The Failure Mode & Effect Analysis of a Fuel Handling System at Cernavoda Unit 2

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ABSTRACT

The FMEA(Failure Mode & Effect Analysis)[3] study was performed for a fuelling machine and a fuel handling system at Cernavoda unit 2 in Romania. The resolution level of the FMEA was to the level of specific Cernavoda unit 2 flowsheets and a major component in the mechanical drawings. Failure of the control and instrumentation components is not included in this task. The FMEA study identified the safety functions during fault conditions such as an internal mechanical fault, an internal fire induced effect, an internal flooding induced effect, an earthquake induced effect and a loss of a support service system(the instrument air, the service water & the electrical power). The results would convey the adequacy of a redundancy in a system, the alarms and indications to the operator in the MCR to develop the additional operating procedure to recover abnormal conditions.

INTRODUCTION

The FMEA was performed by an independent assessor at the request of the regulatory authority CNCAN (Comisia Nationala pentru Controlul Activitatilor Nucleare – National Committee for Nuclear Activities Control in Romania) to provide an independent overview of all the nuclear safety aspects of Cernavoda Unit 2 under construction and an expert opinion as to whether the completed Cernavoda Unit-2 Nuclear Power Plant would satisfy the current Western European nuclear safety objectives and practices. European Union (EU) required the safety level of Cernavoda unit 2 in Romania to be comparable to those of other European Nuclear Power Plants (NPPs). As a part of the activities to meet these requirements, a safety review for its fuel handling system has been performed. The on-power fueling system is one of the unique systems of the CANDU (CAnada Deuterium Uranium) type NPP. It uses a natural uranium and heavy water moderator/coolant and thus requires a daily fueling of new fuel to maintain its criticality due to a small excess reactivity. Because of the importance of the fuel handling system to the reactor operation and the EU country nuclear experts' unfamiliarity with this on-power fueling system, EU requested Romania to perform a Safety Evaluation of this system separately from the conventional safety analysis covering all the Design Bases Accidents when the Cernavoda unit 2 Reconstruction project started in 1995. A report was produced (Cernavoda 2 Nuclear Safety Expert Project, "Task 10–Safety Evaluation Report", A.F. Parsons, NNC Limited, December 2001) and it contains recommendations either mandatory or advisory. The FMEA study, one of the mandatory recommendations, was performed for the fuel handling system and the radioactive waste handling system for Cernavoda unit 2 in Romania. In this paper, only the FMEA study for fuel handling system is presented. This paper presents some of the insights already learned during the safety evaluation project, which is being performed by KHNP(Korea Hydro & Nuclear Power Company) and KAERI(Korea Atomic Energy Research Institute) as requested by SNN (Romanian National Nuclear Company) with the project duration from November 2005 to February 2007.

FUEL HANDLING SYSTEM DESIGN OF CANDU 6

To perform the FMEA study for a fuel handling system, the design characteristics of Cernavoda Units 1 and 2, and Wolsong(reference plants) Units 1 and 2/3/4 in Korea were reviewed to understand the design features of a fuel handling system. In order to ensure that the analysis covers all the parts of the fuel handling system, a study on the system familiarity with design documents, safety analysis reports, internal fire, internal flooding and earthquake hazard analysis reports of Cernavoda Unit 2 and Wolsong Unit(reference plant for this project) 1/2/3/4 were performed.

The fuel handling system is made up of two sets of fueling machines (FMs), FM support carriages and associated supporting tracks, reactor vault bridges/column assemblies, a new fuel transfer, an irradiated fuel discharge and FM calibration facilities, an irradiated fuel transfer system, plus all the associated auxiliaries, power supplies and control systems. The subsystems considered are the D2O supply system, D2O control system, oil hydraulics system, instrument air system, electrical supply system, and the C&I system. One FM is used for the new fuel bundles transfer and the other FM is used for discharging the irradiated fuel bundles for the same fuel channel. Figure 1 shows the movement of a fuel from the new fuel storage area through the reactor to the irradiated fuel storage bay.

The purpose of the fuel handing system of CANDU 6 reactors is to provide an on-power fueling capability at a rate sufficient enough to maintain a continuous reactor operation at a full power. In addition to performing the routine process function noted above, the fuel handling system is also required to meet the following safety requirements:

a) Maintain the primary heat transport (PHT) System pressure boundary while either coupled to an end fitting (on-reactor) or traveling across the reactor face (off-reactor)
b) Remove decay heat from the irradiated fuel bundles in the fueling machine during a transfer and discharge to an irradiated fuel bay.
c) Control the radioactive releases from an irradiated fuel during a normal plant operation.

The normal fuelling operation cycle is based on a fuelling for seven days per week, and considers the addition and removal of 16 bundles per day, with bundles handled at a rate of eight bundles per channel fueled. The fuelling machines have several different operating states (modes) depending on whether they are attached to the reactor, traversing to or from the reactor, or attached to one of the service ports, as shown in Figure 1. The normal fuelling operation cycle is made up of the incremental movements of the F/Ms as they traverse between the maintenance locks and the reactor vaults, inserting new fuel into the reactor and removing spent fuel. The whole operation of the fuel changing operation cycle by the fuelling machine was divided into 11 specific operation modes as shown in Table 1.

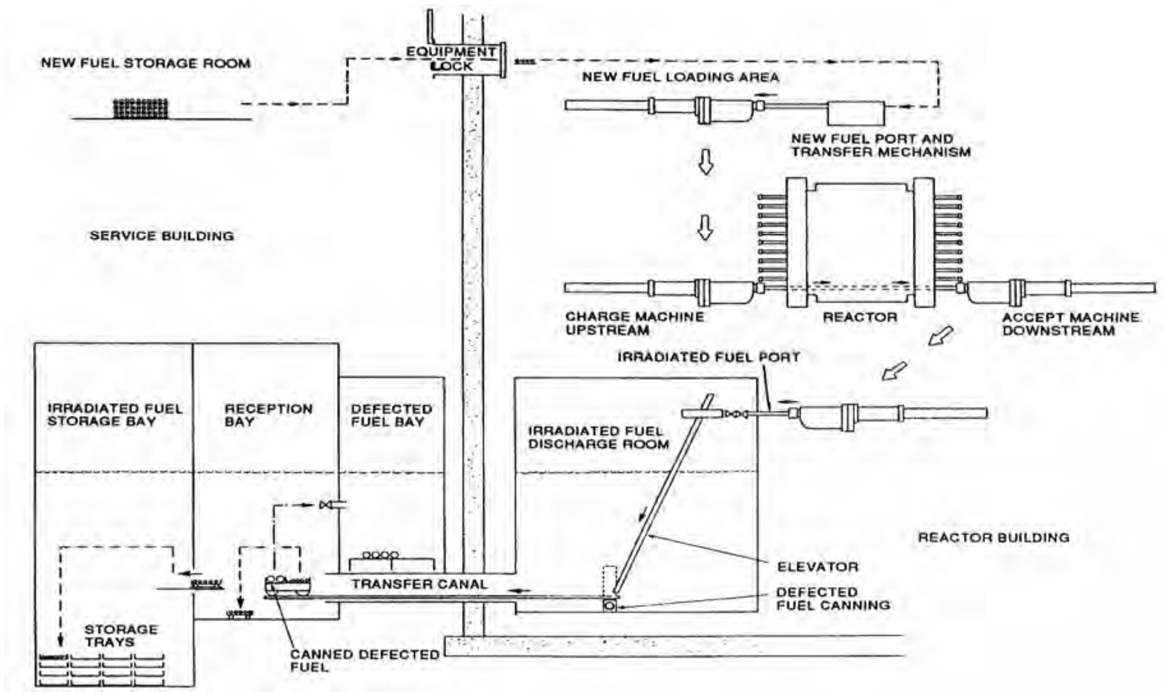

Figure 1. Fuel Handling Sequence of CANDU 6 Plants

Table 1. Fuelling Machine Operation Cycle

Step	Operation	Time(min)
1	FM-A moves to the New Fuel Port (NFP) to pick up eight new fuel bundles	1.0
2	FM-A performs New Fuel duty cycle. During this time FMC moves to NFP and waits for FM-A to complete loading of eight new fuel bundles.	26.4
3	FM-A and FM-C move in parallel from the NFPs to their respective fuelling machine bridges at each face of the reactor.	2.0
4	FM-A and FM-C are raised by the reactor bridges to the pre-selected channel	2.0(average)
5	FM-A and FM-C home and lock onto opposite ends of the same channel. FMA loads eight (8) new fuel bundles into channel and FMC receives eight (8) spent bundles into its magazine.	60.3
6	Bridge with FM-A and FM-C move down to align with maintenance lock tracks	2.0(average)
7	FM-A travels to New Fuel Port and waits for FMC to completed the step 8,9 and 10.	-
8	FM-C travels to Spent Fuel Port (SFP) to discharge spent fuel bundles	4.0
9	FM-C performs its Spent Fuel duty cycle – discharges eight (8) spent fuel bundles at	28.7

	SFP	
10	FM-C moves to NFP to pick up eight new fuel bundles.	1
11	FM-C performs New Fuel Duty Cycle.	26.4

The three fuel handling operation modes which have a potential possibility to release radioactive material were selected for this study as follows. The FMEA study focused on these three selected operation modes.

- on-reactor mode(step 5 in Table 1)
- spent fuel transfer mode(step 8 in Table 1)
- spent fuel discharge mode(step 9 in table 1)

Operating experiences related to the fuel handling systems are collected and reviewed to identify the safety and operational characteristics of the fuel handling system of CANDU-6 plant and to utilize the FMEA. Operating experiences have been collected from the CANDU Owners Group(COG) event records and INPO, WANO, IAEA data bases and the Wolsong plants operational experiences from 1973 to 2006. These operating events for the fueling handling systems were also categorized to utilize the FMEA as a maintenance error, operation error, and system mechanical error, etc. The impacts of the events on a plant's operation were categorized into a forced outage, maintenance outage and unaffected by them also. The most frequent event types can be categorized as follows.

- D2O leak due to catenary hose failure
- Failure to remove guide sleeve after fuel change
- Sticking of L-ram and C-ram stuck due to a loss of hydraulic oil or D2O supply
- Stuck fueling machine on the channel due to a loss of hydraulic oils
- Stuck irradiated fuel bundle on the ladle due to a loss of D2O supply to the C-ram
- Data error of DCC-Y computer

A walkdown of Cernavoda Unit 2, to define a discrepancy between the design and the construction, was also performed.

FAILURE MODE AND EFFECT ANALYSIS FOR INTERNAL EVENTS

For the whole fuel handling system, a FMEA was performed for each function of the system, and for the flow circuits of each function according to the three selected operational modes in the previous section. The redundancies/diversity and annunciation capabilities were identified for each function. The three representative safety functions of the fuel machine and the fuel handling system during fault conditions were identified as follows. The main safety functions of the fuelling machines during a fuel changing operation are to maintain the integrity of the PHT system pressure boundary and to provide a spent fuel cooling. The identified safety functions are the potential possibilities that cause an actuation of the safety systems such as a plant trip system, emergency core cooling system and a release of radioactive materials also.

- Maintain the integrity of the heat transport system pressure boundary during on power refueling
- Protect fuel damage during on power refueling
- Maintain the spent fuel cooling during transfer and discharge to the spent storage bay

The main failure modes that could be vulnerable to the three selected safety functions were classified according to the functions of the fuelling machines and sub-systems during the fuel change operations. The failure modes which can occur during the fuel changing operations are considered as follows.

1) Fuelling Machine Failures
- Clamping functions fails.
- Magazine drive fails to rotate the magazine station.
- One of the 3 ram assemblies (B Ram, Latch Ram, C Ram) fails to remove or replace the fuel bundles, guide sleeve, channel closure, shield plug and snout plug.
- F/M D2O supply system fails to provide D2O.
- F/M Head control D2O system fails to provide D2O.
- F/M catenary system fails.
- F/M bridge/carriage brakes fails to maintain their position.

2) Spent Fuel Transfer System Failures
- Mechanical damage to a spent fuel transfer port
- Mechanical damage to the fuel in a spent fuel transfer port
- Failure of the spent fuel transfer standby cooling (spray) system.

3) D2O supply system
4) Oil hydraulic system
5) D2O control system
6) Class IV Power Failure

7) Class III Power Failure
8) Total Loss of Instrument Air
9) Class II Power Failure
10) Failure of a Recirculated Cooling Water (RCW) and Raw Service Water (RSW)
11) Digital Computer Failure

The failure effects caused by the considered failure mode above are a mechanical failure of the fuel bundles, a loss of the D2O inventory, and the possibilities of a radiation release to the environment. The most severe event scenarios were found to be as follows;

- A breaking of the fuel channel end fitting accompanying the ejection of 12 irradiated fuel bundles.
- Loss of coolant accidents when the FM is in an on-reactor condition
- Mechanical damage to the two irradiated fuel bundles when being lowered to the bottom of the discharge bay floor from the irradiated fuel port accidentally.

The consequences of the failure effects of the fuel handling systems are categorized according to four dimensional impact spaces (i.e., environment impact, health impact, economic impact, and safety impact). A logic diagram was developed and is shown in Figure III-1. Here, we mainly focused on a safety impact such as a LOCA and a mechanical damage of spent fuel bundles. Some of the typical accident scenario groups were identified and the frequencies were estimated from the Reliability Analysis Report for the Fuel handling system also. These accident scenario groups are presented in Figure 2.

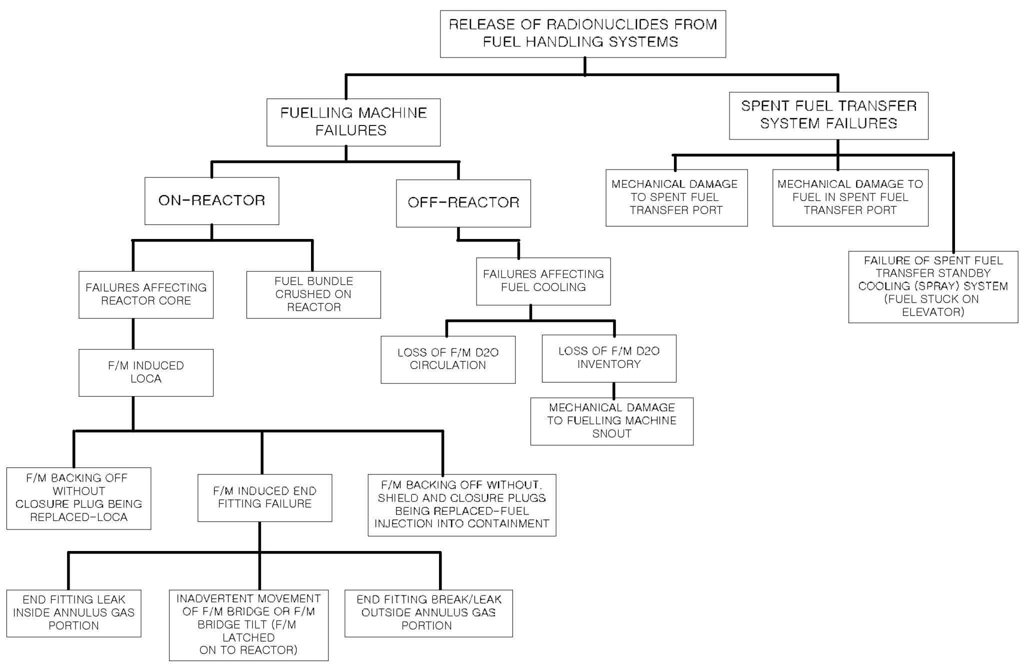

Figure 2. A Logic Diagram for an Identification of Accident Scenario

However these kinds of severe accidents are rare from the review results of the Event History Docket. By its nature there have been many incidents of D2O leaks through catenary hoses. However by a well-established maintenance policy, the frequency of this kind of event could be reduced.

FAILURE MODE AND EFFECT ANALYSIS FOR EXTERNAL EVENTS

The FMEA for external events was performed and the results were as follows. The plant areas were identified to perform the external events FMEA. The identified plant areas that contain all of these components were initially selected for the external events FMEA analysis. In this task, all the identified components based on the internal events FMEA could disturb a successful system operation or change the operation state to cause the four failure modes mentioned in the above section. For this task the CNE-PROD Cernavoda Seismic-Fire-Flood PSA Summary Report and the Wolsong 2/3/4 PSA report were reviewed. A total of 11 plant areas were identified for the external events FMEA and summarized in Table IV 2. For each room an FMEA of the fire and flooding events was performed.

The internal fires FMEA for the fuel handling system at Cernavoda unit 2 was performed to assess the failure modes induced by internal fires, to identify its vulnerabilities to fire-initiated events and the evaluate the potential effect of fires during the performance of the fuel handling system. The most significant fire area is the D2O supply room(R-012) which contains electrical cables, motors and HVAC equipments. The failure effects in this room fire are a total loss of D2O supply to both fuelling machines. It could cause a D2O leak from a fuelling machine during a on-reactor mode and could cause damage of spent fuel bundles during a transfer or discharge mode. Another major fire hazard is a leakage of hydraulic oil from the fuelling machine hydraulic system(pumps and tanks) in R-003 and R-004(Access Area: F/M hydraulic oil supply). The failure effect due to fires in these areas is a loss of hydraulic oil supply to both fuelling machines. A small fire could develop in R-103, 104, 107 and 108, due to a leakage of hydraulic oil from the fuelling machine due to a cable fault. Even though the fire ignition frequency is very low and has not been experienced in these areas, the fires in these areas could cause a D2O leak from a fuelling machine during a on-reactor mode and could cause damage to spent fuel bundles during a transfer or discharge mode due to a difficulty for a recovery and access to suppress the fires.

The internal flooding FMEA analysis for the fuel handling system at Cernavoda unit 2 was performed to assess the failure modes induced by an internal flooding, to identify its vulnerabilities to flooding-initiated events, and to provide recommendations for a plant safety. Internal floods may result from component failures or an incorrect operation of equipment and systems within the reactor building. They may occur, for example, as a result of a rupture of a pipe or a vessel, or be caused by a leakage from a component that is incorrectly assembled or left in a disassembled state after maintenance activities.

Table 2. Identification of the Plant Areas for the External Events FMEA

Subsystem (BSI)	Location	Room Description	Function	Potential Failure Effect
F/M	R/B-103	F/M maintenance Lock(C side)	Stores F/M, New Fuel Loading & Spent Fuel discharge	Failure of New fuel loading, Loss of Fuel discharge
	R/B-107	F/M Vault(C side)	Fuelling	Loss of F/M function
	R/B-104	F/M maintenance Lock(A side)	Stores F/M, New Fuel Loading & Spent Fuel discharge	Failure of New fuel loading, Loss of Fuel discharge
	R/B-108	Fuelling Machine Vault (A side)	Fuelling	Loss of F/M function
F/M D20 Supply (35260)	R/B-012	F/M Auxiliary Room	D2O Supply for F/M (Common)	Loss of D2O Supply
	R/B-501	D2O storage tank Room	D2O Storage tank (common)	Loss of D2O Supply
F/M D2O Control (35230)	R/B-013	F/M Auxiliary Room (Valve Station C side)	D2O Pressure & Level Control (C side)	Loss of D2O Pressure Control (C side)
	R/B-014	F/M Auxiliary Room (Valve Station A side)	D2O Pressure & Level Control (A side)	Loss of D2O Pressure Control (A side)
F/M Hydraulic Oil Control (35240)	R/B-003	Access Area (F/M Hydraulic Oil Supply C side)	Hydraulic Oil Control (C side)	Loss of Oil control system (C side)
	R/B-004	Access Area (F/M Hydraulic Oil Supply A side)	Hydraulic Oil Control (A side)	Loss of Oil control system (A side)
Spent Fuel Discharge	R/B-001	Spent Fuel transfer bay	Spent fuel discharge & interim storage, spent fuel standby cooling	Failure of spent fuel discharge, Loss of spent fuel cooling

As a major potential source of flooding, the dousing tank is capable of producing both the highest flooding rates and levels(the maximum level of water is 2.21m). A pipe break in the moderator, shield cooling, or steam generator feedwater systems results in slower flooding rates than that of the dousing system ,and in general, lower flooding levels, but an unmitigated feedwater line break inside the reactor building may produce flood levels similar to that potentially caused by the dousing system failures. In the reactor building, all the heat exchangers are cooled by the recirculated cooling water (RCW) system. This is a closed loop system, which passes the heat to the raw service water (RSW) system via heat exchangers in the turbine building. The maximum level of water from the basement is 3 feet due to an RCW pipe rupture. The total inventory of the water in the closed loop RCW system is limited to 410 m3 and a complete discharge of this system cannot produce significant flood events.

All the components related to the fuel handling system except 3523-P3 are not affected during flooding conditions because all the components related to the F/M are located 2m from the basement floor. If the instruments and control hardware of the F/M are designed for a "watertight" operation, the water spray due to a dousing system malfunction or feed water pipe break can not affect an F/M operation during an F/Ms on-reactor or transfer mode.

In the seismic analysis of the fuelling machine and support structures for the Wolsong units 2/3/4, the Cernavoda unit 1 F/M and support structure were used as the reference design. Consequently, the seismic models for the Cernavoda unit 1 were adopted for Wolsong units 2/3/4 except for minor modifications

The seismic analysis of the F/M and the support structures was carried out by using the direct integration time-history method. A total of 625 cases according to combinations of the soil stiffness, modeling assumptions in the fuelling machine, position of the fuelling machine and a time history variation was considered.

In the seismic analysis, the following configuration cases were considered.

- F/M Unattached in Reactor Vault
- F/M Attached to Reactor
- F/M on Maintenance Lock Track
- Spent Fuel Port Stands Alone

For the unattached analysis, there are seven channel locations to be considered. The F/M can be in side ‘A’ or side ‘C’ of the reactor building. Hence, a total of fourteen models need to be considered. Furthermore, there are 12 sets of support point time-histories to be considered for Wolsong units 2/3/4. Therefore, the total number of analysis cases considered was 168 cases. For the attached cases, the basic F/M/channel (F/C) configuration was considered for the design of the F/M and the support structure. The total number of analysis cases considered was 84. For the interaction loads on the reactor components, besides the basic F/C configuration, additional variations of the F/C configuration were considered. The number of additional computer runs was 252. Therefore, for the interaction loads on the reactor components, the total number of analysis cases considered was 336.

When the F/M is mounted on the ML track, five configurations were considered. Furthermore, the F/M can be on the side ‘A’ or side ‘C’ ML track. Therefore, the total number of analysis cases considered was 120. The response spectrum method of a seismic analysis was adapted for the SFP standing alone. Only one model for the SFP alone was used.

The seismic analysis methodology follows the requirements of the National Standard of Canada CAN3-N289.3-M81. It take into account the sensitivity of the variations of the soil parameters and the uncertainties of the component frequencies. The seismic analysis of the F/M and support structure covers various operation modes during the fuelling process, in the reactor vault area and in the maintenance lock area. The results of the seismic and deadweight analysis are presented in terms of the nodal accelerations, the beam end forces and the third-level floor response spectra. The results of all the cases analyzed are to be used for the design of an F/M, a support structure, and interacted systems.

The CANDU plant is refueled every day, and the average duration when the fuelling machine is connected to the fuel channel is 1 hour. If a strong earthquake (i.e., beyond the DBE magnitude) were to occur during a fuelling operation, a failure of the connection between the fuelling machine and the fuel channel would lead to a single fuel channel LOCA. A seismic fragility analysis of the fuelling machine of Wolsong units 2/3/4 NPP was performed. Failure mode of the fuelling machine is a structural failure of the fuelling machine/pressure tube connection. The high consequence low probability failure (HCLPF) capacity of the fuelling machine is 0.44g. This means that the fuelling machine has sufficient enough safety margin for a DBE of 0.2g. Ae seismic fragility analysis of the fuelling machine of Cernavoda 2 was performed. The most severe failure mode of the fuelling machine was a structural failure of the fuelling machine/pressure tube connection. The high consequence low probability failure (HCLPF) capacity of the fuelling machine was 0.44g. This means that the fuelling machine had a sufficient enough safety margins for a design basis earthquake (DBE) of 0.2g.

CONCLUSIONS

For the fuel handling system of CANDU 6 plants, it was reviewed from the point of views of its design, operation, and safety. From the design point of view the FMEA approach is used to check the weak points, if any. From the safety point of view the severe accident scenarios analysis is used.

- The most severe event scenarios were found as follows;
- A break of the fuel channel end fitting accompanying an ejection of 12 spent fuel bundles.
- Loss of Coolant Accidents when the F/M is in an on-reactor mode.
- At the spent fuel port, two spent fuel bundles are mechanically damaged when being dropped to the discharge bay floor from the port.

However these kinds of severe accidents are rare from the review results of the Event History Docket. By its nature there have been many incidents of D2O leaks through catenary hoses. However by a well-established maintenance policy, the frequency of this kind of event could be reduced.

The FMEA for external events was performed and the results were as follows. At first the fire areas and flooding areas were defined by reviewing the general arrangement documents and a walkthrough of Cernavoda unit 2. Related to the fuel handling systems a total of 11 rooms inside the reactor building were selected. For each room an FMEA of the fire and flooding events was performed.

For the fire FMEA, the fire ignition sources were identified for each room. The most significant fire area was the D2O supply room (R-012) according to the result of the internal fires FMEA. If a fire occurs in room R-012, two D2O supply pumps (3526-P1 and P2) and pressure control valves will be affected so the F/M could not play its role. However, the fire ignition frequency in this room was very low and there have been no such experiences in CANDU plants.

For the flooding FMEA, the flooding sources were identified in the reactor building. The flooding sources in the reactor building were a spurious operation of the dousing tank spray, a feed line break accident, and a rupture of the recirculated cooling water (RCW) piping. By an analysis, the most significant flooding scenario was identified to be a D2O return pump(3523-P3) failure induced by a malfunction of the dousing system or a feed water pipe break. The D2O return pumps are located on the R-013 and R-014 rooms basements. A failure of these pumps by a flooding of the basement of the reactor building can cause a D2O spill over through a duct of the vapour recovery system in the 3523-TK3. This scenario can only occur in the weir level operation mode. In this case the fuel bundles in the F/M magazine can be damaged due to a loss of D2O inventory to the F/M magazine. The other components related to the fuel handling system except for 3523-P3 are not affected during the flooding conditions because all the components related to the F/M are located 2m from the basement floor.

The seismic fragility analysis of the fuelling machine of the Wolsong unit 2, 3 &4 NPP was performed. The most severe failure mode of the fuelling machine was a structural failure of the fuelling machine/pressure tube connection. The high consequence low probability failure (HCLPF) capacity of the fuelling machine was 0.44g. This means that the fuelling machine had a sufficient enough safety margin for a design basis earthquake (DBE) of 0.2g.

Through this FMEA study on the fuel handling system of CANDU 6 plants the most significant accident scenario was identified as a small LOCA (single fuel channel LOCA). The most severe radiation release event was an ejection of 12 spent fuel bundles on to the reactor vault. This event can usually be confined to the reactor building.

ACKNOWLEDGEMENT

This work has been carried out sponsored by the Korea Overseas Project Department of Korea Hydro & Nuclear Power Co.

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