INSIGHT FROM LOW POWER SHUTDOWN FIRE PRA FOR PLANT UNDER CONSTRUCTION BASED ON NUREG/CR-7114

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Low power and shutdown(LPSD) fire Probabilistic Risk Assessment(PRA) for construction plant was performed based on NUREG/CR-7114 and NUREG/CR-6850. The current framework for LPSD fire PRA doesn't provide sufficiently enough or detailed information for treating the plant status change led by maintenance activities on operating plants as well as plants under construction. There are also many limitations in directly using the methodology which leads many kinds of conservative assumptions in performing LPSD Fire PRA. According to the experience gained through LPSD fire PRA, power supply-related systems such as Unit Aux Transformer(UAT) and Station Aux Transformer(SAT) can be vulnerable depending on a specific Plant Operating Stat(POS) due to the relevant maintenance activities. In addition, unlike at-power operation, charging pump-related operation can be critical from Core Damage Frequency (CDF) and Large Release Frequency (LRF) perspectives because most Reactor Cooling System (RCS) cooling operation is being achieved through Chemical and Volume Control System (CVCS).

I. INTRODUCTION

The objectives of the fire PRA are to estimate the contribution of in-plant fires to overall plant CDF and LRF to identify vulnerabilities and to provide recommendations for reducing fire-induced plant risk. Risk due to internal fire has been one of the major concerns for design and operation of nuclear power plants.

Until now, methods for internal fire events during at-power operation of NPPs have been evolved and applied to identify vulnerabilities into a lot of NPPs. However, fire events during low power and shutdown operation have been out of concerns and the relevant methods also have not been fully developed until “A Framework for Low power/shutdown Fire PRA”, NUREG/CR-7114 (Ref. 1) was issued in 2013. Before NUREG/CR-7114 was issued, just LPSD fire event frequency-related report by EPRI was issued, or limited internal fire event evaluation during significant specific LPSD operation like mid-loop operation for Surry plant in USA was performed under the US-NRC leading.

But, even though NUREG/CR-7114 for LPSD fire PRA was issued, it’s not detailed and fully tested methodology different from NUREG/CR-6850 for full power fire PRA. Namely, NUREG/CR-7114 provides just framework, not detailed methodology and also in the course of development, just a tabletop exercise for two volunteer plants, Seabrook and Peach Bottom plant in USA was conducted in lieu of full pilot application.

In this situation, recently, Korea has performed full scope LPSD fire PRA for Level 1 and Level 2 based on NUREG/CR-7114 and NUREG/CR-6850 (Ref. 2) including Supplement 1 (Ref. 3) for one plant of Advanced Pressurized Reactor(APR) 1400 series under construction.

II. THE APPLICATION OF NUREG/CR-7114

Korea has applied new LPSD Fire PRA methodology, NUREG/CR-7114, to an advanced nuclear power plant under construction. One of the prime design characteristics of the plant analyzed is to adopt quadrant arrangement concept as shown in Fig. 1, where most cables and equipment are located in each quadrant (A/B/C/D).

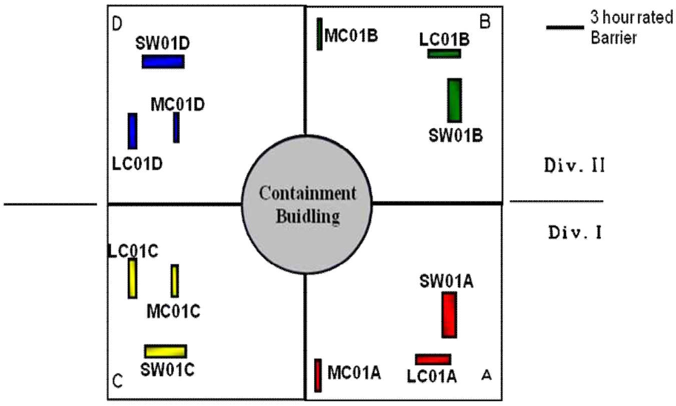

Fig 1. Quadrant arrangement concept in Auxiliary Building

Main Control Room (MCR) has employed fully digitalized control system including Large Display Panel which is one of the differences from the conventional plants.

II.A. LPSD Fire PRA Methodology

The LPSD fire PRA methodology for NPP under construction is based on NUREG/CR-7114 and NUREG/CR-6850. NUREG/CR-7114 provides a framework for quantitative analysis of fire risk during LPSD conditions. NUREG/CR-6850 provides a state-of-the-art methodology for fire PRAs during at-power operation. The steps in the LPSD fire PRA methodology are the same as those used in the at-power internal fire PRA with the exception that they are applied upon the LPSD internal events model.

LPSD Fire PRA methodology, NUREG/CR-7114, is composed of 16 tasks as below and shows task flow like Fig. 2 which is same as NUREG/CR-6850 for at-power fire PRA.

Task 1: Plant Boundary Definition and Partitioning is to define the Global Plant Analysis Boundary, and to divide the Global Plant Analysis Boundary into discrete physical analysis units (fire compartments).

Task 2: Fire PRA Component Selection is to select the plant equipment that will be included and/or credited in the Fire PRA.

Task 3: Fire PRA Cable Selection is to identify the cables associated with all Fire PRA components, and their physical routing throughout the plant.

Task 4: Qualitative Screening is to identify physical analysis units whose potential fire risk contribution can be judged negligible without quantitative analysis.

Task 5: Plant Fire-Induced Risk Model is to create the Fire PRA model that will be used in estimating the fire risk.

Task 6: Fire Ignition Frequency is to determine the fire ignition frequencies for fixed and transient ignition sources on a fire compartment basis.

Task 7A/7B: Quantitative Screening is to screen physical analysis units located within the Global Plant Analysis Boundary from further consideration based on preliminary conservative estimates of fire risk contribution using established quantitative screening criteria.

Task 8: Scoping Fire Modeling is to eliminate or reduce the frequency of those fixed ignition sources in a fire compartment that do not pose a threat to any Fire PRA target.

Task 9: Detailed Circuit Failure Analysis is to conduct a more detailed analysis of circuit operation and functionality to determine equipment responses to specific fire-induced cable failure modes. This information is then used to screen out cables that cannot prevent a component from completing its credited function.

Task 10: Circuit Failure Mode Likelihood Analysis is to quantify the probabilities for fire-induced hot short circuit failures that lead to component failure modes of interest. The failure mode probabilities are estimated for the cables of risk-significant components.

Task 11: Detailed Fire Modeling - In prior tasks, the analyses assumed that a fire would have widespread impact within the fire compartment. In this task, for those fire compartments found to be potentially risk-significant (i.e., unscreened compartments), a detailed analysis approach is provided. As part of the detailed analysis, fire growth and propagation may be modeled. Furthermore, the possibility of fire suppression before damage to a specific target set is analyzed. This task is composed of the following three sub-tasks:

a. Detailed fire modeling of single fire compartments
b. MCR fire analysis
c. Multi-compartment fire analysis.

Task 12A/12B: Post-Fire HRA - In this task, human failure events (HFEs) associated with the fire scenarios are identified, and associated human error probabilities (HEPs) are estimated. Operator actions after fire ignition are assumed to be affected by the fire unless it can be clearly shown otherwise.

Task 13: Seismic Fire Interaction is to identify and correct any weaknesses in the fire protection systems and vulnerabilities in the ignition sources due to seismic events. This is the qualitative evaluation of the potential for: 1) seismically induced fires, 2) degradation of fire suppression systems and features, 3) spurious actuation of fire suppression and/or detection systems, and 4) degradation of manual fire fighting effectiveness.

Task 14: Fire Risk Quantification - In this task of the analysis process, the Fire PRA model is quantified for each final fire scenario, the associated risk values (i.e., CDF and LRF) are computed and risk contributors are identified.

Task 15: Uncertainty and Sensitivity Analyses are to determine, characterize and assess the impact of uncertainty on the CDF and LRF estimates. In addition, sensitivity analyses are used to identify and understand the impact of risk significant modeling assumptions.

Task 16: Fire PRA Documentation is to ensure that the previous analyses are documented in a manner which facilitates review and update.

Before performing LPSD fire PRA, the following information should be completed and available in advance.

- LPSD Internal events
  - Definition of LPSD POS
  - A list of initiating events for each POS
  - A plant response model for each LPSD initiating event and for each relevant POS
  - A list of equipment and their failure modes
  - Human error scenarios in LPSD internal events
- At-power fire PRA
  - Plant partitioning results
  - Equipment List
  - Cable list
  - Initiating events
  - Equipment and ignition source counting and weighting result
  - Control circuit failure modes and effects analysis result
  - Component and cable mapping and routing results

Additionally, the following key assumptions are provided in NUREG/CR-7114.

- At-power fire PRA has been completed
- LPSD internal PRA has been completed
- Development of detailed HRA to LPSD fire PRA lies beyond the scope of NUREG/CR-7114
- LPSD Fire frequencies are estimated based on past plant experience in the same manner as at-power fire PRA
- LPSD fire PRA ends states are limited to CDF and LRF

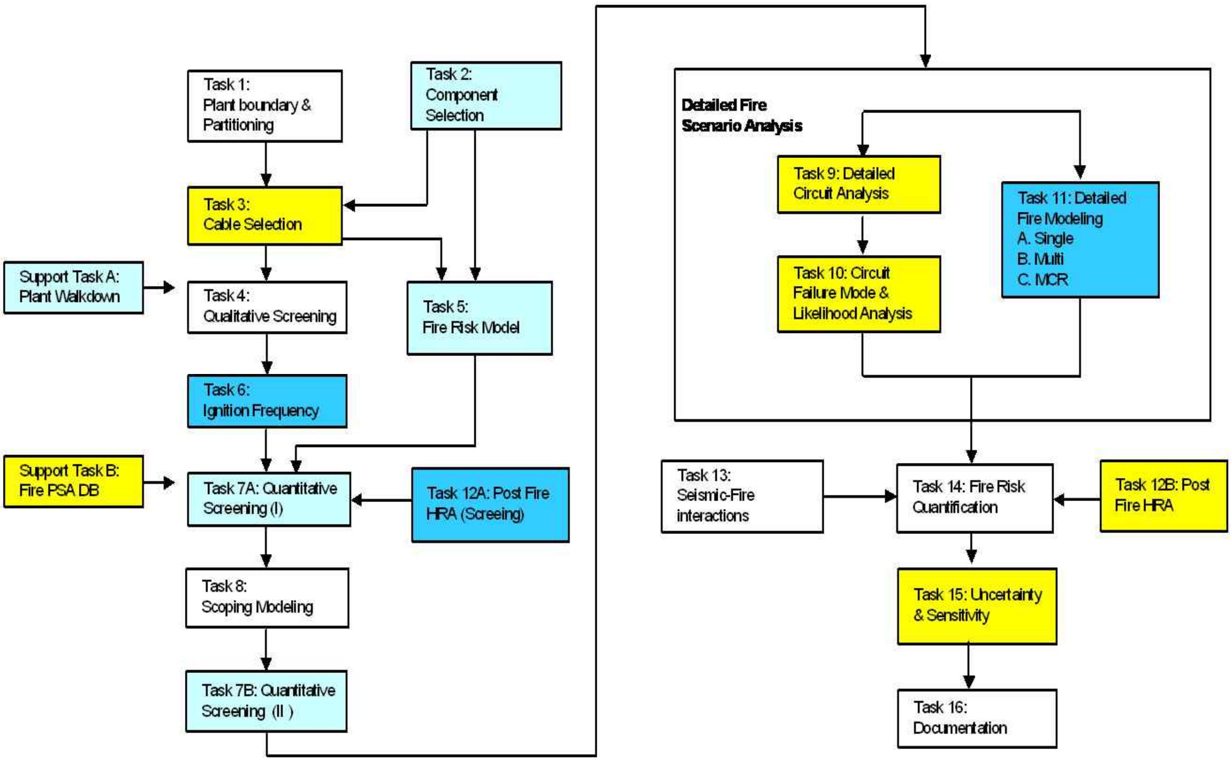

Fig. 2. Overview of the Fire PRA Process in NUREG/CR-7114

II.B. Key Approach and Results

In order to perform LPSD fire PRA, first, Plant Operation State (POS) should be identified and characterized. This analysis followed internal POS development result and it was identified into 18 POS as follows;

TABLE 1. Plant Operational States defined in LPSD Internal Events

POS	Description	Primary System Water Level	Primary System Pressure & Temperature	Mode
1	Reactor Trip and Subcritical Operation	In Pressurizer	2250 psia; 585-548°F	1, 2
2	Cool-down with Steam Generators to 350°F		2250-450 psia; 548–350°F	3
3A	Cool-down with Shutdown Cooling System to 210°F		450-15 psia;350–210°F	4
3B	Cool-down with Shutdown Cooling System below 210°F		450-15 psia; ≤210°F	5
4A	Reactor Coolant System Drain-down (Pressurizer Manway Closed)		Slight positive pressure or depressurized; ≤150°F	5
4B	Reactor Coolant System Drain-down (Manway Open)	Below Reactor Flange	Depressurized; ≤150°F	
5	Reduced Inventory Operation and Nozzle Dam Installation			

TABLE 1. Plant Operational States defined in LPSD Internal Events

<table>
<tr><th>POS</th><th>Description</th><th>Primary System Water Level</th><th>Primary System Pressure & Temperature</th><th>Mode</th></tr>
<tr><td>6</td><td>Fill for Refueling</td><td></td><td rowspan="2"></td><td rowspan="2">6</td></tr>
<tr><td>7</td><td>Off-load</td><td>Cavity flooded</td></tr>
<tr><td>8</td><td>Defueled</td><td>N/A</td><td>N/A</td><td>6</td></tr>
<tr><td>9</td><td>On-load</td><td>Cavity flooded</td><td rowspan="4">Depressurized or slight vacuum during refill; ≤150˚F</td><td rowspan="2">6</td></tr>
<tr><td>10</td><td>Reactor Coolant System Drain-down to Reduced Inventory after Refueling</td><td rowspan="3">Below Reactor Flange</td></tr>
<tr><td>11</td><td>Reduced Inventory Operation with Steam Generator Manway Closure</td><td rowspan="3">5</td></tr>
<tr><td>12A</td><td>Refill Reactor Coolant System (Pressurizer Manway Open)</td></tr>
<tr><td>12B</td><td>Refill Reactor Coolant System (Manway Closed)</td><td rowspan="4">In Pressurizer</td><td>Depressurized, or at a slightly elevated pressure; ≤150˚F</td></tr>
<tr><td>13</td><td>Reactor Coolant System Heat-up with Shutdown Cooling System Isolation</td><td>15-450 psia; 150–350˚F</td><td>4,5</td></tr>
<tr><td>14</td><td>Reactor Coolant System Heat-up with Steam Generators</td><td>450-2250 psia;350–548˚F</td><td>3</td></tr>
<tr><td>15</td><td>Reactor Start-up</td><td>2250 psia; 548-585˚F</td><td>2,1</td></tr>
</table>

Of the above 18 POSs, the internal event LPSD PRA scope is limited to POSs during which fuel is contained in the reactor vessel. So LPSD fire PRA scope also is limited to the POSs where fuel is contained in the reactor vessel. Thus, final POSs considered in LPSD fire PRA are limited into POS 1, 2, 3A, 3B, 4A, 4B, 5, 6, 10, 11, 12A, 12B, 13, 14 and 15. The other POSs, POS 7, 8 and 9 are out of LPSD fire PRA scope whose fire is in scope of spent fuel pool PRA.

For Plant Analysis Unit (PAU), PAUs defined in at-power fire PRA were used without changes in LPSD fire PRA. When defining PAU during LPSD operation without modification of the result from at power fire PRA, partitioning elements can be the primary challenge to LPSD fire PRA. That is, equipment hatch, doors or fire barrier penetrations may be removed, opened or breached during maintenance works. In such case, PAU can be redefined based on the barrier configuration and conditions specific to the POS. Redefining PAU needs far more time and makes this task become burdensome and far more difficult. So, it is efficient to use the same set of PAU as at-power for PAU definition in LPSD fire PRA and to take into account the impact of barrier configuration change in Task 11, multi-compartment analysis. Especially, in case of construction plant, since there is no information on barrier configuration change specific to the POS, it's more efficient approach to use the same set of PAU as at-power fire PRA without change. But, the impact of barrier breach during maintenance activities was evaluated through sensitivity analysis .

In LPSD fire PRA component and cable selection, basically at-power PRA is the base for LPSD fire PRA. That is, LPSD specific accident sequences are reviewed and the relevant equipment and cables are added to at power component and cable list.

Fire- induced potential initiating events during LPSD operation are as follows;

- S2: Unrecoverable Loss of SCS
- SLOCA: Small LOCA
- JL: Unrecoverable LOCA
- SO: Over-drainage During Reduced inventory Operation
- SM: Failure to Maintain Water Level During Reduced Inventory Operation
- LOOP: Loss of Offsite Power
- SBO: Station Blackout
- LOKV: Loss of 4.16kV AC Bus
- CC: Partial Loss of Component Cooling Water
- TC: Total Loss of Component Cooling Water

- LOSW: Loss of Service Water

To calculate ignition source frequency, fixed ignition source and transient ignition source-relevant generic value was applied to all ignition source defined in at-power fire PRA and adjusted by POS. Among fixed ignition sources, turbine generator exciter (Bin33) is removed from the ignition source count because of out-of service during shutdown operation. The following ignition sources are those provided with data gathered during LPSD specific operation condition:

- Bin 02: Reactor Coolant Pump for Containment
- Bin 03: Transients and hotwork(PWR) for Containment
- Bin 05: Cable fires caused by welding and cutting for Aux. Building
- Bin 06: Transient fires caused by welding and cutting for Aux. Building
- Bin 07: Transients for Aux. Building
- Bin 11: Cable fires caused by welding and cutting for Plant Wide
- Bin 22: RPS MG sets for Turbine Building
- Bin 24: Transient fires caused by welding and cutting for Plant Wide
- Bin 25: Transients for Plant Wide
- Bin 27: Yard Transformer-catastrophic for Transformer Yard
- Bin 28: Yard Transformer-noncatastrophic for Transformer Yard
- Bin 29: Yard transformers (others) for Transformer Yard
- Bin 31: Cable fires caused by welding and cutting for Turbine Building
- Bin 32: Main feedwater pumps for Turbine Building
- Bin 34: T/G hydrogen for Turbine Building
- Bin 35: T/G oil for Turbine Building
- Bin 36: Transient fires caused by welding and cutting for Turbine Building
- Bin 37: Transients for Turbine Building

With regard to transient ignition source, transient fire influencing factor was allocated based on reference plant operation experience. Especially, hotwork activities in the fire compartment where equipment is assumed to be in the same status as at-power including just standby mode are assumed to have the same influencing factor as at-power fire PRA. And, one of approaches assigning transient influencing factor is to begin with at-power designations for each PAU and adjust those factors to reflect the outage conditions. The below table presents the example of assigning influencing factor to each room based on at-power result.

TABLE 2. Fire Influencing Factor Allocation Example

	POS 1, POS 15				POS 2 ~ POS 6				POS 10 ~ POS 14				At-Power			
Room No.	H/W	M/T	O/C	S/T	H/W	M/T	O/C	S/T	H/W	M/T	O/C	S/T	H/W	M/T	O/C	S/T
1-055-A07C	L	L	L	L	H	H	H	H	H	H	H	H	L	L	L	L
1-055-A07D	L	L	L	L	H	H	H	H	H	H	H	H	L	L	L	L
1-055-A08C	L	L	L	L	M	M	M	M	M	M	M	M	L	L	L	L
1-055-A08D	L	L	L	L	M	M	M	M	M	M	M	M	L	L	L	L
1-055-A10C	L	L	L	L	M	M	M	M	M	M	M	M	L	L	L	L
1-055-A11D	L	L	L	H	M	M	M	VH	M	M	M	VH	L	L	L	H

H/W: Hotwork	L: Low
M/T: Maintenance.	M: Medium
O/C: Occupancy	H: High
S/T: Storage	VH: Very High

Detailed fire modeling for following critical scenarios to CDF/LRF was performed by POS using fire modeling tool CFAST and FDT as shown Figures 3 and 4 and Table 3.

- F0A0-1A04A: SC PUMP & MINI FLOW HEAT EXCHANGER ROOM
- F0A0-1A04B: SC PUMP & MINI FLOW HEAT EXCHANGER ROOM
- F0A1-1AFH: AUX. BUILDING FUEL HANDLING AREA
- F0A1-1AGAB: GENERAL ACCESS AREA
- F0A2-1AEEB: CLASS 1E SWITCHGEAR 01B ROOM
- F0A2-1AGAD: GENERAL ACCESS AREA
- F0A3-1A05D: ELECTRICAL EQUIPMENT ROOM
- F0A4-1A05D: ELECTRICAL EQUIPMENT ROOM
- F0A4-1AGAD: GENERAL ACCESS AREA
- F0A5-1A11D: ELECTRICAL PENETRATION ROOM (D)
- F0A2-1AGAB: GENERAL ACCESS AREA
- F0A5-1AGAC: GENERAL ACCESS AREA

In the process of detailed fire modeling, it is assumed that the geometry of room and location of ignition source is same as at-power operation except additional targets for LPSD fire PRA. So, for scenarios that are considered in the same PAU as that in at-power PRA, when carrying out detailed fire modeling during at-power fire PRA, additional target information for LPSD fire PRA like cables were made to be included in at-power fire PRA target set. LPSD specific fire scenarios were separately performed for fire growth analysis with LPSD specific target information.

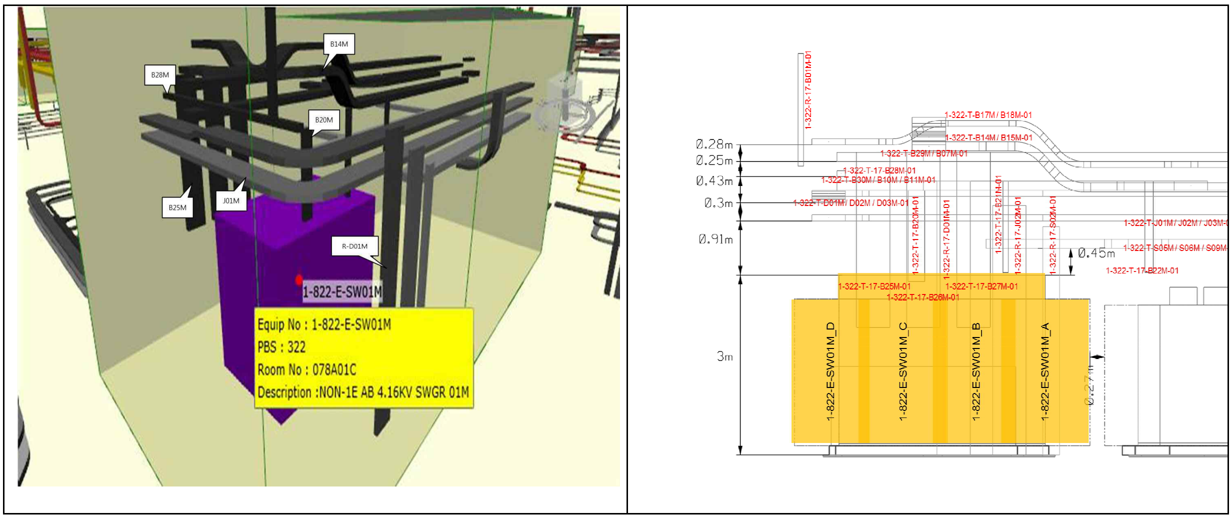

Fig.3. Example of ignition source and target configuration in fire compartment

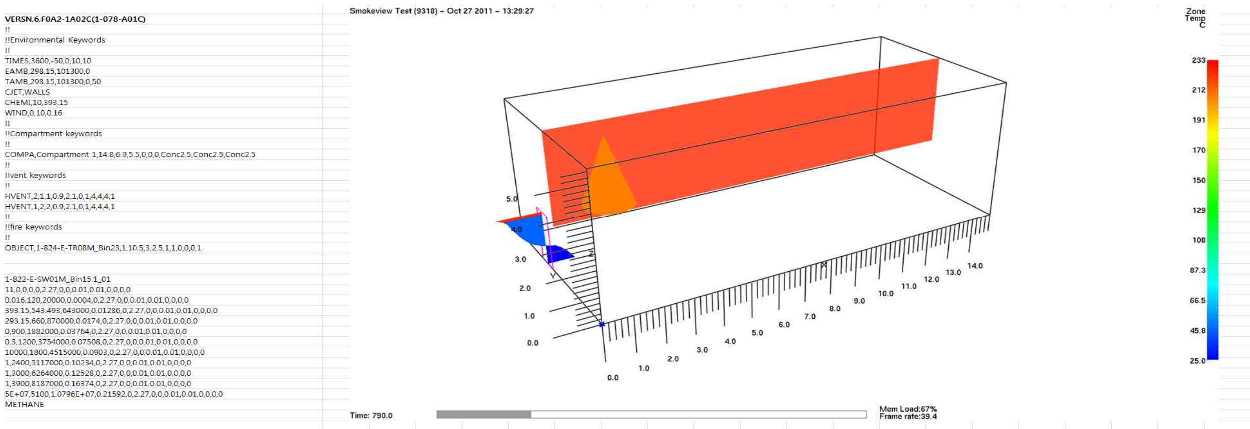

Fig. 4. Example of CFAST result in fire compartment

TABLE 3. Example of fire growth analysis using FDT

Fire Growth Analysis for Electrical Fire					Time (minutes)										
					FDS0	FDS1/2/5 (Detection)				FDS3/6					FDS4/7
Source Type	**Source**	**HRR per Unit [kW]**	**Ignition Time**	**Duration**	**0.0**	**2.0**	**2.3**	**4.3**	**10.0**	**12.0**	**20.0**	**40.0**	**50.0**	**65.0**	**85.0**
Switchgear Cabinet	1-822-E-SW01M_Bin15.1_01	211	0.0	40	0	6	8	27	147	211	211	0	0	0	0
Riser	1-322-T-17-B21M-01	20	0.0	2.3	0	0	0	0	0	0	0	0	0	0	0
Tray	1-322-T-17-S05M-01	20	4.3	40	0	0	0	0	0	0	0	0	0	0	0
Switchgear Cabinet	1-822-E-SW01M_Bin15.1_02	211	10.0	40	0	0	0	0	0	6	147	47	0	0	0
				Total HRR:	**0**	**6**	**8**	**27**	**147**	**217**	**358**	**47**	**0**	**0**	**0**

III. CONCLUSIONS

LPSD fire PRA for NPP under construction was performed per NUREG/CR-7114 and NUREG/CR-6850 in Korea. Since there is no sufficient information associated with operation and maintenance activities for the plant under analysis, many assumptions were set based on reference plants and NUREG/CR-7114. Following insights during LPSD operation could be drawn through LPSD fire PRA. That is, power supply system like UAT, SAT and EDG and Operator action are found to be critical factor impacting to CDF and LRF during LPSD operation.

In case that either UAT or SAT is under maintenance with EDG in some POS, this can cause critical situation of the plant under LPSD operation in terms of power supply. So, accordingly, such maintenance activities should be allocated into POS not affecting to high CDF and LRF. Mid-loop operation is found to be very critical because available time for operator action is very short compared to other POS. Because during LPSD operation, most equipment is operated by operator not automatic signal, and dependency between operator actions is very high, such very short available time for operator action causes severe situation in LPSD fire PRA.

Additionally, in terms of fire compartment, SWGR room, CVCS-related room and Reactor containments are found to be critical to CDF/LRF during LPSD operation. The main reason was analyzed to be that the fire in these fire compartments gives impact to operator action associated with injection to RCS, shutdown cooling operation and charging pump operation.

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3. EPRI 1019259, "Fire Probabilistic Risk Assessment Methods Enhancements: Supplement 1 to NUREG/CR-6850 and EPRI 1011989," EPRI, September 2010.