Insights from Internal Fire PSA of UK ABWR in Generic Design Phase

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Abstract: An Internal Fire PSA (FPSA) model was developed for the UK ABWR generic design as part of the full scope PSA. The FPSA was peer reviewed against ASME/ANS RA-Sb-2013. The FPSA for the reactor included Level 1 and Level 2 analyses at Power, as well as a Level 1 scoping analysis for selected Shutdown Plant Operational States (POSs). A Level 1 scoping analysis of Spent Fuel Storage Pool (SFP) was also conducted. NUREG/CR-6850 and NUREG/CR-7114 as well as related guidance/data were applied. These guidance documents are generally intended for application to an operating plant rather than a plant in design phase. The application of the guidance within a new-build plant generic design brought certain local challenges. Simplified and conservative approaches were initially adopted to overcome these challenges as well as some novel approaches for dealing with multi-compartment scenarios. This paper introduces these approach and then focuses on the methods to reduce the conservatisms as well as the FPSA results and insights, and risk-informed improvements.

Keywords: Internal Fire PSA, UK ABWR, Generic design phase, Risk-informed improvements

1. INTRODUCTION

Hitachi-GE is proposing to build multiple Advanced Boiling Water Reactor (ABWR) plants in the UK, based on an enhanced Japanese ABWR design, incorporating lessons learned from the Fukushima-Daiichi accident. Hitachi-GE developed a full-scope PSA for the UK ABWR generic design as summarised in the Pre-Construction Safety Report (PCSR) Chapter 25 [1]. The PSA had undergone peer reviews [2], and used the PSA to inform the design process as well as demonstrate further evolution to ensure the design is As Low As Reasonably Practicable (ALARP) [1, 3 and 4].

The FPSA for the UK ABWR generic design included Level 1 and Level 2 analyses of reactor at Power, as well as Level 1 scoping analyses for selected Shutdown POSs. The FPSA also included a Level 1 SFP scoping analysis. The FPSA was conducted according to the NUREG/CR-6850 [5], NUREG/CR-7114 [6] and related guidance/data. These guidance documents are generally intended for application to an operating plant rather than a plant in design phase. Application of the guidance within a new-build plant generic design brought certain local challenges such as absence of detailed circuit design, detailed locations of raceways and ignition sources, comprehensive Fire Hazard Analysis (FHA), and various operating procedures. Simplified and conservative approaches were therefore adopted to overcome these local challenges as well as some novel approaches for dealing with Multi Compartment Analysis (MCA) scenarios which were introduced in a previous study [7].

This paper further discusses the approaches to generic design FPSA (Section 2) followed by the approaches to reduce conservatisms (Section 3), risk-informed improvements during the development of FPSA (Section 4), results and insights (Section 5), peer reviews (Section 6) and further risk-informed activities (Section 7).

2. APPROACHES TO GENERIC DESIGN FIRE PSA

The FPSA was structured into 15 tasks (except for documentation) in accordance with NUREG/CR-6850. For the purposes of practical implementation some of these tasks were combined [1], i.e., Task 3

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(FPSA cable selection) and Task 9 (Detailed circuit failure analysis), and Task 8 (Scoping Fire Modeling) and Task 11a (Detailed Fire Modeling for Single Compartments).

The subsections below introduce the specific considerations to the generic design phase and initial simplified approach. Some of the descriptions are overlapped with those in the previous study [7] but are included for the purpose of presenting whole picture of FPSA.

2.1. Task 1 - Plant Boundary Definition and Partitioning

Usually the plant partitioning for the purposes of FPSA is based on that applied in FHA. For the UK ABWR design the FHA subdivided the plant into rather large fire zones consisting of a large number of rooms and housing large number of equipment, in order to separate the redundant, primary safety systems from each other [8]. An example of divisional separation is illustrated in Figure 1. Even though this type of subdivision is suitable for the FHA, it was found not to be practical for the FPSA. Each fire zone defined by the FHA was therefore further compartmentalized to separate fire sources with relatively high frequencies and/or high heat release potential from potentially risk-significant targets (albeit within one fire zone). While the newly defined FPSA compartments (termed Physical Analysis Unites: PAUs) are separated by reinforced concrete walls, floors and ceilings which substantially confine the effects of heat and products of combustion, these barriers are non-rated and contain numerous unsealed penetrations. The effects of fires which could challenge these barriers were evaluated in the MCA introducing a level of complexity not normally seen in that phase of the FPSA.

All the PAU definitions for the at Power analysis were retained for the Shutdown POSs. Potentially degraded boundaries during outage were factored into the MCA.

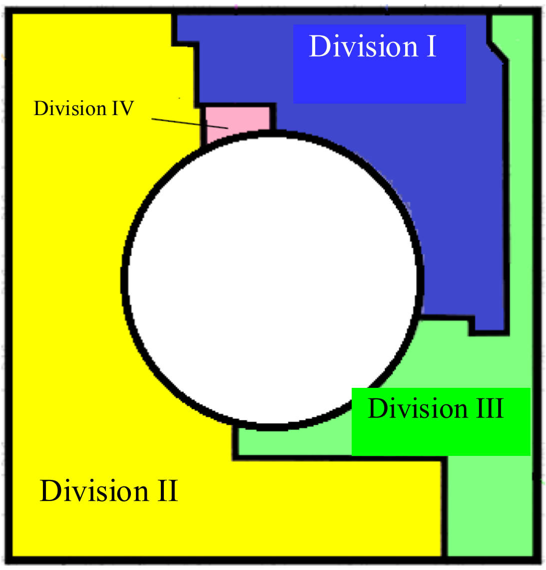

Figure 1: Example of Divisional Separation [9]

2.2. Task 2 - Fire PSA Components Selection

This task defined the equipment list and associated fire-induced failure modes. The equipment selected were those that, if fire damaged, could lead to an initiating event or were required to respond to an initiating event and bring the plant to a safe and stable state. As part of Step 4 in NUREG/CR-6850, Multiple Spurious Operations (MSOs) were systematically identified by an expert panel, exercising the generic MSO list provided in NEI 00-01 [10] and systematically investigating the plant specific design information. Additional MSO panel was convened to address plant shutdown states.

This task also defined the potential fire induced initiating events. For the at Power POS, one of the transient initiators in the internal events PSA was selected as the default initiator and it was conservatively assumed that the default initiator always occurs upon a fire in any PAU. The PSA logic model was constructed such that the risk from more onerous initiators, e.g., MSOs, fire-induced Interfacing System Loss Of Coolant Accident, were automatically captured by minimal cutsets (MCSs). For the Shutdown and SFP analysis, default initiator was not necessary. Occurrence of initiators was linked with fire-induced and/or random failures (including spurious operation).

2.3. Task 3/9 - Cable Selection/Circuit Failure Analysis

A particular challenge to the design stage FPSA was the lack of complete cable routing information. The FPSA for a typical operating power plant either relies on the existing cable routing database or includes developing a cable routing database as a part of the FPSA process, very often relying on walkdowns for filling in the gap where the documentation is incomplete or for confirmation of the data.

The UK ABWR cable routing data at the generic design stage was limited due to availability of detailed design. A simplified, conservative, and bounding approach was used in the FPSA. Cables associated with the components were identified by developing Cable Block Diagrams based on the circuit design of a surrogate ABWR plant. Assumed cable routes between the known cable endpoint locations were developed on a room to room basis following deterministic design requirements such as divisional separation. This was an extensive but worthwhile task involving approximately 1300 cables.

2.4. Task 4 - Qualitative Screening

This task is intended to qualitatively screen PAUs if whole room damage produces no initiating event and no impact to equipment required to mitigate an initiating event.

For the UK ABWR at Power analysis, no PAUs were qualitatively screened, as Task 1 was limited to the selection of buildings defined in the GDA scope comprising essentially the main buildings and their connecting service tunnels [11]. These structures were assumed to lead to the default initiator.

For Shutdown POSs, PAUs do exist in which whole room damage does not cause an initiating event and there is no impact to the credited equipment. However, these PAUs were still retained. The initiators caused by only random failure(s) were still captured by the FPSA logic model. Double-counting of the risk among the internal events PSA and FPSA was judged insignificant.

2.5. Task 5 - Fire Plant Response Model Development

This task developed the probabilistic risk model used to analyze each identified fire scenario. This task also defined the relationship between the fire impacts (e.g. on equipment, cables and operator actions) and the relevant elements of the probabilistic risk model. The internal events PSA was used as the basis for the plant response model and was modified to capture the fire impacts for each scenario, which relate to equipment loss of function or spurious operation, and instrumentation failures.

Importantly, the changes made to the base internal events model were identified in a different colour in the CAFTA software so that it was clear where the fire changes had been made to the underlying model [7]. Given that the plant response model was a combined internal fire and internal flooding model then it was clearly beneficial to reviewers and maintainers of the fire and flooding models [12].

2.6. Task 6 – Fire Ignition Source Frequency Analysis

The methodology for ignition frequency calculation in NUREG/CR-6850 groups the plant equipment in 37 ignition frequency bins, according to the ignition source type and plant location. NUREG-2169 [13] provides the latest generic ignition frequency of each bin. One of the main assumptions in the NUREG/CR-6850 methodology is that all legacy light water reactors are similar enough such that the bin frequencies can be considered constant across all plants. The individual component fire frequency can then be derived from the generic bin frequency divided by the plant specific equipment counts. This assumption can be considered acceptable for the plants as long as the count of the equipment falling into a particular bin does not vary too much from plant to plant.

After comparing the UK ABWR design and general equipment inventory with a typical US BWR, it was concluded that the generic ignition frequencies for the US BWRs were, in general, applicable to the UK ABWR design with some specific exceptions. Structures not found at a typical BWR site, such as the Backup Building (B/B), were identified and associated equipment was considered as additional to that found at a typical plant. In order to avoid underestimating the ignition frequency for individual sources the B/B sources were excluded from the bin component counts. Likewise the transient factors assigned to the B/B were excluded when evaluating the plant transient weighting factors. As the result, the total frequencies of some bins applied to the UK ABWR were raised from those provided in NUREG-2169 by considering additional equipment and PAUs contributing those bins.

The evaluation of transient weighting factors presented a particular challenge as operating history and plant procedures were unavailable. Consequently, the transient weighting factors were developed relying upon the judgement and experience of the PSA analysts. The weighting factors were reviewed against generic guidance provided in the NEI FAQ 12-0064 to ensure reasonable consistency.

2.7. Task 7 - Quantitative Screening

This task produced an initial quantification using the initial fire scenario definitions (Tasks 1-3 & 6) and plant response model (Task 5). At this stage, the fire scenarios were defined on the basis of whole PAU damage. This means that any ignition source within the PAU leads to a loss of all of the equipment and cables (including spurious operations) within the compartment.

The screening criteria were developed based on the current ASME/ANS combined PRA standard [14] and other considerations. Following the outcome of the evaluation against the quantitative screening criteria, a number of PAUs were identified for subsequent Detailed Fire Modelling (DFM) or scenario analysis in Task 11 as the existing whole compartment burnup scenario was too conservative.

2.8. Task 10 - Circuit Failure Mode Likelihood Analysis

This task provided the likelihood that a cable will experience one or more specific fire-induced failure modes resulting in spurious operation of equipment, based on NUREG/CR-7150, Volume 2 [15]. The spurious operation probabilities were based on a number of factors including component type, cable type and power source. Spurious actuation resulting from damage to fibre optic cables, three phase power cables and DC motor power cables was considered incredible and was excluded. The output from Task 2 was used to develop the spurious operation probabilities for affected components.

2.9. Task 11/8 – Detailed Fire Modeling

Fundamentally the output of Task 11 was a set of refined fire scenarios replacing or supplementing the existing fire scenarios quantified as part of Task 7. The refined fire scenarios were added to the FRANX for quantification in Task 14. Task 8 (Scoping Fire Modeling) was performed as part of Task 11 to simplifying the process at the generic design stage. This task consists of three main subtasks, namely Task 11a Single Compartment Analysis (SCA), Task 11b Main Control Room (MCR) analysis and Task 11c MCA. There is a fourth activity associated with structural steel analysis which is not formally part of Task 11 according to the NUREG/CR-6850. This is called Task 11d in this study.

Task 11a - Single Compartment Analysis

For each PAU retained from Task 7 quantitative screening, a DFM was developed that identified and characterized fire growth and target damage likelihood including the following aspects: a) PAU geometries and penetrations, b) fire detection and suppression, c) ignition source characteristics including applicable Heat Release Rate (HRR) profile, severity factors, and secondary combustibles, and d) the location of targets. This information was all collated to conduct fire propagation and growth analysis, and used to identify specific fire damage states and associated probabilities including the suppression terms. The new scenarios represented multiple damage states ranging from limited damage to target sets through to whole compartment damage.

The lack of cable routing information, which has been discussed already, continued to be hinderance in this task. While the cable routes by room were identified in Task 3/9, DFM requires a knowledge of specific cable locations. In order to overcome the lack of cable routing information the cables within a PAU were grouped into the critical target sets and the non-critical targets based on their risk significance. Assumed routings were developed for the critical cables based on the known room entry and exit points or end points within the room, as well as preliminary cable tray layout drawings. Non critical cables were assumed to be failed for all fire scenarios with in the PAU under evaluation.

Task 11b - Main Control Room Analysis

Task 11b shares similarities with Task 11a but with some scenarios requiring calculation of the probability of MCR abandonment due to adverse habitability conditions caused by a fire. The adverse habitability conditions was predicted using a fire modelling tool CFAST which provided times at which the assumed abandonment criteria were reached for various scenarios. The probability of forced abandonment of the MCR for each peak HRR value was calculated as the product of the corresponding severity factor and the probability of failure to suppress the fire before abandonment conditions were reached. This was combined with the failure of the operators to successfully mitigate the fire scenario impacts from a reserve control room or panel.

Fire growth and damage propagation between Main Control Board cabinet sections, and from cabinets to under floor cable raceways, was modeled utilizing NUREG/6850 Appendix S guidelines and Monte Carlo simulations representing the likelihood of fire growth within the cabinet section according to the process described in NUREG/CR 6850 Appendix L.

Task 11c - Multi Compartment Analysis

This task consisted of a number of steps which first identified the potential exposing and exposed compartment combinations. This was performed using a matrix providing a listing of connected or adjacent PAUs. Successive screening criteria were applied that were both qualitative (screening) and quantitative (prioritisation for further refinement). A staged MCA approach was adopted which helped keeping a reasonable amount of effort. In order to provide the appropriate treatment of the multi compartment fires affecting the rated and non-rated fire barriers and impacting different type of equipment, the staged approach required the MCA scenarios to be categorized as four types:

- Type 1: Impacting temperature sensitive equipment in exposed PAUs by Hot Gas Layer (HGL).
- Type 2: Not producing a damaging HGL in the exposing PAU but potentially impacting PSA equipment/cables on the opposite side of a non-rated barrier by plume or radiant heat.
- Type 3: Producing a damaging HGL in the exposing compartment, and conservatively assuming all equipment and cables in the associated fire zone, surrounded by fire barriers, are damaged.
- Type 4: Associated Type 3 scenario with further impact on adjacent fire zone with evaluated Barrier Failure Probability.

Because of the plant configuration and plant partition method adopted for the UK ABWR, the challenges in performing the MCA were significantly greater than for typical LWRs. More information on the staged MCA approach is available in the previous study [7].

Task 11d - Fire Impact on Structural Steel

This task was a review of fire scenarios which had the potential to generate damaging effects that could damage exposed structural steel. This task used the existing fire scenario definitions coupled with locations where exposed structural steel was present to identify whether those fire scenarios could challenge the structural steel and thus lead to conditions not bounded by the existing fire scenarios.

2.10. Task 12 – Human Reliability Analysis

The Human Reliability Analysis (HRA) focused on three tasks:

- Modification of the existing internal events Human Error Probabilities (HEPs) to reflect the potentially adverse impacts of a fire, including the specific level of instrumentation degradation.
- Development of fire specific operator actions and their respective HEPs.

- Dependency analysis to recognize potential dependencies between multiple operator actions in a single sequence, based on the approach as described in NUREG-1921 [16]

More information on the staged MCA approach is available in the previous study [7].

2.11. Task 13 – Seismic Fire Interactions

This was a qualitative review to identify specific scenarios where seismically induced failure of equipment could lead to a fire or affect fire detection/suppression and manual firefighting equipment. The output of this task was a set of recommendations related to ensuring the capability of the UK ABWR design in the later construction phase. The latest consensus information regarding the potential for seismically induced fires [17] was reviewed and adapted to form the basis for this analysis.

2.12. Task 14 – Internal Fire Risk Quantification

The development of the fire risk quantification was an iterative process involving Tasks 7 through 12. As analysis refinements were developed, they were incorporated into the fire risk model. Each fire scenario was defined by the following characteristics:

- Scenario frequency.
- Damaged compartment set for the resulting fire.
- Conditional Core Damage Probability (CCDP), Conditional Large Release Probability (CLRP) and Conditional Fuel Damage Probability (CFDP). Note CFDP was for Shutdown POSs and SFP.
- Core Damage Frequency (CDF), Large Release Frequency (LRF) and Fuel Damage Frequency (FDF). Note FDF was for Shutdown POSs and SFP.

Advanced Cutset Upper Bound Estimator (ACUBE) [18] was applied to the at Power analysis as there were a number of high probability basic events (e.g., fire-induced spurious operations) in the MCSs.

2.13. Task 15 – Internal Fire Risk Uncertainty Analysis

The development of a risk assessment inherently resulted in uncertainty. Task 15 involved the identification and treatment of uncertainty and sensitivity analyses in the overall FPSA. The guidance provided in NUREG/CR-6850, Appendix V was followed. The sources of uncertainty for each task in the FPSA were identified and characterized (including whether they were modelling or data uncertainties), and appropriate treatment determined and applied consistent with current industry prevailing good practices. The final results from Task 14 were re-run, using alternate data and models, as appropriate to understand the sensitivity to selected assumptions, modelling and inputs.

Parametric uncertainties associated with ignition frequencies, hot short probabilities, human errors and random/common cause equipment failures were propagated through the model accounting for state of knowledge correlation where appropriate. Distributions of fire induced CDF and LRF were developed.

3. APPROACHES TO REDUCE CONSERVATISMS

Previous sections went through the FPSA tasks in terms of applying NUREG/CR-6850 methodology to the UK ABWR generic design. A number of conservatisms were initially built in the FPSA model. This section introduces typical modeling approaches taken to reduce the conservatisms. Note that the refinements were mainly applied to the at Power FPSA since the scoping analyses for Shutdown POSs and SFP aimed at understanding the risk level and not propagating to the Level 3 PSA in the GDA.

3.1. Task 5 – Refinement of Plant Response Model

The plant response model was based on the internal events PSA model which involved known conservatisms. Some of them were insignificant in the internal events PSA but became significant when applied to the FPSA. Examples of the FPSA plant response model refinements include:

- Update of success criteria and event trees from the internal events model.
- Credit for additional function which was not credited in the internal events model.
- Credit for additional interlocks which were not credited in the internal events model.
- Credit for more instrumentations supporting operator actions.

3.2. Task 5 / Task 10 – Spurious Operation Duration Analysis

NUREG/CR-7150 Volume 2 assessed the likelihood of a spurious event clearing. In general, Motor Operated Valves (MOVs) fail as-is while many of the Solenoid Operated Valves (SOVs) return to a fail-safe position once spurious operation clears. For example, the BWR generic MSO list in NEI 00-01 includes spurious energizations of fail-safe type SOVs for Main Steam Isolation Valves (MSIVs), Safety Relief Valves (SRVs) and testable check valves (for core injection lines).

Preliminary quantification in Task 14 found that some accident sequences involving fire-induced spurious operation(s) of fail-safe type SOVs were risk significant. For the model refinement, spurious operation duration analysis was conducted based on the guidance in NUREG/CR-7150 Volume 2. In order to achieve this it was necessary to determine the timing at which clearing of the spurious operation altered the accident sequences and/or success criteria. Existing success criteria analyses were reviewed and additional thermal-hydraulic analyses were performed to determined and justify the timing for each set of spurious operation(s). Then new basic events were established in Task 10 to represent the conditional failure probability to clear spurious operation by predetermined timing. Different event trees were applied with/without clearing the spurious operation(s), e.g., SRV opening.

3.3. Task 11a – Refinement of Single Compartment Scenarios

Preliminary quantification in Task 14 identified the PAUs which involves SCA scenarios significantly contributing to the CDF and/or LRF. Typical approaches for refinements are discussed below.

Specific ignition sources were screened for a POS if these are always de-energized during that POS by interlocks and/or strict administrative control.

The radiant Zone Of Influence (ZOI) was generally applied at the edge of the closest ignition source or secondary combustible when determining target damage which provides conservative target failures. For risk significant scenarios, however, the fire modeling was reviewed to determine the dominant contributor to the total HRR. If the total HRR was mainly contributed by the ignition source or secondary combustible not closest to the target, the center of ZOI was shifted to the location still justifiable (e.g., center of the closest ignition source to the target rather than the edge).

As previously discussed, the cables within a PAU were grouped into the critical target sets and the non-critical targets. The cables driving the risk could change as other tasks evolved. Minimal cutsets were iteratively reviewed to understand the critical component failures and subsequently refine the cables assigned to the critical target sets.

In addition, the design drawings which became newly available as the design progressed were utilized to refine specific information on ignition source, secondary combustible and target locations.

3.4. Task 11c – Refinement of Multi Compartment Scenarios

As introduced in Section 2.9, four types of MCA scenarios were initially developed as a staged MCA approach for keeping a reasonable amount of effort and identifying risk significant scenarios requiring refinements. A number of refinement approaches were applied. Typical ones are discussed below.

For the risk significant Type 2 MCA scenarios, where all the targets in the exposing and adjacent exposed compartments (via non-rated barriers) were initially assumed failed by local effect such as fire plume and flame radiation, the locations of ignition sources, secondary combustibles and targets were determined as much as possible based on the generic design information. This information enabled the screening or refinement of a number of risk significant scenarios.

In some cases Type 2 MCA scenarios resulted from the assumed fire propagation along continuous cable trays through non-rated electrical penetrations to the exposed PAU. Cables of the UK ABWR meet appropriate standards for flame spread [8]. Based on the flame propagation rate as shown in Section R.4.1.2 in NUREG/CR-6850, the realistic duration of fire required to damage the exposed PAU was determined and used as a basis for screening the scenario or crediting manual suppression.

For the risk significant Type 3 and Type 4 MCA scenarios, where overall area(s) surrounded by rated barriers were initially assumed failed by HGL, individual exposed PAUs were screened if the peak HRR was found to be less than the HRR required to damage these PAUs. CFAST modelling was used for some scenarios to consider oxygen depletion, in addition to the Fire Dynamics Tools (FDTs) [19].

In addition, the design drawings which became newly available as the design progressed were utilized to specify the fire ratings of specific barriers.

3.5. Task 12 – Refinement of Human Reliability Analysis

The HRA for UK ABWR PSA was performed based on Tabular Task Analysis (TTA) and Human Error Analysis (HEA) [20]. In the FPSA Task 12, a screening approach was applied to the development of the HEPs depending on the availability of instrumentation [7]. The screening criteria and multiplier provided in NUREG-1921 were applied with minor modifications. Preliminary quantification in Task 14 identified risk-significant HEPs. For these HEPs, the factor of 10 multiplier recommended in NUREG-1921 was refined with justification based on the TTA/HEA.

4. RISK INFORMED IMPROVEMENTS DURING FPSA DEVELOPMENT

Generic design of UK ABWR was developed in parallel to the PSA development. This resulted in various opportunities for risk-informed improvements based on the preliminary PSA results [3 and 4]. Specific improvements based on the preliminary FPSA results are discussed below.

High-level cable routing was determined at the beginning of the FPSA Task 3 based on deterministic design requirement such as divisional separation [21]. The preliminary quantification identified critical cables which greatly impacted the fire risk, although the cable routing satisfied the deterministic design requirements. Feasibility of re-routing these cables was discussed and some were assumed re-routed and captured in the design assumptions. This resulted in a significant reduction of the risk from internal fire. The design process is ongoing to capture these assumptions in the detailed design.

The preliminary quantification found that fire scenarios impacting multiple PAUs within a fire zone (determined by FHA) contributed significantly to the overall fire risk. The design of intra-fire zone boundaries was not specified at the beginning of the FPSA development and thus they were assumed all non-fire rated. This insight was one of the drivers to apply fire rating to many intra-fire zone boundaries. This significantly reduced the fire risk from intra-divisional multi compartment scenarios.

5. RESULTS AND INSIGHTS

5.1. Reactor At Power

The results of the at Power FPSA are summarised in Table 1. The CDF was reduced to the same order as of the internal events by the model refinements as much as practically feasible given the generic design progress and project schedule, as well as the risk informed improvements of cable routing and barrier design. The major insights obtained from the at Power FPSA are summarised as below.

- Fires originating in Reactor Building (R/B) electrical rooms contributed the most of any plant area in terms of CDF and LRF. This was in large part due to existence of a large number of ignition sources (cabinets) and critical cables.
- Fire risk originating in R/B was high (nearly 70 percent of total LRF). This was in large part due to the high contributions from the R/B electrical rooms as well as the Type 4 MCA scenarios impacting two divisions of Reactor Vessel Instrument (RVI).
- Fire risk originating in B/B, Control Building (C/B) and Turbine Building (T/B) was relatively low, which implied the effectiveness of fire rated boundaries additionally introduced (beyond the deterministic requirements) for defense-in-depth and per risk-informed recommendations.
- The contribution of MCR fire scenarios was low mainly for two reasons:
  - Digital C&I controller for emergency injection is separated from the MCR fire zone [8].
  - Two remote shutdown system rooms and a B/B control panel room are available [9] even when operators abandon the MCR.
- AE (Large LOCA with loss of injection) was the highest contributor to CDF among the Accident Classes as shown in Figure 2. This was due to the high contribution from the MSO scenarios involving spurious operations of more than 7 SRVs.
- LRF to CDF ratio was high (over 50 %). This was manly due to the contribution from the Accident Classes involving containment failure / bypass, as shown in Figure 2, and additional fire-induced failures in the Level 2 PSA.

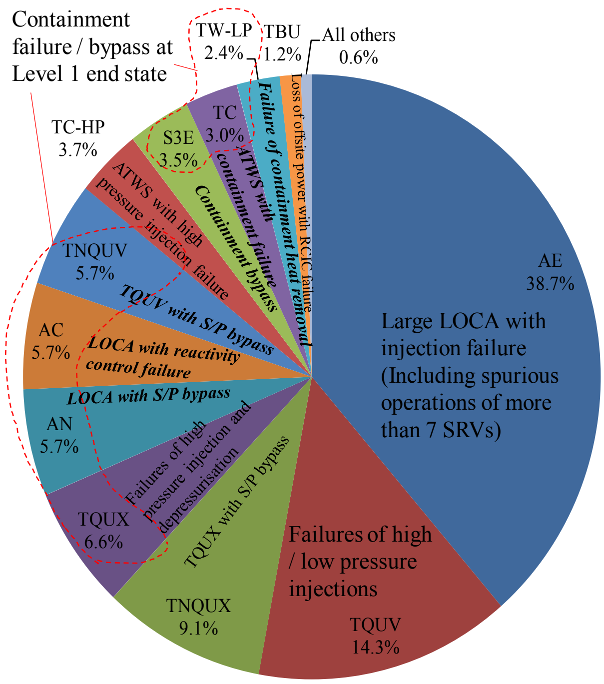

Figure 2: Contribution of Accident Class to CDF

Table 1: Summary of Internal Fire At Power PSA Results

	CDF (/y)	Contribution to Fire at Power CDF	LRF (/y)	Contribution to Fire at Power LRF
Task 11a Detailed Fire Models	2.09E-07	42.2 %	1.78E-07	67.2 %
Task 11b Main Control Room	7.82E-09	1.6 %	1.95E-09	0.7 %
Task 7 Whole Room Damage	8.24E-08	16.6 %	3.42E-08	12.9 %
ALL Single Compartment	2.99E-07	60.4 %	2.14E-07	80.8 %
Task 11c Multi Compartment Type 1*	5.38E-09	1.1 %	3.97E-09	1.5 %
Task 11c Multi Compartment Type 2*	2.12E-08	4.3 %	6.13E-09	2.3 %
Task 11c Multi Compartment Type 3*	7.15E-08	14.4 %	1.18E-08	4.4 %
Task 11c Multi Compartment Type 4*	9.82E-08	19.8 %	2.90E-08	10.9 %
ALL Multi Compartment	1.96E-07	39.6 %	5.08E-08	19.2 %
At Power Fire Total	4.95E-07	-	2.65E-07	-
Internal Events (for comparison)	*2.27E-07*	-	*5.20E-08*	-

* MCA scenario "Types" are explained in Section 2.9

5.2. Scoping Analyses of Shutdown POSs

NUREG/CR-7114 was additionally used for the scoping analyses of Shutdown POSs. The internal events Shutdown PSA model was expanded to the FPSA model. Quantification was limited to POS C and POS B-2. POS C "Transition to closed condition of PCV/RPV heads with Divisions 1 and 3 in maintenance" was selected due to the highest risk contribution in the internal events Shutdown PSA (see Section 25.8 of the PCSR [1]). POS B-2 "Full water level in reactor well and gate open with Divisions 1 and 3 in maintenance" was additionally included due to the unique condition, i.e., SFP risk was covered due to open pool gate, and less mitigation systems available compared to POS B-1. More information of the POS definitions is available in Section 25.8 of the PCSR [1].

The results are summarised in Table 2. The internal fire FDF for each POS was close to the internal events FDF of the same POS. The internal fire FDFs during POS C and B-2 were sufficiently lower than the internal fire at Power LRF. Since POS C and B-2 were deemed dominant contributor to the FDF, the fire risk during Shutdown is expected to be insignificant compared to the at Power fire risk. Note that many of the model refinements and risk-informed improvements considered for the at Power analysis (see Sections 3 and 4) had not yet been implemented into the scoping analysis, such that the level of conservativeness was greater than the at Power FPSA. The specific insights are listed below.

- Fires in PCV (unique to shutdown states due to de-inerted condition) had small contribution to the fire risk because of limited cables potentially causing a fire-induced initiating event.
- The large contribution of B/B fires comes from the potential plant impact due to spurious injection to reactor or SFP by the Flooder System of Specific Safety Facility (FLSS) which was assumed to cause overfill and internal flooding.
- The large contribution of T/B fires came from the potential plant impact due to loss of offsite power, as well as the high transient fire frequencies during shutdown per NUREG-2169.

Table 2: Summary of Internal Fire Scoping Analysis Results for Shutdown POSs

	FDF (/y) of POS C	Contribution to FDF of POS C	FDF (/y) of POS B-2	Contribution to FDF of POS B-2
ALL Single Compartment	1.68E-08	38.2 %	6.58E-09	33.8 %
ALL Multi Compartment	2.72E-08	61.8 %	1.29E-08	66.2 %
Fire Total for each POS	4.40E-08	-	1.95E-08	-
Internal Events (for comparison)	*5.38E-08*	-	*1.46E-08*	-

5.3. Scoping Analysis of SFP

The internal events SFP PSA model was expanded to the FPSA model. Quantification was limited to at Power POS due to the highest risk contribution in the internal events SFP PSA (see Section 25.9 of the PCSR [1]). Note that the fire risk of SFP during Shutdown POSs was representatively captured by the scoping analysis of reactor during POS B-2 where the SFP risk was covered by the Shutdown PSA.

The results are summarised in Table 3. The internal fire FDF of SFP at Power was found to be close to the internal events FDF of SFP at Power and the internal fire LRF of reactor at Power. Note that many of the model refinements and risk-informed improvements considered for the at Power analysis (see Sections 3 and 4) had not yet been implemented into the scoping analysis, such that the level of conservativeness was greater than the at Power FPSA. The specific insights are listed below.

Additionally, a number of conservatisms were in place in the scoping analysis of SFP. Sensitivity analyses characterized the major conservatisms as summarised in Table 25.10.2-11 of the PCSR [1].

- *Consider realistic time available for terminating fire-induced flooding – 15% reduction in FDF*
- *Consider realistic consequence from PCV failure without core damage (Level 1 PSA success sequences) – 20% reduction in FDF*

- *Remove FDF which is double-counting the LRF of reactor – 30% reduction in FDF*

By considering the above sensitivity analyses and further factoring the long time available to fuel damage in the risk-significant sequences (more than 300 hours), it was concluded that the fire risk of SFP was insignificant compared to the at Power fire risk of reactor.

Table 3: Summary of Internal Fire Scoping Analysis Results for SFP at Power POS

	FDF (/y) at Power	Contribution to Fire FDF of SFP at Power
ALL Single Compartment	1.95E-07	32.7 %
ALL Multi Compartment	4.03E-07	67.3 %
Fire Total for SFP at Power POS	5.98E-07	-
Internal Events (for comparison)	*3.17E-08*	-

6. PEER REVIEWS

Multiple peer reviews for FPSA were performed (e.g., in-process, final and follow-on reviews) by an independent peer review team organized by the US industry experts [2]. The peer reviews utilized the NEI 07-12 process [22], the ASME/ANS PRA Standard for Fire Events (Part 4 of ASME/ANS RASb-2013 [14]) and the UK Technical Assessment Guide (TAG) [23 and 24].

The peer review process included documentation of any peer review comments, as well as resulting responses. A draft product for a specific peer review had an initial set of comments generated from the initial review, and these comments were then addressed prior to the final review session. During the follow-on review, additional comments were generated based on the updated information. The disposition of the previous comments was noted and new comments were also generated as necessary.

7. ADDITIONAL RISK-INFORMED ACTIVITIES

Following the development of the UK ABWR PSA, it was used to identify further risk-reduction options to be considered in the later project phases [3 and 4]. The systematic review of the FPSA results identified some risk-reduction options, including use of closed cable ducts for risk-significant cables to avoid ignition (as secondary combustibles) and/or delay damage due to radiant heat, and de-powering specific valves (not used during normal operation) to avoid risk-significant MSO scenarios.

The FPSA was also used to support specific decision making, including allocation of electrical panels to specific fire zones, and justification of changing the number of specific transformers [3 and 4].

8. CONCLUSION

The FPSA of UK ABWR generic design encountered challenges unique to applying the existing guidance which were intended for application to operating plants. These challenges were overcome by the initial simplified approaches followed by model refinements to the extent possible given the status of the design, as well as accounting for risk-informed improvements identified during the generic design development. As the result, it was possible to demonstrate that the internal fire risk of UK ABWR was reduced as low as reasonably practicable at the generic design phase. It is intended to demonstrate further risk reduction in the later project phase based on more detailed design / operational information and continued risk-informed improvements.

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