An Approach to Estimate the Compartment Fire Ignition Frequency for HTGR NPP Based on LWR Generic Data

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Abstract: TASK 6 of NUREG/CR-6850 provides the detailed approach on how to estimate the fire frequencies of compartments and scenarios in Fire PRA. The approach is based on the historic data of light water reactor nuclear power plant, and suitable for the operating plants. However, lack of operational experience is an obvious issue for the new type of reactor, e.g. the High Temperature Gas Cooled Reactor (HTGR). We still can use NUREG/CR-6850 as the methodological reference. In this research, key issues for ignition frequency evaluation are discussed firstly, which are arisen during the fire PRA development of the first HTGR nuclear power plant demonstration project in China (HTR-PM). Two methods are developed accordingly to estimate compartment fire frequency for HTGR plant, namely, one is based on plant-level information and the other is based on component-level information. A real and typical compartment of HTR-PM (switchgear room) is subsequently piloted to verify the two proposals.

Keywords: **C**ompartment fire ignition frequency; NUREG/CR-6850; HTGR

1. INTRODUCTION

The famous and important document NUREG/CR-6850[1] provides the detailed method and a complete process for Fire Probabilistic Risk Assessment(PRA) implementation. However it is developed on the base of Light Water Reactor(LWR) Nuclear Power Plant(NPP) at large. For example, databases and typical fire models/scenarios that are discussed in the document are heavily associated with LWR NPP characteristics and experiences. Therefore, applicability analysis against the other reactor types is an essential step before using NUREG/CR-6850 to guide the Fire PRA work for non-LWR reactors, including the High Temperature Gas Cooled Reactor (HTGR).

As a candidate of the fourth generation reactors, HTGR nuclear power plant intends to be technologically-advanced, more safe, and more environmental friendly. Just as what the ongoing HTGR demonstration nuclear power plant (HTR-PM) in China has already encountered, during the licensing and industrialization process, full-scope PRAs of the new reactors are required to demonstrate that various internal and external hazards will not have significant effect on the safety, including the internal fire hazards that are frequent for the currently operating nuclear power plants and have resulted in significant losses in the past years.

HTR-PM PRA team completed the internal event PRA under power operation mode in 2009, and submitted the PRA report for regulatory review to support the preliminary safety review as one of the necessary licensing milestones. Some feedbacks on both the PRA model development and the pilot risk-informed applications are summarized in papers [2,3]. Recently HTR-PM PRA team completed the PRA for the spent fuel storage facility of HTR-PM plant in 2013, which adopted dry storage solution. The other extended scope PRAs, such as low power and shutdown mode, internal fire and flood and external events (seismic), are ongoing in accordance with the HTR-PM construction.

In this paper, the focus is limited on the compartment fire ignition frequency estimating approach of HTGR NPP, which is one of key technical issues encountered during the fire PRA development. As

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mentioned above, NUREG/CR-6850 is used to guide the HTR-PM Fire PRA development as the methodological reference. Preliminary examination of NUREG/CR-6850 is performed in advance to identify the key technical elements which are expected to come up against the differences between LWR and HTGR. Compartment fire ignition frequency is one of the most significant among these findings.

On the other hand, estimating compartment fire ignition frequency serves as an important connecting link in the Fire PRA methodology. The accuracy of compartment fire frequencies may seriously impact the subsequent tasks and even the whole Fire PRA model. Therefore, the approach to estimate compartment fire frequency for HTGR NPP must be carefully discussed and set up. The paper summarizes the intermediate solution to estimate compartment fire ignition frequency with respect to HTGR NPP.

2. REVIEW OF NUREG/CR-6850 APPROACH

Task 6 of NUREG/CR-6850 describes the proposed approach to estimating compartment fire frequency [1]. The approach is composed of 8 steps, as summarized in Table 1.

Table 1: NUREG/CR-6850 Steps to Estimate Compartment Fire Ignition Frequency

Step	Definition	Purpose and Technological Key Points
1	Mapping plant ignition sources to generic sources	To map all plant components that can initiate a fire to one of the 37 bins listed in Table 6-1 documented in NUREG/CR-6850 report. For the ordinary ignition sources, the mapping needs to be updated as more information is collected from the specific plant, and those sources should be verified that they can be mapped to one of the basic bins. For the ignition source identified with no matching bin, much information, such as characteristics of the source, any history of fire events, etc. should be gathered and then used to estimate the fire ignition frequency associated with that source.
2	Plant fire event data collection and review	In this step, it is necessary to assume that there are no unusual fire occurrence patterns in the plant so that we can reasonably use the generic fire frequency data. Plant-specific information should be collected based on plant fire event records from various pathways, then all collected fire events will be screened and classified by location, ignition source and mode of operation, and to obtain the number of fire events in the plant and total reactor years of the plant associated with each bin.
3	Plant specific updates of generic ignition frequencies	The generic bin frequencies should be updated using Bayesian approach and plant-specific fire event data.
4	Mapping plant-specific locations to generic locations	NUREG/CR-6850 uses a set of generic plant locations in defining the ignition sources bins. These generic locations are derived based on variety of plant constructions and naming practices. In order to use the generic frequency model, the analyst should assign various plant locations to one of the generic locations. The step usually raises a number of questions, since plants are generally configured differently. The primary criterion used in mapping deals with the location of equipment that serve the same or similar functions as the one in the generic database.
5	Location weighting factors	It is necessary to conduct this step in multi-unit sites. The location weighting factor is used to adjust the generic fire frequencies to account for location and/or equipment shared among the units in multi-unit sites.

6	Fixed fire ignition source counts	The total number of items per the equipment type is counted for establishing the ignition source weighting factor. There are two approaches to counting equipment: (1) visual examination according to plant drawings and walkdowns; and (2) use of an electronic database. However, electronic database may not be more efficient than plant walkdowns. Also, in this step, specific counting method of each equipment is provided in Task 6.
7	Ignition source weighting factors	Ignition source weighting factor, which is the fraction of an ignition source that is present in a certain compartment, should be calculated from three categories: countable items, transients, and large systems. The approach to counting equipment discussed in step 6 should be used for the category 'countable items', meanwhile, in transients category analysts should use the specific approach of high-transient fire 'influence factor' based on engineering judgment and actual operation experiences.
8	Ignition source and compartment fire frequency evaluation	The mean value of fire frequency for each ignition source can be calculated by using the mean value of the uncertainty distribution for the various parameters of the summation.

Based on the above dissection of NUREG/CR-6850's Task 6, it is concluded that several technological factors are playing the significant roles in conducting the task of fire ignition frequency estimate, as follows.

2.1. Equation used to Estimate the Ignition Source Frequency

The frequency $\lambda_{IS,J}$ associated with the ignition source present in a certain compartment can be estimated from the following equation:

$$\lambda_{IS,J} = \lambda_{IS} W_L W_{IS,J,L} \qquad (1)$$

Where,

λ_{IS} = Plant-level fire frequency associated with ignition source IS.

W_L = Location weighting factor associated with the ignition source.

$W_{IS,J,L}$ = Ignition source weighting factor reflecting the quantity of the ignition source type present in compartment J of location L. In general terms, Ignition source weighting factor is the fraction of an ignition source type found in a specific compartment.

Compartment level fire frequency would then be calculated from the sum of all frequencies $\lambda_{IS,J}$ in the same compartment.

$$\lambda_{J,L} = \sum \lambda_{IS} W_L W_{IS,J,L} \qquad (2)$$

Where,

$\lambda_{J,L}$ = Compartment level fire frequency in compartment J of Location L

The equation pattern, using multipliers to revise the basic reference frequency, fundamentally determines the fact that W_L and $W_{IS,J,L}$ will have the crucial impact on the accuracy of the final estimate. The equation establishes the linear relationship between $\lambda_{J,L}$ and the two mentioned factors. The varieties in the two factors are usually step changes, since they are associated with numbers of items in the scope being studied. So we can see that W_L and $W_{IS,J,L}$ are usually more sensitive to the final estimate than the ignition source frequency λ_{IS} itself.

2.2. Table 6-1 "Fire Frequency Bins and Generic Frequencies"

Task 6 provides the list of 37 fire frequency bins and generic frequencies (hereafter refers to Table 6-1) which forms the essential basis to estimate compartment fire ignition frequency. Appendix C of NUREG/CR-6850 provides the discussion of the basis of the frequencies and their derivation methods. It is understood that the underlying fire event data was taken from EPRI's Fire Event Database (FEDB). For LWR NPP, the methodology has stood on the contribution by the whole industry and has provided the best available foundation. It's hard and wasteful to set up another household.

Besides the equipment types, potential fire types, e.g. electrical, oil, and transient can also be postulated from the list. This information is also important for the new reactor PRA development. The information can facilitate not only the other Fire PRA tasks such as compartment screening, but also some supporting tasks, e.g. fire equipment electronic database architecture. It is an important experience that PRA usually pushes forward the systematic collection of various and multi-dimensional information about the nuclear power plant, these information and data are also sincerely expected by the design engineers.

2.3. Plant specific information

Plant specific information plays important roles in NUREG/CR-6850 approach. Almost all the steps are associated with certain requirements to reflect the plant specific situation. However, lack of plant specific information is a common issue for the new nuclear power plant. In our opinion, it's suggested to separate the requirements into two categories. One category is related with the plant specific historical operating records, e.g. Step 2 and 3, and the other is related with plant specific design information, e.g. Step 1, 4, 5, 6 and 7. The categorization may lead to different solutions for the new plant to deal with the lack of plant specific information issue. Namely, for all the new plants, the plant specific design issue can be gradually and eventually resolved. What we need to do is to get the best available design information and keep PRA updated as necessary. Nevertheless, first-kind new plants might never be able to resolve the plant specific historic record issue before the plant can operate. We may have no choice but to skip the related steps.

3. PROPOSED APPROACH TO ESTIMATE FIRE IGNITION FREQUENCY FOR HTR-PM BASED ON LWR EXPERIENCE

Before the formulation of HTGR Fire PRA approach, the literature review on design phase PRA of other new reactors is carried out.

AP1000 PRA[4] continued to use the same fire analysis methodology with AP600 PRA, and the AP1000 fire ignition frequencies were based mainly on the results of the AP600 evaluation. Sensitivity studies were performed by using the different fire ignition frequencies. Slight differences between AP600 and AP1000 were found, and the orders of magnitude between the two were same. As presented in the PRA documents, AP600 used FIVE methodology and generic data information from EPRI's Fire Events Database to calculate the fire ignition frequencies. FIVE provides detailed guidance for determining both location weighting factors and ignition source weighting factors and a formalized documentation process for recording input data and calculating fire frequencies. Hence it can be concluded that AP1000/AP600 approach is basically similar to NUREG/CR-6850, however it may generate the fire bins from the underlying event database, instead of using the generic bins proposed by NUREG/CR-6850.

The ESBWR Internal Fire PRA was performed according to the guidance in NUREG/CR-6850 as a whole. In doing the task of fire ignition frequency, it adopted a set of assumptions to revise the NUREG/CR-6850 approach. Key assumptions are summarized as follows [5].

- The design inputs are subject to changes as a result of more detailed designs. However, it is reasonable to assume that the major components and their locations have been well designed and will not have significant changes in the final designs.
- It is assumed that all ignition source type bins are applicable with some exceptions which are obviously not applicable to ESBWR plants.
- Generic bin for the control room is assumed to be applicable to the main control room although the ESBWR main control room design is completely digital as opposed to the traditional electro-mechanical designs
- Although the ESBWR plant may be located with the existing nuclear power plants, the plant location weighting factors are assumed to be 1 because the ESBWR plant is designed as a single-unit plant with no shared buildings.
- Some equipment types in certain generic bins are slightly adjusted according to ESBWR design information.
- Weighting factor evaluation is simplified. It is conservatively assumed that all compartments have the same transient fire influencing factors. Potential exceptions are the main control room and the turbine building general area, for which area the weighting factor is increased by a factor of 10.

HTR-PM Fire PRA cannot exactly follow the NUREG/CR-6850 approach either. Lack of operational experience, limited information during the design phase, and more significant differences in the plant configuration are the significant factors which should be considered during the HTR-PM Fire PRA approach formulation. One decision is made to suspend some steps/sub-steps for the time being, e.g. plant fire event data collection and review (Step2), plant specific updates of generic ignition frequencies (Step 3) and counting the fixed fire ignition sources by walkdowns (Step 6), till the condition is all set. Another decision is made to explore the possibility how to estimate the compartment fire ignition frequency for HTR-PM based on LWR generic data, because it is practically impossible to get HTGR specific operation records from the reality.

In this study, two approaches are proposed for investigation.

3.1. Based on Plant-Level Generic Fire Frequency

Despite conspicuous differences in plant design among reactor types, a considerable portion of equipment types are found still similar between HTGR and LWR, especially the electrical equipments which fortunately contribute to the majority of 37 generic fire frequency bins of NUREG/CR-6850. Therefore, using the fire frequency bins summarized by NUREG/CR-6850 to estimate the fire ignition frequencies of HTGR plants has the practical possibility.

The 37 generic bins are reviewed to exclude the bins which are obviously not applicable to HTGR plants, as shown in Table 2.

Table 2 Fire bins being excluded from the generic list

ID	Location	Ignition Source (Equipment Type)
2	Containment (PWR)	Reactor Coolant Pump
3	Containment (PWR)	Transients and Hotwork
20	Plant-wide components	Off-gas/H2 Recombiner (BWR)
22	Plant-wide components	RPS MG Sets

To continue implementing the method, a typical LWR plant will be selected as the benchmark. The total number of a certain ignition source (for example, electrical cabinet) will be counted respectively for the LWR plant and the HTR-PM plant, and marked as N^P and N^H. A new plant-level weighting factor is proposed as:

$$W_{IS}^{PH} = N^H / N^P \quad (3)$$

Then, plant-level generic fire frequency associated with ignition source IS of HTGR NPP is estimated from the equation:

$$\lambda_{IS}^{H} = \lambda_{IS}^{P} W_{IS}^{PH} \qquad (4)$$

Where,

λ_{IS}^{H} = plant-level generic fire frequency associated with ignition source IS of HTGR NPP.

λ_{IS}^{P} = plant-level generic fire frequency associated with ignition source IS of LWR NPP.

W_{IS}^{PH} = plant-level weighting factor between LWR NPP and HTGR NPP concerning a certain ignition source. Practically it can differ from ignition sources.

Accordingly, the original equations from Task 6 of NUREG/CR-6850 can be modified to obtain the compartment level fire frequencies for HTGR plants:

$$\lambda_{IS,J,L}^{H} = \lambda_{IS}^{H} W_{L} W_{IS,J,L} \qquad (5)$$

$$\lambda_{J,L}^{H} = \sum_{IS} \lambda_{IS,J,L}^{H} = \sum_{IS} \lambda_{IS}^{H} W_{L} W_{IS,J,L} \qquad (6)$$

Where

$\lambda_{IS,J,L}^{H}$ = Compartment fire frequency associated with ignition source IS presented in compartment J of Location L in HTGR NPP

$\lambda_{J,L}^{H}$ = Compartment fire frequency associated with all the ignition sources presented in compartment J of Location L in HTGR NPP

3.2. Based on Component-Level Generic Fire Frequency

Although NUREG/CR-6850 continues the approach to set up the generic fire frequencies on the plant level, related criticisms can be found along the Fire PRA methodology development history, especially the per-item fire frequency may vary from plant to plant due to variations in the total population of a given equipment type present in the plant. Sometimes the variety can be significant, e.g. the results from a two loop Pressurized Water Reactor (PWR) plant versus a four loop PWR plant.

Some modern Fire PRAs are exploring the approach to use the component-level generic frequencies to cover the above defect. The Fire PRA of Unit 1 in Surry NPP [6] is one of the representatives. Component-level fire frequencies are estimated based on its operation records and the procession of Bayesian Updating in Surry PRA.

Besides the methodological consideration above, HTR-PM PRA has another important consideration for the proposal of the approach based on component-level frequencies. It seems that HTGR plants can never have sufficient operating events to set up the specific generic event database and then the generic frequencies. We cannot expect that hundreds of HTGR reactors can be built in the future, like the current LWR reactors, even in the world range. Collecting available data from other similar facilities, including non-reactor and non-nuclear facilities, should be the essential way for the HTGR specific equipment. LWR data and similar facility data should be combined together to build the whole set of generic frequencies required by HTGR Fire PRA. HTGR specific operating records can then be used to update the generic frequency database by Bayesian process. In order to merge these data together, it will be more appropriate to execute the work in the component level than in the plant level.

Given that we have already had the component-level fire frequency associated with ignition source IS $\lambda_{IS}^{H,C}$, the compartment level fire frequency of compartment J in Location L in HTGR plant associated with ignition source IS $\lambda_{IS,J,L}^{H}$ can be summed over the population of ignition source IS. The final compartment level fire ignition frequency can then be calculated as:

$$\lambda_{IS,J,L}^{H} = \sum_{C} \lambda_{IS}^{H,C} \qquad (7)$$

$$\lambda_{J,L}^{H} = \sum_{IS} \lambda_{IS,J,L}^{H} = \sum_{IS} \sum_{C} \lambda_{IS}^{H,C} \qquad (8)$$

Where

$\lambda_{IS}^{H,C}$ = Component-level fire frequency associated with ignition source IS

$\lambda_{IS,J,L}^{H}$ = Compartment level fire frequency associated with ignition source IS in compartment J of Location L in HTGR NPP

$\lambda_{J,L}^{H}$ = Compartment fire frequency associated with all the ignition sources presented in compartment J of Location L in HTGR NPP

4. CASE STUDY

In this section, a real switchgear room of HTR-PM is taken to verify the two proposed approaches.

4.1. Introduction of the Compartment

The layout of the candidate room is shown in Fig. 1 and Fig. 2. The room is designed to serve as one division of Emergency Power Supply System, Reactor Protection System, Safety-related Power Supply System, Uninterrupted Power Supply System and Direct-Current Power Supply System. In the room, there are 14 emergency power distribution cabinets, 8 safety-related power distribution cabinets, 1 DC power distribution cabinet, 1 uninterrupted power supply distribution set that contains 6 cabinets, and 2 reactor trip breaker cabinets. So the whole room contains 31 electrical cabinets, all of them are employed by modular low voltage cabinet. In the cabinets there are a large number of combustibles such as cables, components and switches. The whole design is subject to the international requirements and standards for commercial nuclear power plant, e.g. fireproof, spatial separation, environment condition control, etc.

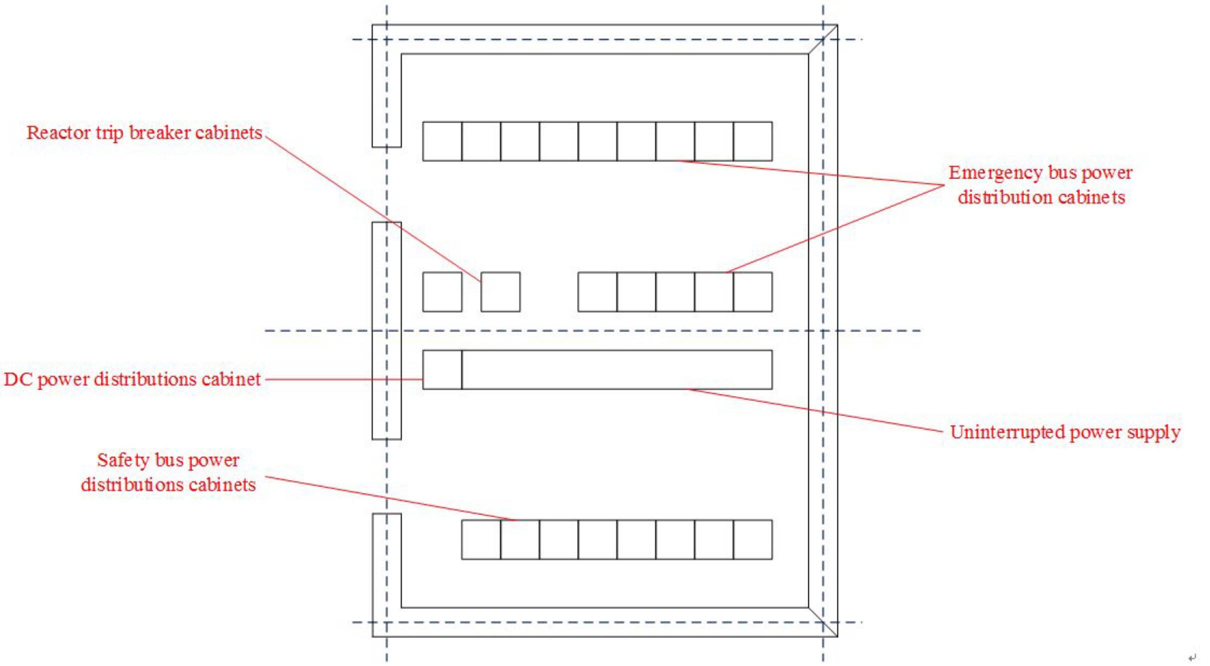

Fig. 1 Schematic plan of switchgear room

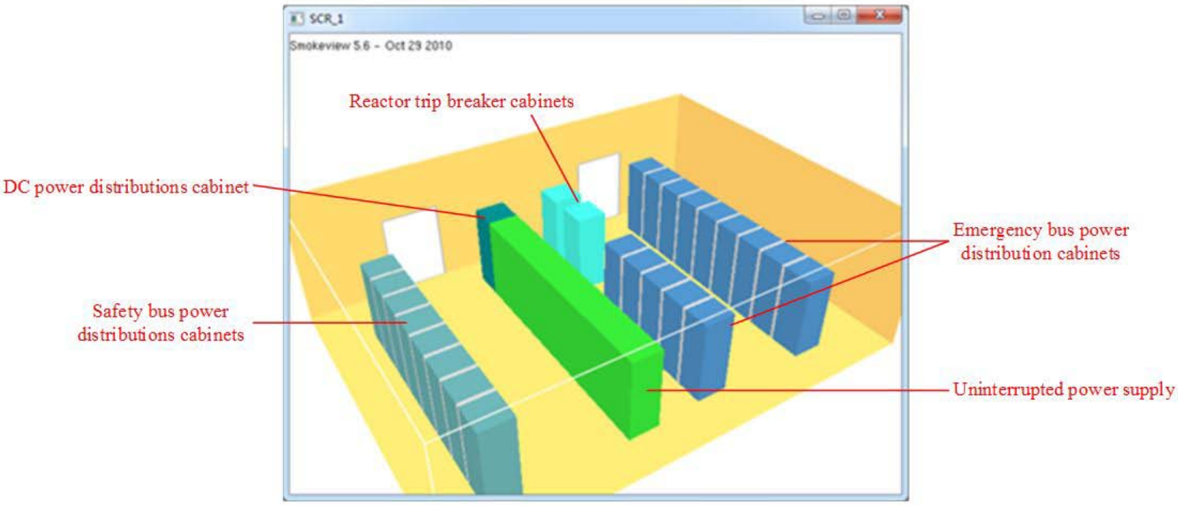

Fig. 2 FDS simulation diagram of switchgear room

4.2. Quantitative Analysis

In the study, it is assumed as usual that all the cabinets have the same contribution to the total fire frequency of the room, despite the actual differences among the cabinets.

Proposed Approach 1

Under the approach framework based on plant-level fire frequency, fire frequency bin, which is appropriate to the room being studied, is selected from the proposed generic fire bins of NUREG/CR-6850 as the first step, that is the Bin 15 (electrical cabinets) with the value of 0.045 event/reactor year and a 100% contribution from electrical fire type.

The ESBWR is determined to be the LWR benchmark. The ESBWR design intends to have significantly lower numbers of pumps, motors and other active components than the currently operating nuclear power plants. Hence it will lead to the conservative result. The total number of electrical cabinets in the designed ESBWR[5] is 530. Counting the items according to the currently available drawings and documents of HTR-PM gives the corresponding number of 286. Then, the plant-level weighting factor W_{IS}^{PH} is calculated as:

$$W_{IS}^{PH} = N^H/N^P = 286/530 = 0.5396 \qquad (9)$$

The revised plant-level fire ignition frequency is:

$$\lambda_{IS}^{H} = \lambda_{IS}^{P} W_{IS}^{PH} = 0.045 \times 0.5396 = 2.43 \times 10^{-2} \qquad (10)$$

The ‘location’ feature of Bin 15 is ‘Plant-Wide Components’, so we need to determine the relevant ignition source weighting factor.

$$W_{IS,J,L} = 31/286 = 0.1084 \qquad (11)$$

The location weighting factor W_L is determined as 2 due to the reason that HTR-PM plant consists of two reactors[2,3]. Hence the final compartment level fire frequency of the room being studied is determined as:

$$\lambda_{J,L}^{H} = \sum_{IS} \lambda_{IS}^{H} W_L W_{IS,J,L} = 2.43 \times 10^{-2} \times 2 \times 0.1084 = 5.26 \times 10^{-3} \qquad (11)$$

Proposed Approach 2

Under the approach based on component-level fire frequency, component-level fire frequencies from the Fire PRA Report of Unit 1, Surry NPP[6] are taken to build the generic fire frequency database, as shown in Table 3.

According to the generic component-level frequencies, Item 3 'Bus Small Fire' is determined as the most similar component type. The generic component-level fire frequency 2.6×10^{-4} is selected accordingly. According to the note (see the footnote of Table 3), the generic data is further divided by 7 to get the estimate for cabinet fire.

Table 3 Component level generic fire frequency data from Surry PRA

ID	Component Type	Frequency/Plant	Pieces*	Frequency/Unit Eq't
1	MCC Small Fire	6.6-3	34	1.9-4
2	MCC Large Fire	6.2-4	34	1.8-5
3	Bus Small Fire	5.2-3	20	2.6-4
4	Bus Large Fire	1.3-3	20	6.5-5
5	Transformer Small Fire	2.9-3	19	1.5-4
6	Transformer Large Fire	2.2-3	19	1.2-4
7	Pump Small Fire	8.8-3	4	2.2-3
8	UPS	1.7-3	4	4.2-4
9	Relay Small Fire	1.0-2	10	1.0-3
10	Relay Medium Fire	6.2-4	10	6.2-5

* Panels, not individual cabinets for switchgear equipment; there are about 40 cabinets/MCC, 7 cabinets/bus panel.

Then the compartment level fire frequency of the switchgear room is calculated as:

$$\lambda_{J,L}^{H} = \sum_{IS}\sum_{C}\lambda_{IS,J,L}^{H,C} = 31\times(2.6\times10^{-4}/7) = 1.15\times10^{-3} \quad (12)$$

5. DISCUSSION AND CONCLUSION

In spite of the inconsistency of generic database resources, the pilot results from the two proposed approaches are generally in the same order of magnitude. It's fortunate and interesting. We will further check the similarity against more ignition sources in the next stage.

It is planned that the two approaches will be combined together to establish the generic fire bins for HTGR plant in accordance with equipment types. On the one hand, LWR generic fire bins can facilitate the classification of HTGR ignition sources which are similar with those of LWR. Plant-level weighting factor can be a feasible solution to regulate the LWR generic fire frequencies. On the other hand, fire frequencies of HTGR specific equipment types shall rely more on the second approach, which intends to collect component-level fire data from other similar resources including non-reactor or non-nuclear industries. Expert option and engineering judgment based on the best available knowledge will be used to remedy the resource inconsistency. Meanwhile, we will endeavor to set up the systematic process of specific event collection aiming at HTR-PM project, so that the Bayesian updating steps can be integrated into the iteration process in the near future

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