Spent Fuel Pool PRA for measuring risk change by action on response to the Fukushima accident

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Fukushima nuclear accident was not one of the accident scenarios which has preparedness plan, due to low frequency. But because the catastrophic accident was occurred in Fukushima, it became necessary changes in the nuclear safety framework. The major insight of Fukushima accident was necessity to prepare prevention and mitigation plan for beyond design basis accidents at multiple units. In addition, through the case of the incident of 4th unit of Fukushima, spent fuel is also important factor of the radiation release. Integrated risk assessment for whole site is necessary for developing preparedness plan for severe accident such as Fukushima event. The purpose of this paper is to acquire the information for developing spent fuel pool PSA (SFP PSA) and integrate risk from SFP into current PSA framework.

I. Introduction

SFP requires the continuous cooling ability due to heat generated by radioactive decay as with nuclear reactor. If cooling ability is lost, pool will be drain out and the occur accident which spent fuel damage and radioactive release. In fact, this situation is suspected in Fukushima Daiichi Unit 4 due to station black out accident caused by tsunami. Than the government of Republic of Korea followed up of these risks from Fukushima accident and adopted action plan for improving redundancy of SFP cooling and inventory make up ability (The action on response to the Fukushima accident, 3-5, Countermeasure for Loss of SFP cooling ability). However such an action is performed, it was impossible to measure risk changes in quantitative way because PSA for spent fuel was not conducted yet.

The purpose of this paper is to develop a method for integrating SFP risk into current PSA framework. For integrating risk of SFP accident, this paper provides example based on Korean commercial nuclear power plant such as possible initiating events, design of SFP and related systems and mitigating strategy.

II. Design Features of spent fuel pool

The SFP cooling and cleanup system is composed of two redundant 100 percent capacity cooling divisions that are used to remove heat from the SFP and two 100 percent capacity combined cleanup divisions that are used to purify water in the SFP, refueling water storage tank or (IRWST for APR1400), the fuel transfer canal, and the refueling pool. System description written down below is based on DCD of APR1400 (Ref. 1) and these documents follow NRC Regulatory guide 1.13, "Spent Fuel Storage Facility Design Basis" (Ref. 2).

II.A. Spent fuel pool cooling & cleanup system

Each cooling division consists of one heat exchanger and pump, and associated piping, valves, and instrumentation. Each cooling division is designed to maintain the SFP water temperature below 60 °C (140 °F) during normal and accident conditions. The SFP cooling system removes decay heat from fuel stored in the SFP. Decay heat is transferred from the SFP cooling system, through two heat exchangers, by using the component cooling water system.

The SFP cooling system is located in a seismic Category I building (Auxiliary Building) that provides protection from the effects of natural phenomena and external missiles. SFP cooling system components such as piping, pumps, valves, and heat exchangers are safety-related and designed as safety Class 3. Each cleanup division consists of a strainer, a pump, a cleanup filter, a demineralizer, and a demineralizer filter to maintain the clarity and purity of SFP, fuel transfer canal, refueling pool, and RWST water. This cleanup loop capacity is sufficient for removing fission products and other contaminants that may be introduced if a leaking fuel assembly is transferred to the SFP. The cleanup division can clean and purify the refueling water while SFP heat removal operations proceed.

II.B. Relative system

SFP cooling system has support system such as 480V AC power source for operating motor driven pumps for driving force. The supporting system failure occurs loss of spent fuel pool cooling ability.

II.A.1. Makeup water sources

The SFP is initially filled with water that has a boron concentration range of 4000 to 4400 ppm. The SFP receives normal borated makeup water from the RWST (boric acid storage tank for APR1400). RWST and all associated piping and valves are classified as seismic Category I and safety Class 3. And one of the other makeup water source is condensate storage tank (AFWST for APR1400). The makeup water is delivered to the SFP by the CCW makeup pumps. Also CST and all associated piping and valves are classified as seismic category I and safety class 3. The non-seismic category makeup water source is the demineralized water storage tank (DWST), and the makeup water is delivered via a manually operated valve in the connecting line. Makeup water compensates for normal evaporative losses. The simplified P&ID for spent fuel pool and makeup water source is shown in figure.1 down below.

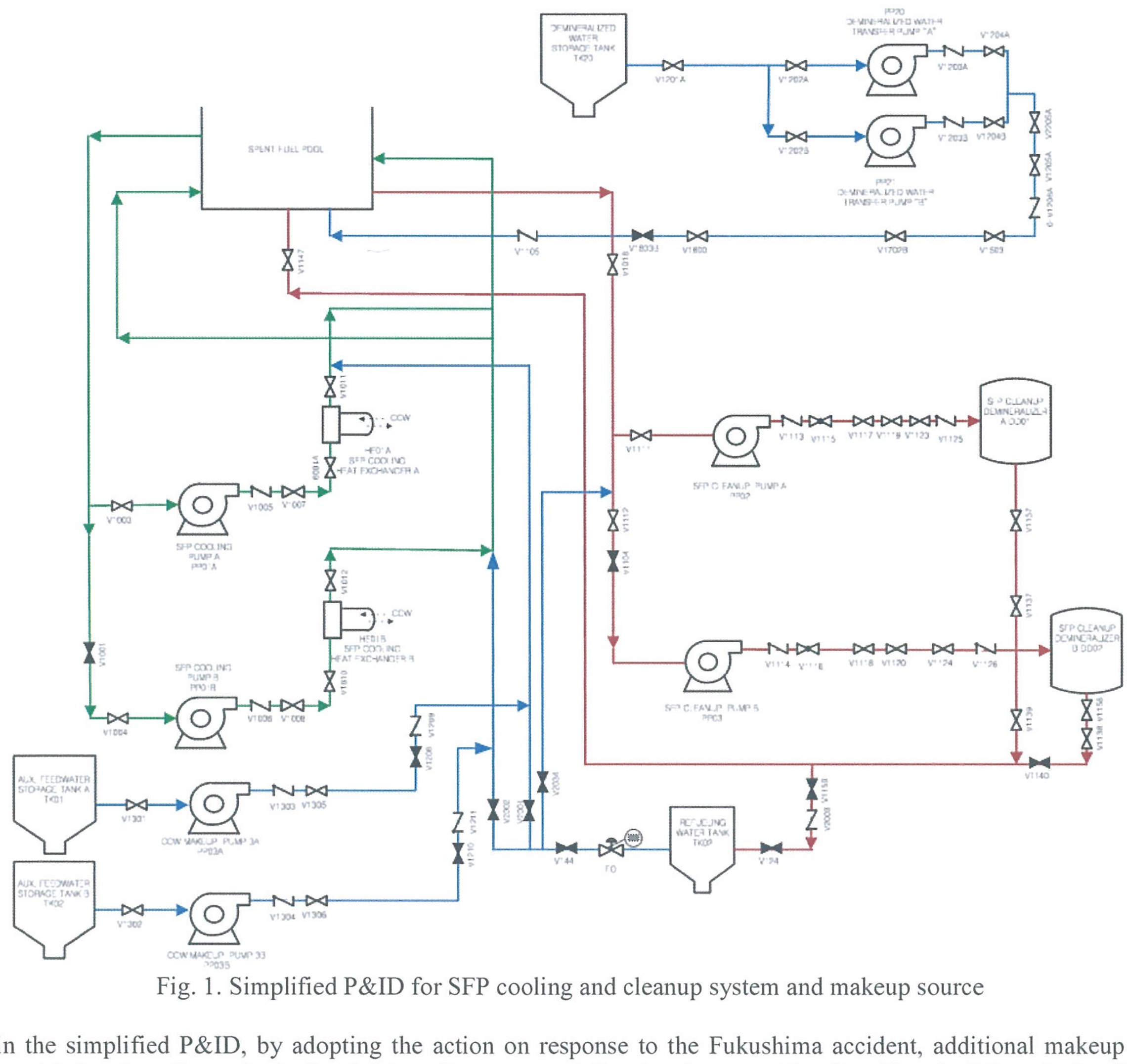

Fig. 1. Simplified P&ID for SFP cooling and cleanup system and makeup source

Not in the simplified P&ID, by adopting the action on response to the Fukushima accident, additional makeup water sources are added such as fire tank via diesel driven fire pump or delivering from outside of auxiliary building via fire fighting vehicle.

II.A.2. Power source

SFP cooling pump requires 480V AC power for operation. SFP cooling pump is non-safety pump but power supply is Class 1E 480V power source. The 480V Class 1E load centers and MCCs are located indoors in seismic Category I buildings. Each load center and MCC is provided with potential transformers, relays, and current transformers. Load center transformers connected to the Class 1E 4.16 kV buses provide power to Class 1E 480V load center buses. The Class 1E 480V MCC buses are connected to the Class 1E load center buses.

The 480V onsite ac power system is energized by the 13.8 kV and 4.16 kV switchgears through 13.8 kV/480V and 4.16 kV/480V transformers. Following a LOOP, the associated Class 1E EDGs are started and the safety buses are isolated from offsite sources and fed solely from the associated EDG. The four load sequencers (one for each Class 1E bus) used for bus load shedding and load sequencing are independent from one another. For calculating Class 1E loads for load sequence, SFP cooling pumps were in manual loads group. Manual load are added to the Class 1E buses by operator in case plant conditions require usage.

By adopting the action on response to the Fukushima accident, newly designed plant changes load sequence group of SFP cooling pump from manual group to A and B group which are energized immediately upon closure of the EDG incoming breaker.

II.A.3. Instrumentation & Control equipment

During normal operation, system performance is verified by monitoring system pressures, temperatures, levels, and flows. SFP cooling system temperature and level instrumentation are powered from the Class 1E electrical system.

Instrumentation classified as safety Class 3 is provided to measure the temperature of the water in the SFP, and non-safety instrumentation is needed to measure the temperature of the refueling pool. The instrumentation is provided to give local and MCR indication as well as annunciations in the MCR when there is a deviation from normal temperatures.

Instrumentation installed downstream of the SFP heat exchanger measures the SFP cooling portion flow and shows local indication of the SFP cooling portion flow. This instrument is used to check whether the flow rate of the cooling water returning to the SFP via the SFP heat exchanger is maintained at the specified value. Alarms that indicate a loss of cooling function are provided to the MCR to detect low flow rates. A local flow indicator for measuring the purification flow is installed at the outlet of each purification line.

Two safety-related SFP water level transmitters are installed in the SFP to measure the SFP water level from a 100 percent water level to the top level of the spent fuel assemblies. The SFP water level transmitters annunciate high water level, low water level, and low-low water level of the SFP to the MCR, RSR, and locally. The SFP cooling pump and cleanup pump are interlocked with SFP water level to stop the pumps automatically as the SFP water level is decreased to a predetermined set point. The interlock prevent the pumps from cavitation and failure.

III. Target Accident Scenario for actions on response to the Fukushima accident

The action on response to the Fukushima accident for SFP focused on cooling and inventory makeup ability for LOOP and SBO accident. The changes of design and mitigating strategy is shown table below.

TABLE 1. The action on response to the Fukushima accident for SFP

	Action Taken
Inventory Makeup Ability	Diesel Driven Fire Pump Portable makeup pump (Fire fighting vehicle)
Power Source	Load sequence group changes (Automatically energized by EDG and AAC)

For measuring risk change, event tree for Loss of SFP cooling (LSFPC) due to LOOP and SBO accident is required. The success path for LSFPC due to LOOP and SBO is recovering cooling ability for spent fuel. SFP cooling pump requires 480V AC power and SFP cooling heat exchanger needs CCW for delivering heat. If EDG is available, power source for SFP cooling pumps and CCW pump shall be operable. So the First heading of event tree is EDG. If both EDGs are fail, AAC DG can supply 1 SFP cooling division.

The SFP water volume allows an approximately 3.7-hour margin prior to SFP water boiling during a total loss of cooling condition or SBO at full core offloads in reference plant. Diesel fuel for operating EDG and AAC is available for 8 hours, so available time for recover SFP cooling without inventory makeup is 3.7 hours for total loss scenario and 11.7 hours for scenarios which is EDG or AAC is available.

After SFP boil off, SFP cooling pump is not operable due to water level down below suction line and pump cavitation. For recovering SFP water level and temperature, delivering normal borated makeup water from the BAST via the BAMP is available in this scenario. The AFWSTs are also possible water sources in other scenario but not for LOOP and SBO because AFWS is operated for secondary heat removal for RCS cooling. If AC power is recovered in time, DWST can be delivered via a manually operated valve in the connecting line. All of these mitigating actions fail, only portable devices which were planned for post Fukushima action are available. By these information, event tree for LSFPC due to LOOP and SBO accident is shown figure down below.

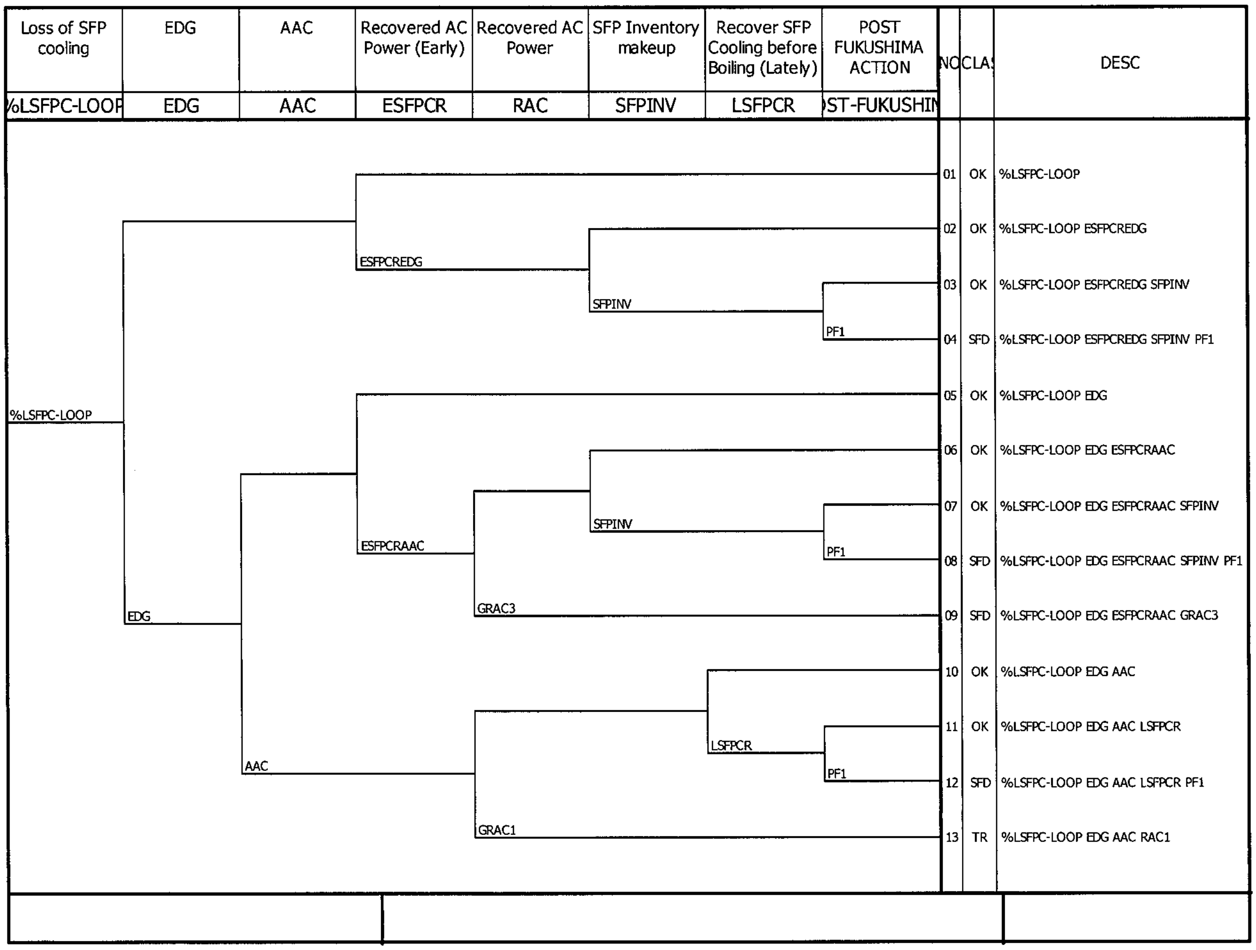

Fig. 2. Event tree for LSFPC due to LOOP and SBO accident

IV. Fault Tree Analysis

For each system considered in the accident sequence event trees, a fault tree is constructed to allow for quantification of the system unavailability to perform the required accident mitigation function. Fault trees are constructed for the systems represented in the top functional events in the event trees and various systems needed to support these systems. The system dependencies are explicitly considered. The fault trees for EDG and AAC are referred to exist PSA model.

IV.A SFP Cooling System

Each SFP cooling division consists of one heat exchanger and pump, valves, and instrumentation. Among these components, SFP cooling system needs support systems such as Class 1E AC power system, Cubicle cooler for room cooling, CCWS for heat exchanger, and instrumentation & control equipment for activating signal. Cubicle cooler requires Essential chiller and Class 1E power source and the activating signal for re-operating SFP cooling pumps are consist of Operator action and EDG Load sequencer (after action taken to Fukushima accident). All of these components are safety related equipment than it is able to operate for LOOP and SBO accident. SFP Cooling system FT is shown Figure down below.

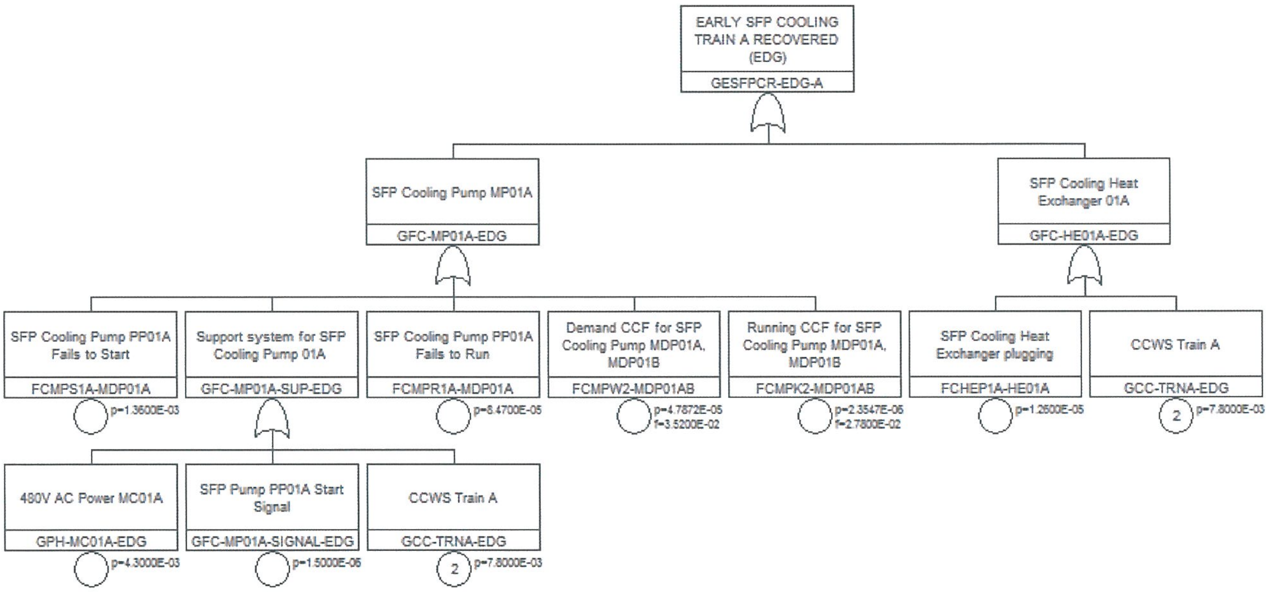

Fig. 3. SFP Cooling system fault tree

IV.B. SFP Inventory make up

BAST can be connected to SFP cleanup line via BAMP. The SFP cleanup system has independent flow paths along with components that are physically separated from the SFP cooling system. For delivering coolant from BAST to SFP, both SFP cleanup pump and BAMP should be operated and operator needs to line up many manual valves at fuel handling area. These systems and components are non-safety class, offsite power should be recovered before inventory make up. And DWST is another make up source. Demineralized water from a DWST makeup water source is used to make up for the normal evaporation losses of the SFP and the makeup water is delivered via a manually operated valve in the connecting line. For delivering coolant from DWST to SFP, both SFP cleanup pump and Demineralized water transfer pump should be operated and operator needs to line up many manual valves at fuel handling area. These systems and components are non-safety class, offsite power should be recovered before inventory make up. Fault trees for delivering normal borated makeup water from the BAST via the BAMP and DWST delivering demineralized water from DWST via transfer pump are shown figure down below.

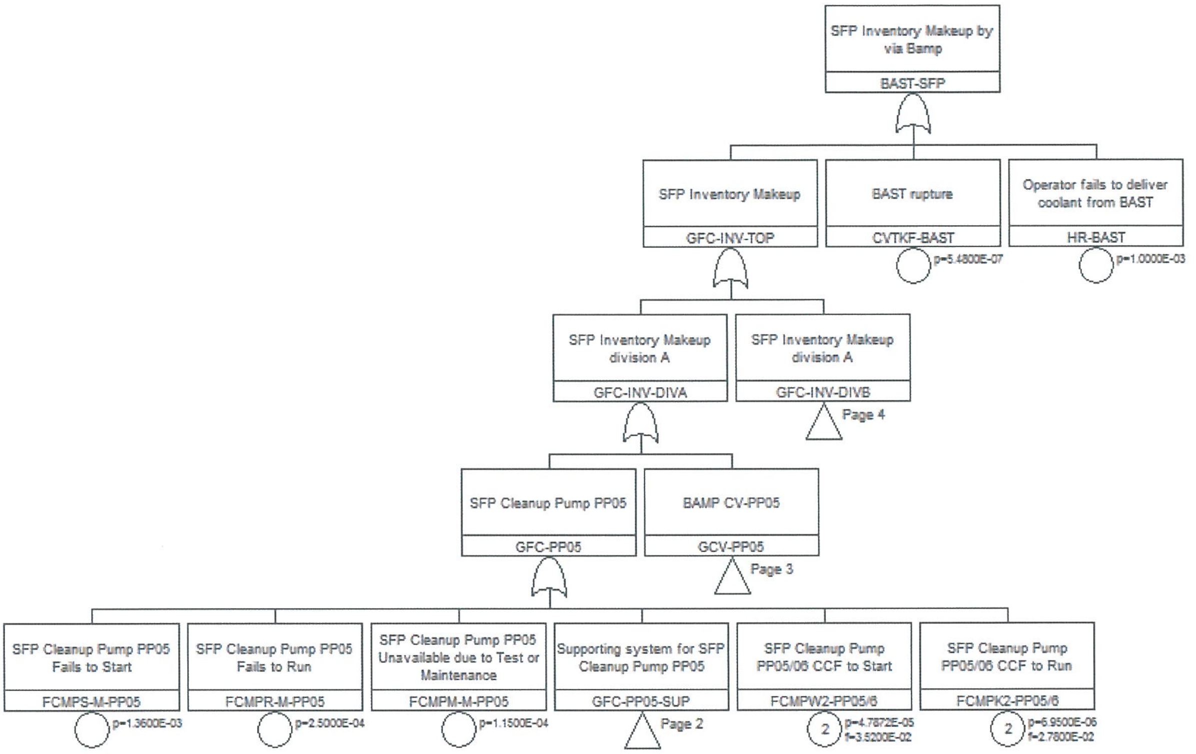

Fig. 4. Fault tree for delivering normal borated makeup water from the BAST via the BAMP

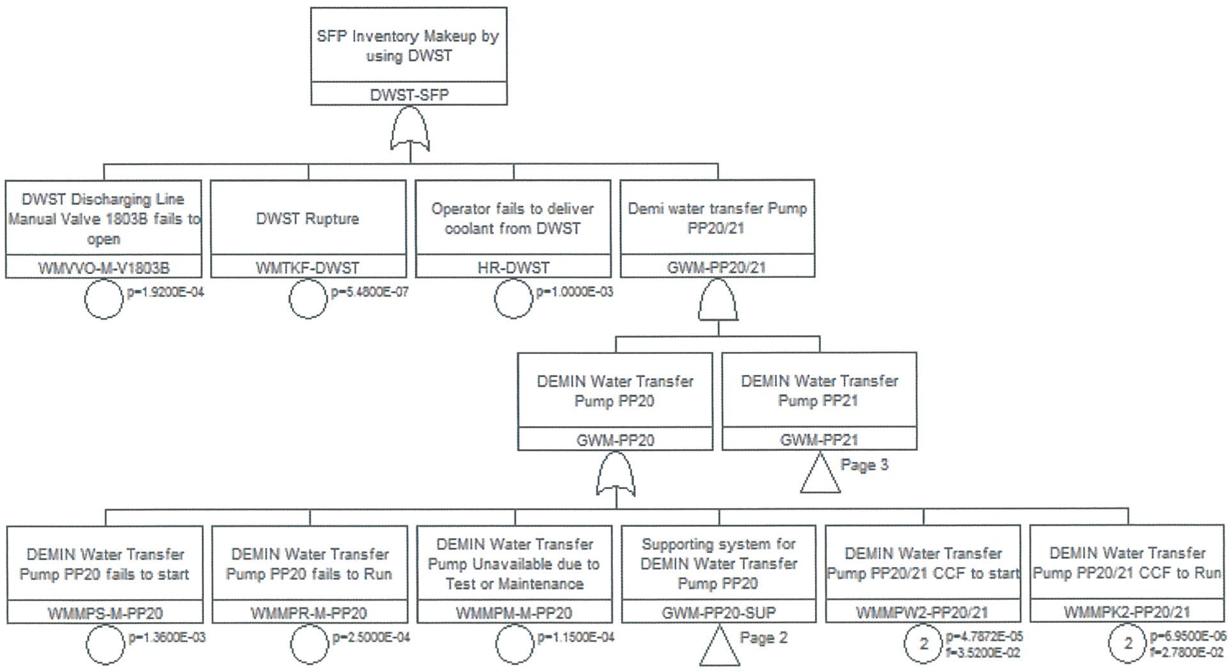

Fig. 5. Fault tree for delivering water from the DWST via the Demineralized water transfer pumps

IV.C. Post Fukushima Action

As mentioned in the previous section, BAMPs and Demineralized water transfer pumps requires 480V non-1E AC power, so these inventory makeup sources are unavailable before offsite power is recovered. In consideration of these points, other safety features and operating procedures which includes diesel driven fire pumps and fire fighting vehicles for LOOP, SBO scenarios were added to mitigating strategy. These mitigating strategies provide defense in depth to the offsite and on-site emergency electrical power systems including the safety related on-site diesel generators and SBO generators. However there are no applicable methodology for assessment for crediting these plant independent mitigating strategies developed yet. Therefore, degrees of reliability factor will be assumed by engineering judgement. In order to calculate risk changes, sensitivity analysis performed by changing reliability factor. Fault tree for these mitigating strategies is shown in figure down below.

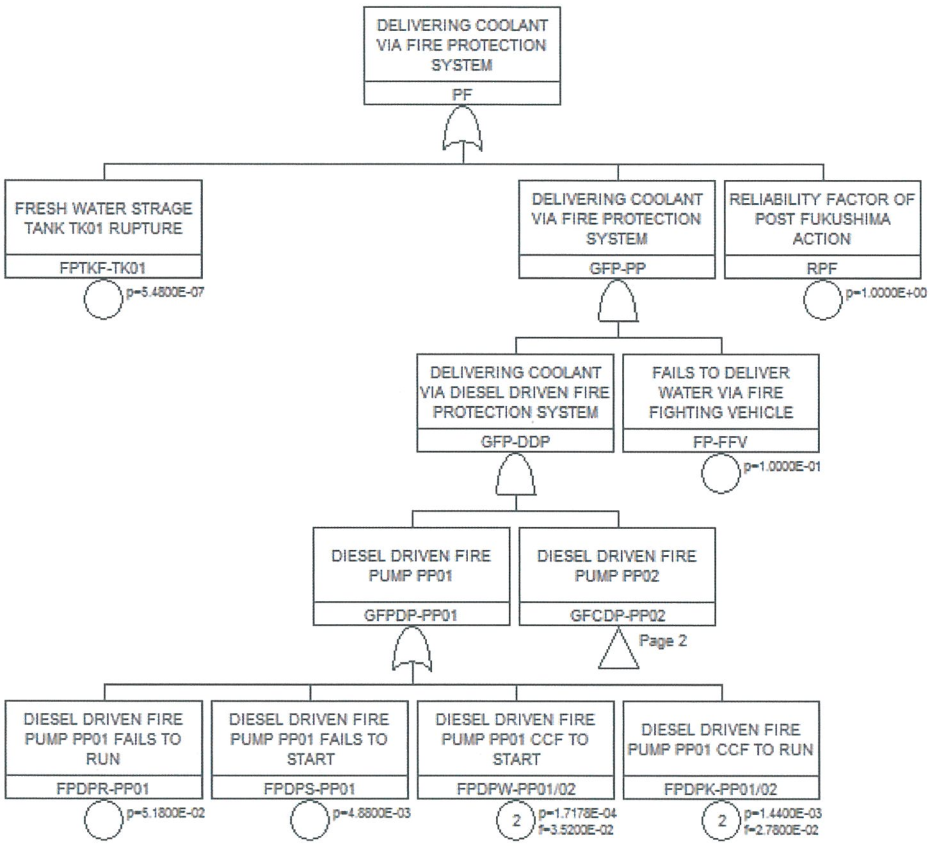

Fig. 5. Fault tree for plant independent mitigating strategies (Post Fukushima Action)

IV.D. Assumptions

Assumptions used in this report are as follows.
- AAC is assumed to cover only division A. (division B unavailable)
- When both EDG & AAC fails, sequence is transfer to exist PSA event tree (not core damage, AFTDP remains).
- If EDG is available, it is assumed to have sufficient time to recover offsite power.
- Fire pumps and Fire fighting vehicle are assumed to be unavailable in worst case (for operating ECSBS).

V. Quantification result & sensitivity analysis

The accident sequences are dominated by sequence number 9. This sequence has no credit for plant independent mitigating strategies because these equipment also contributes ECSBS for reactor core. For mechanical component, 480AC bus and CCW system are the outliers. The outliers support for most of key safety systems which failure would result in the inability to operate these systems.

A sensitivity analysis was performed to evaluate the impact of risk changes due to adopt plant independent mitigating strategies. The base model does not credit any mobile equipment that may be available as a result of Fukushima accident action items. A sensitivity case was evaluated to examine the potential impact of crediting for fire pumps and fire fighting vehicles in the PSA model. This was accomplished by decreasing the reliability factor of the Post Fukushima Action (basic event RPF) and the result showed that there is only a minor decrease in CDF. The other sensitivity case gives credit to plant independent mitigating strategies for sequence number 9. The result showed a major decrease in CDF.

VI. Conclusion

The outliers show that the risk is strongly influenced by the performance of support systems. And the plant independent mitigating strategies such as Post Fukushima Action will help reduce the risk from some contributors. However, it requires ensuring that the equipment, plan and operator in the portion of the scenario has not to be failed. For ensuring capability of these strategies, securing trained staffs, organizing necessary command & control system, and making plans for guarantee the function of equipment should be obtained.

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