Fire PRA for a Model Plant[1] at NRRC

Tsuyoshi Uchida[a*], Koji Shirai[b], Motomu Suzuki[a], Kohei Nonose[a], Junghoon Ji[b]
[a] Central Research Institute of Electric Power Industry, Yokosuka Kanagawa, Japan
[b] Central Research Institute of Electric Power Industry, Abiko Chiba, Japan

Abstract: Fires can be a significant risk contributor to Nuclear Power Plants (NPPs). In 2020, the Nuclear Risk Research Center (NRRC) of the Central Research Institute of Electric Power Industry (CRIEPI) developed the Fire PRA Guide (NRRC FPRAG hereafter) to provide the nuclear power industry in Japan a consistent methodology and supporting data to implement Fire PRAs (FPRA).

NRRC implements an FPRA for a typical Japanese PWR to ensure the applicability of the NRRC FPRAG to FPRAs for actual NPPs and identify issues for future revision of NRRC FPRAG.

In this study, NRRC identified 217 fire compartments within the global plant boundary of the model plant. Furthermore, NRRC implements detailed analyses such as fire modeling, detailed HRA, circuit failure mode likelihood analyses, and development/modification of the Plant Response Model (PRM) for several fire compartments. The FPRA in this study suggests that the implemented methods can identify potential vulnerabilities for internal fires in the target plant. Hence, NRRC FPRAG can apply to FPRAs for actual NPPs. Furthermore, during this study, NRRC clarifies the methods to relax conservatisms succeeded from internal events PRM and are introduced during the FPRA. Since these methods to relax conservatisms would be helpful for FPRA analysts, they are expected to be included in NRRC FPRAG appendices.

Keywords: Fire PRA, NRRC FPRAG, Plant Response Model, CDF, HRA

1. INTRODUCTION

Fires can be a significant risk contributor to Nuclear Power Plants (NPPs). The Nuclear Risk Research Center (NRRC) of the Central Research Institute of Electric Power Industry (CRIEPI) developed Fire PRA Guide (NRRC FPRAG hereafter) in 2020 to provide the nuclear power industry in Japan a consistent methodology and supporting data to implement Fire PRAs (FPRA) [1]. NRRC implements a FPRA for a typical Japanese PWR to ensure the applicability of the NRRC FPRAG to FPRAs for actual NPPs and identify issues for future revision of NRRC FPRAG.

The methodology described in NRRC FPRAG starts with the development of Plant Response Model for FPRA (FPRM) and fire scenarios. FPRM is based on Internal Event Plant Response Model (IEPRM). Generally, IEPRMs include simplifications and conservative assumptions because of the low risk of internal events. Furthermore, simplified conservative assumptions can be introduced to fire scenarios. Hence, reducing conservatism by refining FPRM and fire scenarios is important.

Through the FPRA for a model plant, it can be concluded that the methodology and guidance described in NRRC FPRAG are applicable to FPRAs for actual NPPs. Also, the FPRA in this study demonstrates the methods to identify and resolve excessive conservatism in FPRM and fire scenarios. Since the methods to identify and relax conservatism will be helpful for FPRA analysts, they are expected to be included in NRRC FPRAG appendices.

2. METHODOLOGY OVERVIEW

The overall task flow of the FPRA methodology described in NRRC FPRAG is shown in Figure 1. This methodology consists of Phase-A and B. Phase-A contains the tasks of identifying of fire scenarios and quantifying their fire ignition frequencies. At the end of Phase-A, Core Damage Frequencies (CDFs) are quantified under simplified conservative assumptions (Task 9). Also, FPRA Plant Response Model (FPRM) is developed in this phase (Task 1). Phase-B contains the tasks for detailed analyses to reduce conservatism in the scenarios and the FPRM developed in Phase-A. Phase-B consists of three detailed analysis tasks: Fire Modeling, Detailed Human Reliability Analysis (HRA), and Circuit Failure Mode Likelihood Analysis

---

[1] Model Plant is a typical Japanese LWR.

(CFMLA), which are Tasks 14, 15, and 16, respectively. FPRM developed in Task 1 of Phase-A can be modified by feedback from Task 9 and the tasks in Phase B to reduce conservatisms in FPRM.

It should be noted that there is no task in the NRRC FPRG on quantitative screening such as Task-7 in NUREG/CR-6850. The NRRC FPRAG does not allow to numerically screen out any scenarios. In other words, all scenarios survived from qualitative screening shall be kept.

Fire scenarios are identified by iteration process of Task2 to Task 5 in Phase-A as shown in Figure 1. Furthermore. Detailed Analyses (Phase-B) are implemented iteratively. Also, FPRM and fire scenarios can be refined by feedbacks from Phase-3 tasks.

NRRC implements Phase-A tasks for all compartments within Global Plant Analysis Boundary (GPAB) identified in Task 2. On the other hand, Phase-B tasks are conducted for several selected compartments to identify and resolve conservative assumptions introduced by IEPRM and Phase-A of FPRA.

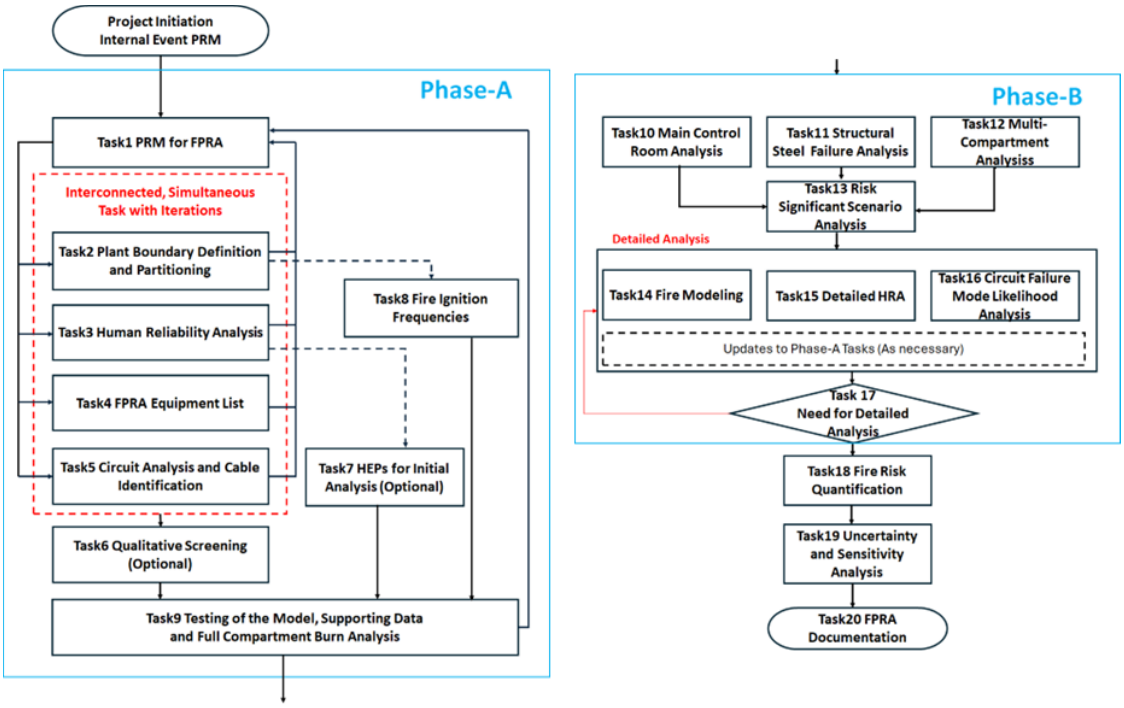

Figure 1 Overall Task Flow of NRRC FPRAG methodology [1]

3. FPRA UNDER CONSERVATIVE ASSUMPTIONS

3.1. Fire PRA Plant Response Model (FPRM)

The FPRM is developed by modifying the IEPRM developed in 2019; the IEPRM employs random failure rates based on the operational experiences of Japanese LWRs [2]. The total CDF due to internal events quantified by the IEPRM is around 1×10^{-6} /ry.

a. Initiating Events

Fires could cause initiating events due to failure of Structures, Systems and Components (SSCs) with prevention functions. Also, due to technical specifications of the target plant, a manual reactor shutdown could be required in case of failure of safety related SSCs with mitigating functions. On the other hand, fires could generally not cause initiating events due to pipe ruptures, such as pipe rupture LOCAs and SGTRs, because the thermal loads from fires would not be sufficient to cause pipe ruptures.

Most of initiating events due to failures of SSCs with prevention functions are considered in the IEPRM. Hence, such initiating events are succeeded from the IEPRM. Also, fire specific initiating events are identified for this FPRA.

Table 1 summarizes the initiating events considered in this study. The majority of initiating events in fire events are caused by Multiple Spurious Operations (MSOs). This suggests that they can be risk significant contributors.

Table 1. Fire Induced Initiating Events

Category	**Initiating Events**
LOCA	PORV LOCA due to MSO [3]
ISLOCA	ISLOCA (RHR) due to MSO [3] ISLOCA (Unbalance of Charging/Letdown) [3]
Excessive Secondary Side Cooling	Spurious opening of MSRVs due to MSO [3] Spurious open of TBVs due to MSO [3] Excessive FW to SGs [3]
Loss of Secondary Side Cooling	Partial/Total Loss of MFWS due to MSO [3]
General Transient	Spurious Closure of MSIVs Load Rejection (Turbine Trip) General Transient w/o challenging PORV/PSV General Transient with challenging PORV/PSV [3]
Loss of Support Functions	Loss of Offsite Power (LOOP) Partial Loss of High Voltage Emergency Buses Partial Loss of Low Voltage Emergency Buses Partial Loss of 2 trains of Emergency Instrumental buses Total Loss of Instrumental Air Partial Loss of DC buses Partial/Total Loss of CCWS [3] Partial Loss of SWS
Reactivity-Induced Event	Spurious Boron Dilution due to MSO [3]

b. System Modeling

The IEPRM needs to be modified to model fire specific impacts (e.g., MSO). Table 2 summarizes the modifications of the FPRM.

Table 2. Modification of System Models for FPRA

Systems	**Modeled Fire Impacts**
Power Supply System	Spurious closure of power circuit breakers of MC switchgear Failure of DG due to overload Spurious closure of DG breakers
Refuel Water Storage System	Loss of RWST inventory due to the following: ・ Spurious Open of ECCS sump isolation valve & leak of check valve on recirculation line ・ Spurious Open of CV spray sump isolation valve & leak of check valve on recirculation line ・ Spurious operation of CV spray pump & its isolation valve
AFW/MSRV	Failure of TD-AFWP due to excessive FW to SGs Loss of secondary side cooling due to excessive FW to SGs Failure to isolate FW in case of spurious opening of MSRVs Loss of AFW due to failure to close the valves on SG blowdown lines
Isolation of Main Steam Lines	Failure to isolate MSL Failure to isolate the steam supply to TD-AFWP
RCP Seal LOCA	Loss of seal injection & Loss of cooling thermal barrier & Failure of preventive measures for RCP Seal LOCA
Isolation of ISLOCA	Failure to close isolation valves on letdown or charging lines in case of letdown/charging unbalance
Spurious Boron Dilution	Failure to stop boron dilution by closure of valves
Alternative Air-Cooled Generators	Failure of Generators due to overload
Isolation of MFW	Failure to isolate MFW in case of excessive FW to SGs

3.2. Identification of Fire Compartments

The site boundary of the target plant is selected as GPAB. The selected GPAB includes the followings:

- The compartments include SSCs only for the target plant.
- The compartments include SSCs for both target and adjacent plants.
- The compartments include SSCs shared with target and adjacent plants.
- The compartments include SSCs only for the adjacent plant but have fire propagation paths to the compartments that include SSCs relevant to the target plant

As a result, the 217 compartments are identified referring to the fire zones defined in fire protection regulation [4] shown in Table 3.

The following criteria are applied to qualitatively screen out the compartments not considered in the FPRA.
Criterion 1: Include FPRA Components or Cables?
Criterion 2: Relevant to HFEs identified in Task 3?
Criterion 3: Automatic/manual plant trip will be caused in case of fire in the compartment?
Criterion 4: The compartment adjacent to those surviving either above 3 criteria?

The following 8 compartments are qualitatively screened out for further analyses:

- SG Storage Building / 2 Compartments
- Solidified Waste Processing Building / 1 Compartment
- Solid Waste Processing Building / 1 Compartment
- Solid Waste Storage Building / 4 Compartments

Table 3. Number of Fire Compartments Identified

Buildings	**COMPs**	**Buildings**	**COMPs**
Containment	2	Aux. Building	35
Control Building	39	DG Area	3
Intermediate Building	19	Yard	10
Reactor Building	35	Turbine Building	1
Waste Processing Building	5	SG Storage Building	2
Solidified Waste Processing Building	1	Solid Waste Processing Building	1
Solid Waste Storage Building	4	SWPs Room	1
ES Building	1	Oil Storage Tank	2
Demineralized Water Tank Area	1	Turbine Building (Other Plants)	1
Electrical Component Room for SWPs	1	Demineralized Water Equipment Room	1
Areas of Adjacent Plant	52	Total	217

- COMPs: Compartments

3.3. HRA and Initial HEPs in Phase-A

a. Screening of HFEs based on the IEPRM

HRA in Phase-A (Task 3) screens out HFEs that are credited in the IEPRA and not relevant to fire conditions using the following 3 criteria:
Criterion 1: HFEs only relevant to initiating events not considered in FPRM should be screened out.
Criterion 2: HFEs only relevant to mitigative operator actions not credited in FPRM are screened out.
Criterion 3: HFEs with cues due to alarms are screened out assuming the congestion of spurious alarms.

As a result, the 31 HFEs are qualitatively screened out by the above three criteria as follows:
Criterion 1: The 9 HFEs specific to SGTR are qualitatively screened out.
Criterion 2: The 7 HFEs relevant to operation for MCR HVAC (Heating, Ventilation and Air Conditioning) fans are qualitatively screened out.
Criterion 3: The 25 HFEs relevant to the following are qualitatively screened:

- Startup or switch over of HVAC system and chiller.
- Startup of CCWPs and open/close valves in CCWS

- Reading pressure in SWS headers
- Switchover strainers of SWS

b. Identification of HFEs specific to fires

Spurious operations of SSCs due to fire, which worsens plant conditions, may provide Error Forcing Contexts (EFCs) to operators. From this point of view, the following HFEs are identified:

- Failure to control RHR flow.
- Failure to control AFW flow.

These operations control the flow rate in RHR or AFW by adjusting flow control valve openings. However, in case of spurious opening of these flow control valves, operators could not adjust the opening of these valves. Hence, these spurious operations of flow control valves are EFC for the above HFEs.

Also, due to spurious alarms caused by fires, operators may attempt Undesirable Actions (UAs) that prevent safe shutdown operations.

Based on Alarm Response Procedure (ARP), the following possible UAs are identified:

- Stop CH/HPIPs due to a spurious alarm of “High Bearing Temperature of CH/HPIP”.
- Stop RHRPs due to a spurious alarm of “Automatically Closed RHR Suction Valve”.
- Stop IA (Instrumental Air) compressors due to a spurious alarm of “IA Compressors Tripped”.

The above alarms could be EFCs because operators may attempt to stop the components to protect these important components. However, they could not be EFCs if ARP requires operators to ensure the actual conditions of these components prior to stopping them. The feasibility of such EFCs is analyzed in Detailed HRA (Task 15).

c. Initial HEPs

NRRC FPRAG provides initial HEPs for HFEs depending on fire conditions [1]. A typical initial HEP is 10 times the HEPs in the IEPRM, which is for HFEs not modified in Task 1 (FPRM) or Task 3 (HRA). The HEPs of fire specific HFEs and HFEs affected by spurious operations are set to 1.0.

The initial HEPs are so conservative that they should be reduced by Detailed HRA (Task 15).

3.4. Fire Ignition Frequency

The generic distributions of fire ignition frequencies (FIFs) based on the operating experiences [2] are applied to this FPRA. The generic distributions of FIFs for individual fire ignition categories are apportioned to every fire compartment by equation (1):

$$\lambda_j = \sum_{All\ IS} \lambda_{IS} W_{IS,j} \tag{1}$$

$$\lambda_j = FIF\ of\ Compartment\ j$$

$$\lambda_{IS} = FIF\ of\ fire\ ignition\ category\ IS$$

$$W_{IS,j} = Weighting\ factor\ of\ IS\ in\ compartment\ j$$

The weighting factors $W_{IS,j}$ can be set as follows:

Countable Components	: Population of IS category in component j
Cables	: Cable loads in compartment j
Transient Combustibles	: Rating of amount transient combustibles (High, Medium, Low, Very Low)

3.5. Main Control Room Fires

The NRRC FPRAG recommends that the following fire scenarios in the main control room (MCR) should be considered:

- Circuit fires in Main Control Board (MCB), affecting control sectors within the board.
- Fires in electrical cabinets other than MCB, affecting other cabinets including MCB.

- Transient fires outside electrical cabinets, affecting electrical cabinets including MCB.

a. Circuit Fires in MCB

The detailed scenarios for MCB fires are defined by dividing MCB into sectors such as the “HPI sector” and the “RHR/LPI sector”. The FIF of each detailed scenario is defined by apportionment of FIF based on the area of each sector. The integrated severity factor for each detailed scenario is defined depending on the distance between the fire ignition source sector and the target sectors [1]. It should be noted that the effect of the incipient fire detection system, which could reduce non suppression factors, is not included in the integrated fire severity factor.

As a result, the 161 detailed scenarios affecting target sectors are identified. The 64 of 161 scenarios include MCR Abandonment (MCRA) due to large ZOIs (ZOI ≧2.1m within MCB). Also, the 27 of 161 detailed scenarios tin which fire impacts remain within fire ignition source sector are identified.

b. Electrical Cabinet Fires outside MCB

The damage criteria defined in NRRC FPRAG are as follows:

Target Type	Radiative Heat Flux [kW/m2]	Temperature [deg.-C]
Cable TP	6	205
Cable TS	11	330
Sensitive Device	3	65

NRRC FPRAG also defines the criteria for MCRA as follows:

- MCRA due to Loss of Habitability (LOH) : Height of Hot Gas Layer ≦ 1.8m above the floor
- MCRA due to damage of MCB

The temperature of hot gas layers due to electrical cabinet fires in MCR predicted by BRI2-CRIEPI [5] is less than 65 [deg.-C]. It can be, hence, concluded that the target electrical cabinets would not be damaged due to thermal effect of hot gas layer in case of electrical cabinet fires in MCR.

Also, a total of the 53 electrical cabinets are identified where a hot gas layer could be formed during a fire, reaching up 1.8m or less above the floor. In these cases, BRI2-CRIEPI predicts that a hot gas layer could reach 1.8m above the floor in 17–37 minutes after ignition.

A total of the 40 detailed scenarios that damage the targets are identified, the 12 of which include MCRA. The 3 scenarios of MCRA without damaging the targets (i.e., MCRA due to LOH only) are identified.

c. Transient Fires outside MCB

The temperature of hot gas layers in case of transient fires predicted by BRI2-CRIEPI assuming peak HRR of 98 percentile is so low (<65 deg.-C) and thus any electrical cabinets in MCR would not be damaged due to thermal effects of hot gas layer. In other words, it can be concluded that electric cabinets, especially MCB, would be damaged due to radiative heat flux.

d. MCR Abandonment (MCRA)

It is assumed that MCRA would be attempted if the scenarios satisfy the following criteria:

[For Circuit Fires in MCB]

- ZOI ≧2.1m within MCB

[For Fires outside MCR]

- The radiative heat flux to MCB is greater than damage criteria (i.e., 6 kW/m2 for Cables of Thermo-Plastic, 3 kW/m2 for Sensitive Devices), and/or
- Height of Hot Gas Layer ≦ 1.8m above the floor

In case of MCRA, HEPs relevant to remote shutdown operations are quantified.

3.6. Fire Compartment CDFs under Conservative Assumptions

NRRC FPRAG recommends quantifying CDFs for scenarios with initial HEPs, scenario frequencies and FPRM under full compartment burn assumption to test data and FPRM identified/developed in Phase-A. Since MCR fires can be a risk significant contributor in general, detailed scenarios are identified and quantified in Task 10. However, even Task10 introduces some conservative assumptions, such as providing no credit to alternative instrumentation (see Section 4).

The fire compartment CDFs under conservative assumptions are summarized in Table 4. A total of the 157 fire compartments relevant to the target plant that survived from qualitative screening are identified. Of these 93 fire compartments (59%) have CDFs ≦ 10^{-8}/ry. The CDFs of these compartments are so low that they are not target compartments for detailed analysis to relax conservatism. On the other hand, the top 49 compartments have so high CDFs that it is necessary to investigate/resolve the conservative assumptions in scenarios and FPRM to obtain more realistic CDFs. Furthermore, despite the detailed analysis, the CDF due to MCR fires is still so high (order of 10^{-5}/ry), that further analysis is required to identify the conservatism in detailed scenarios and FPRM. Hence, NRRC selected several compartments as representatives for detailed analyses in terms of conservative assumptions introduced into scenarios and FPRM in this study (see. Section 4).

Table 4. Fire Compartment CDFs under Conservative Assumptions

CDFs	Number of Compartments
≧ 10^{-4}/ry	49
10^{-5}/ry	3
10^{-6}/ry	4
10^{-7}/ry	8
≦ 10^{-8}/ry	93

4. REDUCTION OF CONSERVATISM BY DETAILED ANALYSES

The CDFs of about 60% of the fire compartments are so low (≦10^{-8}/ry) that it is not necessary to reduce the conservatism for these compartments. On the other hand, the CDFs of about 33% are so high (≧10^{-5}/ry) that it is necessary to identify and resolve excessively conservative assumptions for these compartments.
In this study, the fire compartments whose CDFs≧ 10^{-4}/ry are grouped in terms of conservative assumptions. Then, for the representative fire compartment of each group, the methods to reduce conservatisms by detailed analyses and modification of FPRM are developed.

4.1. Methods to Reduce Conservatism

The conservative assumptions identified and the methods to resolve them are shown in Table 5. The methods in Table 5 are relevant to Fire Modeling (Task 14), Detailed HRA (Task 15), Circuit Failure Mode Likelihood Analyses (Task 16) and feedback to FPRM (Task 1) of NRRC FPRA Methodology. These methods are efforts to make the FPRM and fire scenarios more realistic.

4.2. CDFs for Representative Compartments

In this study, NRRC selects Containment Vessel, Turbine Bldg., Relay Room, Aux. Bldg. Isle @ EL+10.5m, Emergency Switchgear Room (ESGR) A, and MCR as the representative compartments to resolve conservative assumptions. The CDFs for the representative compartments are shown in Figure 2. The CDFs of Containment, Turbine Bldg., and Aux. Bldg. Isle @EL+10.5m are all in the order of 10^{-7}/ry. It, hence, can be concluded that these compartments become no longer risk significant contributors by reducing conservatism. On the other hand, CDFs for Relay Room, ESGR-A, and MCR are still so high (≧ 10^{-6}/ry) in spite of conservative reduction methods shown in Table 5.

a. Relay Room

The 254 detailed scenarios are identified for Relay Room. The total CDF for Relay Room is 4×10^{-6}/ry. Top 13 of detailed scenarios have the CDFs in the order of 10^{-7}/ry and sum of these is 3×10^{-6}/ry. In other words, the 87% of the total CDF for Relay Room is dominated by these 13 detailed scenarios.

b. Emergency Switchgear Room (ESGR)-A

For ESGR-A, the 142 detailed scenarios are identified. The total CDF for ESGR-A is 1×10^{-6}/ry even though the CDFs for all individual detailed scenarios $\leqq 10^{-8}$/ry. The CDF of the top 27 of detailed scenarios is in the order of 10^{-8}/ry and the total CDF due to these scenarios is 8×10^{-7}/ry. In other words, around 80% of the total CDF for ESGR-A is dominated by these 27 detailed scenarios.

c. MCR

For MCR, the 320 detailed scenarios are identified. The total CDF for MCR is 2×10^{-5}/ry. The top 5 of the detailed scenarios have the CDFs in the order of 10^{-6}/ry. These 5 scenarios contribute 42% of the total CDF for MCR. The CDFs of 35 scenarios following to the top 5 scenarios are all in the order of 10^{-7}/ry. The contribution of the top 40 scenarios with CDFs $\geqq 10^{-7}$/ry to the total CDF in MCR is 73%.

The top 2 scenarios with the CDFs of 6×10^{-6}/ry and 1×10^{-6}/ry, respectively are both relevant for transient fires affecting MCB. These 2 scenarios contribute 29% to the total CDF in MCR.

4.3. Significant Risk Contributors

The significant risk scenarios identified in this study are relevant to MSOs due to hot shorts in electrical cabinets as follows:

- RCP Seal LOCA due to MSOs causing loss of RCP thermal barrier cooling and seal injection
- PORV LOCA due to MSOs
- ISLOCA (Letdown/Charging unbalance) in CVCS due to MSOs
- Loss of ECCS / Secondary Side Cooling

It should be noted that MSOs affecting non-emergency systems could potentially cause risk significant consequential/initiating events as RCP Seal LOCA and ISLOCA (Unbalance between Letdown/Charging), respectively. This finding suggests that FPRAs can identify significant risk scenarios that are relevant not only to the emergency systems but also to non-emergency systems. On the other hand, in this study, MSOs due to hot shorts in cables are not so risk significant because of the timing factor to resolve hot short of cables in NUREG/CR-7150 [6] and system separations by fire barriers.

In Phase-A analyses, UAs due to spurious alarms and spurious indications could significantly affect operators' actions. However, Detailed HRA (Task 15) reveals that there is no EFC due to spurious alarms causing UA. Also, the task reveals that alternative parameters are available for cognitions in case of spurious indications. It suggests that ensuring the components prior to stopping them, and alternative indications, are important to avoid core damage.

Task 9 of Phase-A analysis assumes that the components/cables in a fire compartment would entirely fail (i.e., Full Compartment Burn Assumption). This assumption does not consider ZOIs in compartments. In Task 14 of Phase-B, detailed fire scenarios and their ZOIs are identified by Fire Modeling. In many cases, the Fire Modeling for the detailed scenarios reveals that ZOIs could be limited by HRRs of fire ignition sources, behaviors of hot gas layers, and fire barriers within compartments. It suggests that purging of hot gas and fire barriers separating system trains and combustibles within compartments is important to avoid core damage. Also, fire suppression prior to damaging targets is important to reduce risk due to fire. The allowable time could be extended and reduce CDFs in case of detailed scenarios relevant to electrical cabinets if the recent methods described in NUREG-2178 vol.2 [7] and NUREG-2230 [8], which are not reflected in the methodology in this study, are reflected.

From the viewpoint of fire ignition sources, this study identifies Transient Fires as a risk significant contributor and suggests that the control of combustibles and hot works is important to reduce fire risk. However, CDFs of scenarios relevant to Transient Fires in Relay Room and MCR, where better combustible controls are generally expected than other fire compartments might be reduced if the recent methods described in NUREG-2233 [9], which is not reflected in the methodology in this study, are reflected.

Table 5. Major Methods to Resolve Conservative Assumptions

Conservative Assumptions	**Methods**
Full Compartment Burn Assumption	・Detailed scenarios based on individual fire ignition sources and targets. ・Integrated Fire Severity Factors including Non suppression Factors.
Conservative ZOIs	・Detailed scenarios within vertical cabinets (MCB and RCC) ・Detailed ZOIs including those of hydrogen jet fire scenarios by fire modeling.
Conservative HRA/HEPs	・Detailed HRA based on narratives on operators' actions. ・Realistic time windows for operator actions based on fire modeling. ・Backup operations, SAMs and recovery actions with redundant trains. ・Alternative parameters for cognitions, especially in MCR fires. ・Detailed analyses for EFCs on UAs.
Conservative Plant Responses	・Remove conservative assumptions on system dependencies in IEPRM. ・Realistic system configurations/responses and layouts of components ・Circuit Failure Mode Likelihood Analyses ・Remove MSOs due to failure of optic fiber cables [3]. ・Remove the target cables separated by fire barriers within a compartment.

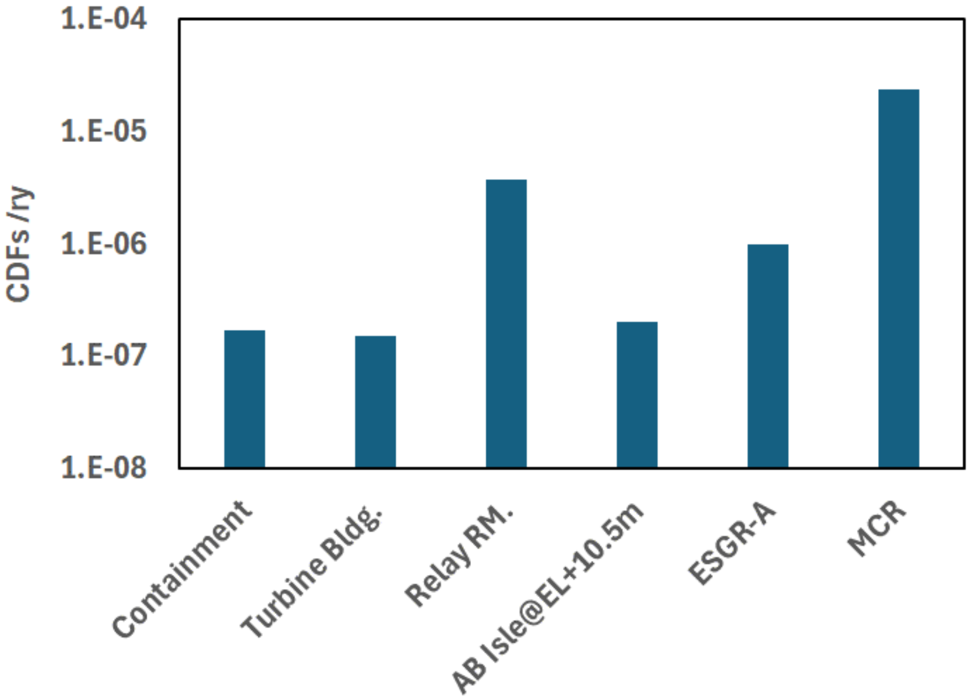

Figure 2 CDFs of Representative Fire Compartments

5. CONCLUSION

Through the FPRA for a model plant, this study ensures that NRRC FPRAG as well as FIFs based on the operational experiences are applicable to FPRAs for actual NPPs of Japan. Furthermore, this study clarifies the methods to relax conservatisms in FPRM and fire scenarios.

This study demonstrates that FPRAs can identify risk significant contributors such as MSOs due to hot shorts in electrical cabinets if excessive conservatism is reduced by detailed analysis and modification of FPRM. In other words, unnecessary simplifications and conservatisms in FPRM and fire scenarios should be removed or relaxed to identify risk significant contributors.

These methods to relax conservatisms would be helpful for FPRA analysts and are expected to include them in NRRC FPRAG.

As far as fire modeling, the recent methods relevant to fire severities described in NUREG-2178 vol.2 [7], NUREG-2230 [8] and NUREG-2233 [9] will be included in NRRC FPRAG [1] in the near future.

It can be concluded that the methodology of NRRC PRAG can identify risk significant contributors. Also, reducing excessive conservatism by detailed analyses is a key for FPRA to derive insights on fire risks. NRRC will update NRRC FPRAG based on the insights gained by this study and recent FPRA methods.

Acknowledgements

In this study, FPRA for a model plant is performed under the sponsorship by Kansai Electric Power Company (EPC), Hokkaido EPC, Shikoku EPC, Kyushu EPC and JAPC. For the planning and performance of this study, the above EPCs provided NRRC with tremendous help. Also, Dr. George Apostolakis, the director of NRRC, gave us helpful advice on the methods and results of this study. We, the authors, would like to express our deepest gratitude to them.

References

[1] T. Uchida, K. Shirai, J. Ji, K. Tasaka, G. Apostlakis, and M. Kazarians, O20001, Development of Fire PRA Guide for Japanese Nuclear Power Plants, 2020.
[2] T. Uchida, Y. Nagata, T. Yoshida, and K. Shirai, NR21003, Estimation of Generic Fire Ignition Frequency Distributions for Japanese Nuclear Power Plants (in Japanese), 2022.
[3] Nuclear Energy Institute, NEI00-01 [Rev4] Guidance for Post Fire Safe Shutdown Circuit Analysis, 2019.
[4] Nuclear Regulation Authority, The Guidance for Assessment of Internal Fires in Nuclear Power Plants [Rev3] (in Japanese), 2019.
[5] K. Shirai, J. Ji, K. Tasaka, and T. Udagawa, Development of two-layer zone model BRI2-CRIEPI applicable to fire PRA for nuclear power plants, Fire Safety Journal, 2023.
[6] USNRC, NUREG/CR-7150 vol.2, Joint Assessment of Cable Damage and Quantification of Effects from Fire (JACQUE-FIRE)-Final Report, 2014.
[7] USNRC, NUREG-2178, Refining and Characterizing Heat Release Rates form Electrical Enclosures During Fire Volume 2, 2020.
[8] USNRC, NUREG-2230, Methodology for Modeling Fire Growth and Suppression Response for Electrical Cabinet Fires in Nuclear Power Plants, 2020.
[9] USNRC, NUREG-2233, Methodology for Modeling Transient Fires in Nuclear Power Plant Fire Probabilistic Risk Assessment, 2020.