequences are as like first worst condition, so frequency of second worst condition is 7.743E-13 per year. Third worst condition is pessimistic condition which all mitigating systems fail and frequency of this condition is 4.561E-17 per year.

There are 8 sequences for fire initiating events, 3 sequences are worst condition (fuel uncovery). First worst condition, operators know that initiating event occurred but spent fuel pool cooling system fail. Also, operators fail to recovery using diesel fire pumps and offsite sources. Frequency of this condition is 3.864E-08 per year. Second worst condition, if control room alarm fail but operators can detect initiating event because other indications, therefore spent fuel pool cooling system was damaged. More, operators fail to recovery using diesel fire pumps and offsite sources. Frequency of second condition is 1.128E-09 per year. Third worst condition is pessimistic condition which all mitigating systems fail and frequency of this condition is 2.190E-10 per year.

For loss of offsite power initiating event, there are 2 fuel uncovery condition from 7 sequences. First worst condition, Operator used the other electric line after iniating event occured, but cooling system fail to restart and rerun. Moreover, operators fail to recovery using makeup system and offsite sources. Frequency of first condition is 8.044E-11 per year. Third worst condition is pessimistic condition and has frequency of 1.261E-09 per year.

Loss of inventory iniating event has 19 sequences that are 6 sequences are worst condition. The first worst condition, leakage is within normal makeup capacity and can be detected from control room alarm. Moreover, operators fail to initiate spent fuel pool makeup also operators fail to recovery using fire pumps and offsite sources. Frequency of this condition is 2.198E-09 per year. The second worst condition like as the first condition but Initiating event detected from the other indication. Frequency of second worst condition is 5.037E-12 per year. The third worst condition is identical with second condition but initiating event can't be detected because control room alarm and the other indication fail. Frequency of third worst condition is 6.045E-11 per year. The fourth worst condition, leakage is more than normal makeup capacity, so the spent fuel pool cooling system has not effect. Initiating event can be detected from control room alarm, but operator fail to isolate leak and to initiate spent fuel pool makeup. More, operator fail to recovery using fire pumps and offsite sources. Frequency of this condition is 2.388E-10 per year. The fifth worst condition is identical with the fourth worst condition but initiating event can detected from the other indications. Frequency of the fifth worst condition is 1.891E-10 per year. The sixth worst condition is pessimistic condition and has frequency of 3.450E-12 per year.

The result indicate fuel uncovery frequency of about 10^{-8} per year. This value is sufficiently below the upper limit of interval estimation for safety target as defined by NUREG-1738 (about 5E-07 per year).

Reliability of the spent fuel pool system is high because the failure probability is about 7.435E-04 per year and this value becomes about 2.794E-06 per year if residual heat removal system is included for analysis. Therefore, RHR system can be considered in the accident management during decommissioning. On the other hand, the maintenance cost increases by keeping the RHR system during decommissioning.

The largest contribution to fuel uncovery is fire initiating event. This is because the fire initiating event is not caused of the system failure. More, the fuel uncovery probability is slightly different if RHR included because the largest contribution is from the fire initiating event, but the fuel uncovery probability is caused the loss of cooling initiating event can be reduced by more than 50%.

To complete this analysis, evaluation for the thermal-hydraulic characteristic of the spent fuel storage in SFP of decommissioning plants should be done. This result is to determine the time available for plant operators to take actions to prevent a Zr fire. The focus was the time available before fuel uncovery and the time available before the Zr ignites after fuel uncovery. Based-on NUREG, some events for example operator recover or pump repair is limited for 85 hours (recovery effort is not effective if when than this time). This value is determined based on safety analysis of NPP in US.

5. Conclusion

The spent fuel pool of Fugen NPS is safe enough during decommissioning because of the fuel uncovery probability is below the upper limit from safety target as NUREG defined (5E-07 per year). Moreover, the spent fuel pool cooling system has high reliability.

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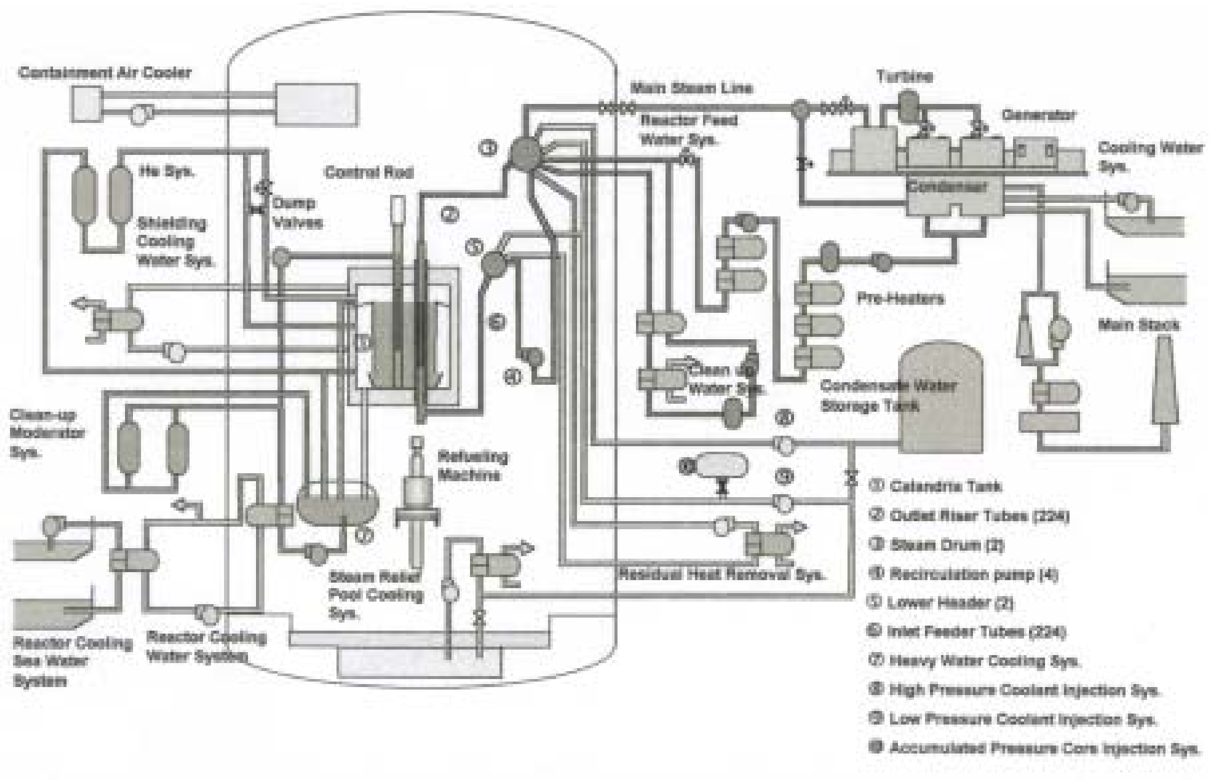

Figure 1. Layout of Fugen System

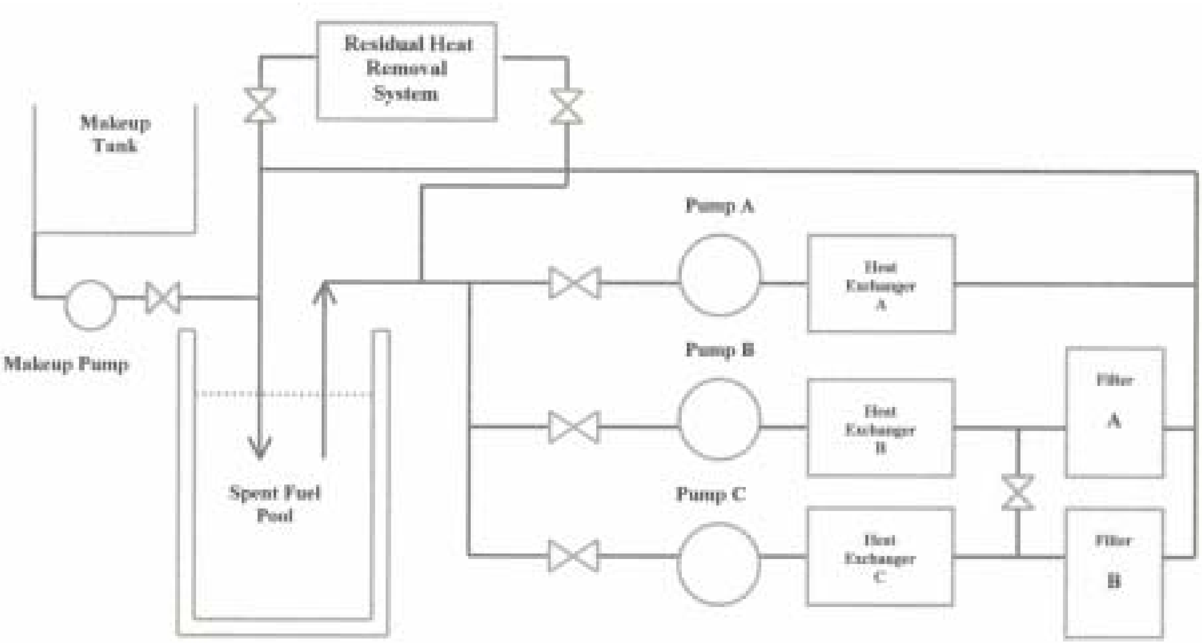

Figure 2. Block Diagram of Spent Fuel Pool Cooling System

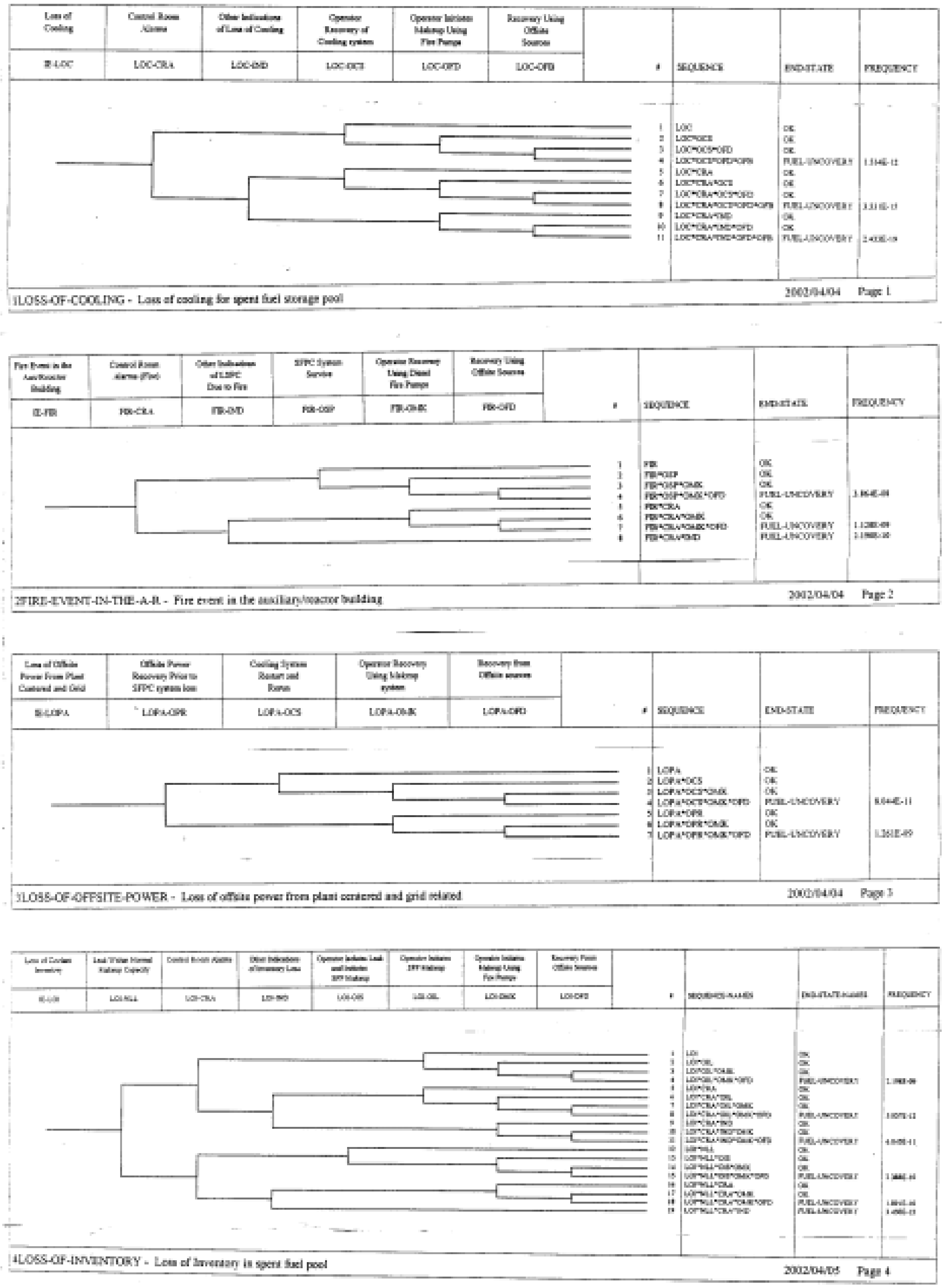

Figure 3. Event Tree for Spent Fuel Decommissioning of the Fugen NPS