Gentilly-2 CANDU Nuclear Power Plant level 1 Fire and Flood PSA – Insights on a Work in Progress

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Abstract
The objective of this report is to present a summary of work performed to date on the Level 1 Internal Fire and Flood PSA for the Hydro-Québec Gentilly-2 CANDU Nuclear Power Plant. The overview will present findings, observations, challenges, and solutions that have been developed to supplement the NUREG/CR-6850 and EPRI-1019194 methodologies.

1. INTRODUCTION

The Hydro-Québec Gentilly-2 (G-2) CANDU Nuclear Power Plant (NPP) is a 675 MW(electric) pressurized heavy-water (D2O) power reactor located in Bécancourt, Québec, Canada. As part of a proposed life extension program and to achieve compliance with evolving regulatory requirements and commitments, a Level 2 Internal Event (Full Power) PSA is currently being developed. The development of the Level 1 Internal Event Fire and Flood PSAs is currently being performed by GENIVAR LP to complement the overall suite of Probabilistic Assessments currently underway.

The G-2 Internal Fire PSA methodology is, in general, based on NUREG/CR-6850 [1] as illustrated by the process shown in Figure 1. The G-2 Internal Flood PSA is based primarily on EPRI-1019194 [2]. The process for the G-2 Flood PSA is shown in Figure 5.

3. LEVEL 1 PSA AND DETERMINISTIC FIRE PROTECTION INITIATIVES

At the onset of the Fire and Flood PSAs, the Level 1 At-Power Internal Events PSA was still under development. This somewhat parallel development poses configuration control and coordination challenges. In addition, the Fire Hazard Assessment and Fire Safe Shutdown Assessment are also being developed in parallel with the Fire PSA. While there are challenges involved with this, there are also opportunities to collaborate and/or ensure that duplicate efforts are not performed where information can be shared, cross-checked, or verified amongst the various initiatives.

The G-2 Internal Events PSA includes approximately 15000 Basic Events that are associated to approximately 9000 components or devices. There are 52 Initiating Event (IE) trees that have been developed for the Internal Events PSA. The IE frequencies are all single value estimates derived mainly from industry operating experience combined with specific G-2 historical plant data using a Bayesian approach [3].

Table 1: List of Internal Initiating Event Trees

Label	Description	Label	Description
LL1	Large LOCA - Large Diameter Pipe Break with Discharge Inside Containment	**FWB2A**	Large Feedwater Line Break Inside Turbine Building
LL2	Large LOCA with Containment Bypass due to Blowback from HTS to MPECC (Containment Bypass)	**FWB3**	Asymmetric FW Line Break Inside R/B Downstream of SG Check Valve
SL	Small LOCA - 2.5% RIH Break	**FWB2**	Asymmetric FW Line Break Inside R/B

Label	**Description**	**Label**	**Description**
			Upstream of SG Check Valve
PBPRZ	Pipe Break Upstream of Pressurizer Relief / Steam Bleed Valves	**FWB4**	Symmetric FW Line Break Outside R/B Upstream of FW Regulating Station
BMTR	Small LOCA - Multiple Steam Generator Tube Rupture - Containment Bypass	**FWB6**	Symmetric SG Blowdown Line Break Inside R/B
HXMTR	Small LOCA - Multiple Tube Rupture in any RSW HX - Containment Bypass	**MSL1**	Main Steam Line Leak Inside R/B
GSC	Loss of Gland Seal Cooling to all HTS Pumps	**MSL2**	Small Steam Line Break Inside T/B
FSB	Feeder Stagnation Break	**MSL2A**	Large Main Steam Line Break inside T/B
FMFE	F/M Induced LOCA with Fuel Ejection	**MSL4**	Main Steam Line Between R/B & S/B Leak Directed at MCR Roof
FMNFE	F/M Induced LOCA without Fuel Ejection	**MSL3**	Small Steam line Break Causing Low Deareator (DA) Level
FMEFF	F/M Induced End Fitting Failure	**LOCD**	Loss of Condensate Flow to Deaerator
PCTR	Pressure Tube and Calandria Tube Rupture	**LOCV**	Loss of Condenser Vacuum
LKC1	HTS Leak within operating D2O feed pump capacity	**MCTL**	Total Loss of Moderator Heat Sink
LKAG	Pressure Tube / End Fitting Leak into Annulus Gas System	**MCPL**	Partial Loss of Moderator Heat Sink
SGTR	Single Steam Generator Tube Rupture - Containment Bypass	**CIOB**	Calandria Inlet/Outlet Pipe Break Outside Calandria Vault
LKHX	HTS Coolant HX Single Tube Rupture with Discharge into RSW System- Containment Bypass	**MLBI**	Moderator Pipe Break Inside Calandria Vault
LORS	Loss of Reactivity Control Slow Events	**MHXS**	Moderator Heat Exchanger Single Tube Rupture
LORF	Loss of Reactivity Control - Fast Events	**MHXM**	Moderator Heat Exchanger Multiple Tube Rupture
HPCH	HTS Pressure Control Fails High	**ESCF**	Loss of End Shield Cooling Flow
HPCL	Loss of HTS Inventory Control Low	**ESCH**	Loss of ESC Heat Sink
LRVO	HTS Liquid Relief Valve (LRV) Fail Open	**ESCB**	ESC System Pipe Break
PRVO	Pressurizer Relief / Steam Bleed Valves Fail Open	**IA**	Total Loss of Instrument Air Supply
HPFT	Total Loss of HTS Pumped Flow	**DCC**	Dual Computer Control Failure
FWPV	Total Loss of Main FW Flow to Steam Generators	**CL4**	Total Loss of Class IV Power Supply
FW1V	Loss of FW Flow to One SG	**SW**	Total Loss of Service Water Reactor Operating at Full Power
FWB1	Asymmetric FW Line Break Outside R/B Downstream of FW Regulating Station	**GENT**	General Transient

4. FIRE PSA PROGRESS REPORT

The G-2 Fire PSA work is divided in 14 tasks similar to NUREG/CR-6850 [1] (see Figure 1).

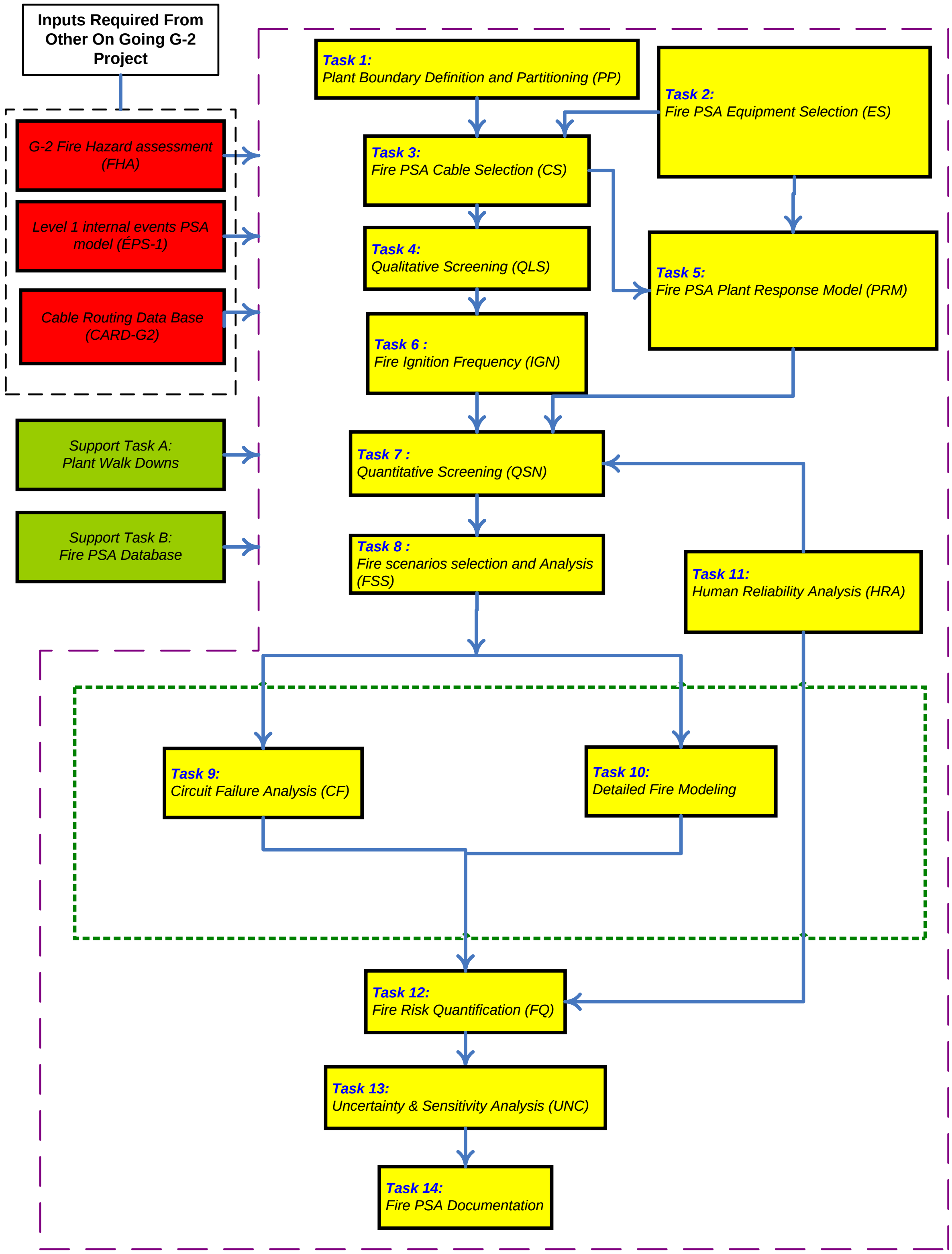

Figure 1 Internal Fire PSA Process

3.1. Task 1 – Plant Boundary Definition and Partitioning

The global plant partitioning task identifies the G-2 buildings of potential interest to the Fire PSA. Unimportant areas with respect to fire induced core damage within this boundary are identified and eliminated from further analysis. Plant buildings are retained for further analysis if they meet one of these two conditions:

1. Building that contains Level 1 PSA equipment with internal fire potential;
2. Adjacent building to those identified in step 1 and that poses fire propagation potential.

The deterministic Fire Hazard Assessment provided the basis for the delimitation of the Fire PSA compartments in G-2. In general, the compartment delimitations follow the physical room boundaries except for open areas such as those found in the Reactor and Turbine Buildings. Subsequent work could result in the revision of compartment boundaries to refine the analysis.

3.2. Task 2 – Fire PSA Components Selection

Given that the G-2 Level 1 IE PSA development overlaps that of the Fire and Flood PSAs, preliminary versions of the Level 1 PSA have been used to establish a working list of Fire PRA components. This poses a configuration management challenge as each revision of the PSA represents additional data mapping and impacts parallel work in other Fire PSA tasks.

A significant portion of time and effort was dedicated to resolving differences between the different databases implicated in the Fire PSA. The Level 1 PSA Basic Event names were based on equipment identification codes as found in the Hydro-Quebec SIE equipment database. Between the Basic Event names and the SIE equipment ID, subtle differences were found, such as missing "-" or added spaces. Thus, just the identification of the actual component or part of a component (contacts of a relay) required automated filtering, followed by extensive manual verification and revision. Given new revisions of the Level I IE PSA, this effort was repeated several times based on changes to the Basic Events and thus changes to the PSA equipment list. The G-2 Internal Events PSA includes approximately 15000 Basic Events that are associated to approximately 9000 components or devices.

The G-2 Internal Events PSA, in general, models spurious operation failure modes which reduces the need to review the model to include such modes as suggested by NUREG/CR-6850 [1].

3.3. Task 3 - Fire PSA Cable Selection

A G-2 cable and raceway routing database, CARD-G2, is currently being developed to support cable selection for the Fire PSA. This database builds on existing station configuration data by adding the raceway (cabletray) location per room and consequently per fire compartment. This results in a list of all cables located in each compartment. To select the critical cables (i.e., cables that could potentially impact one or more PSA components) a module has been developed to facilitate the extraction of electrical circuit data to support the identification and analysis of electrical devices affected by fire damage to cables. As expected, electrical circuit data represents the external physical connections from device to device. In order to extract a more representative set of electrical circuit data, potential electrical continuities, such as relay contacts, handswitch contacts, and other unrepresented electrical continuities such as resistors, diodes, and relay coils were identified and connected virtually. As illustrated in Figure 2 given that RL-1D is a PSA device the database will associate programmatically wires 4301, 4302, 4330, 4331, 4332 and 4333 to this coil. All of the wires/cables between the load (RL-1D) and the source (FU-105 and FU-106) are associated to a unique wire grouping. Depending on the circuit configuration, fire induced failure of cables associated to the wire grouping may lead to the failure of the device.

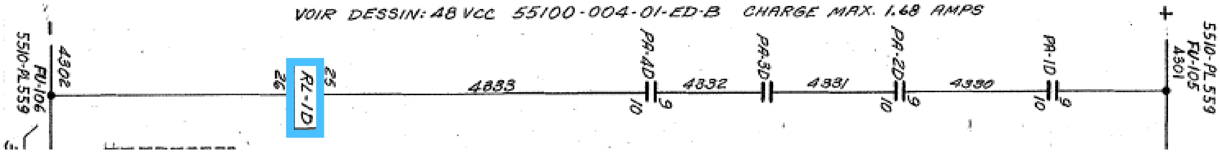

Figure 2 Wire/Cable selection

The G-2 design features ~300,000 electrical power and control circuit connections, as represented in the station configuration data. Approximately ~100,000 virtual connections were added to support the extraction of potential devices affected by fire.

3.4. Task 4 – Qualitative Screening

Since the cable selection task is still ongoing this task has not yet started.

3.5. Task 5 – Fire Induced Risk Model

At the time of submission of this paper, the G-2 Level 1 PSA Accident Sequence Quantification (ASQ) is still being performed and could lead to changes in the Level 1 PSA Model. Therefore, the adaptation of the model will only be initiated once the Internal Event PSA Model is issued. The FRANX [4] software utility will be used for developing and analyzing the Fire Risk Model.

3.6. Task 6 – Fire Ignition Frequencies

The mapping of plant equipment to the NUREG/CR-6850 [1] Fire Ignition Source (IS) frequency bins and the compartment Ignition Frequency calculation was completed with the following observations.

3.6.1. Fixed Fire Ignition Source Counts

Table 2 gives IS count per bin and Ignition Fire Frequency per IS applicable to G-2 for countable items.

It is to note that plant wide location is somehow used differently for each bin and contradicts the definition given in Table 6-2 of NUREG/CR-6850 [1] which defines this location as: "*All plant locations inside the fence other than the containment, fuel handling building, office buildings, maintenance yard, maintenance shop, etc*". However, when considering some of the bins such as bin 14 for the electrical motors, the motor count in the entire plant selected boundary includes consideration of the containment building.

Table 2 Equipment Count per Bin and Fire Frequency per IS

Bin	Location	IS	Generic Frequency	IS Count	G-2 Fire Frequency
01	Battery Room	Batteries	3.26E-04	15	2.17E-05
02	Containment (PWR)	Reactor Coolant Pump	2.35E-03	4	5.87E-04
04	Control Room	Main Control Board	8.24E-04	1	8.24E-04
08	Diesel Generator Room	Diesel Generators	5.04E-03	6	8.40E-04
09	Plant-Wide Components	Air Compressors	4.65E-03	3	1.55E-03
10	Plant-Wide Components	Battery Chargers	1.18E-03	24	4.92E-05
13	Plant-Wide Components	Dryers	4.20E-04	5	8.40E-05
14	Plant-Wide Components	Electric Motors	3.41E-03	49	6.96E-05
15.1	Plant-Wide Components	Electrical Cabinets Non-HEAF	2.36E-02	1664	1.42E-05
15.2	Plant-Wide Components	Electrical Cabinets-HEAF	1.06E-03	247	4.29E-06
16.1	Plant-Wide Components	Bus Ducts	1.27E-03		1.27E-03
16.2	Plant-Wide Components	Iso-phase Ducts	8.24E-04	8	1.03E-04
17	Plant-Wide Components	Hydrogen Tanks	1.18E-03	3	3.93E-04

Bin	Location	IS	Generic Frequency	IS Count	G-2 Fire Frequency
18	Plant-Wide Components	Junction Boxes	1.11E-03	1630	6.81E-07
21	Plant-Wide Components	Pumps	1.42E-02	151	9.40E-05
23	Plant-Wide Components	Transformers	8.02E-03	29	2.77E-04
26	Plant-Wide Components	Ventilation Subsystems	6.12E-03	130	4.71E-05
27	Transformer Yard	Transformer - Catastrophic	1.62E-03	3	5.40E-04
28	Transformer Yard	Transformer - Non Catastrophic	8.38E-03	3	2.79E-03
30	Turbine Building	Boiler	9.78E-04	3	3.26E-04
32	Turbine Building	Main Feedwater Pumps	5.44E-03	3	1.81E-03
33	Turbine Building	Turbine Generator Excitor	2.10E-03	1	2.10E-03

The following rules are proposed for counting electrical cabinets in G-2 using documents or during the walkdowns:

1. Simple wall-mounted panels housing less than four switches may be excluded from the counting process;
2. Well-sealed electrical cabinets that have robustly secured doors (and/or access panels) and that house only circuits below 440V should be excluded from the counting process.

Counting rule 1 was applied to the panel (PL) IS illustrated in Figure 3 which is excluded from the count. IS identified as “sectionneurs” and “interrupteurs” (DS, SW) are not counted in this bin even though some of these switches are 600 V.

In the context of G-2 the terms “well-sealed” and “robustly secured” are interpreted as environmentally qualified (EQ) panels.

Figure 3 Equipments not counted as IS electrical cabinets

While applying the screening criteria to the panel a question was raised concerning the application of the same criteria to the junction boxes count (JB). The NUREG/CR-6850 [1] does not provide any criteria for the JB bin. However, it was considered that the same rules should be applied to the JBs since JBs can be treated in essence as PLs without functional components inside. Since JBs are generally wall-mounted with no switches as illustrated in Figure 4, almost all JBs were screened in this step.

Figure 4 JB excluded from the counting process

3.6.2. Transient Fire Influencing Factors

As per NUREG/CR-6850 [1] the five rating levels, No (0), Low (1), Medium (3), High (10) and Very High (50) were used to quantify each of the three influencing factors, maintenance, occupancy and storage, for each fire compartment :

- The maintenance factor is evaluated for each compartment based on a relative ranking using the number of work orders issued during power operation for a five year time period;
- For occupancy and storage factors a working meeting with fire protection personnel was used to evaluate these two factors.

It is to note that Bin 3 – Transients and Hotwork (Containment; PWR): combines transient and hot work although the influence factor calculation is different for each fire type. The transient includes all three influencing factors whereas for hotwork only the maintenance influencing factor should be considered. It is recommended to separate this bin or alternatively to credits that there is no welding or cutting in the containment while the reactor is at power.

3.7. Task 7 – Quantitative Screening

This task is currently not started subject to the completion of the Internal Event PSA Model.

3.8. Task 8 – Scoping Fire Modeling

The implementation of the method for scoping fire modeling has included the development of local affect zones of influence (ZOI) for ignition source types and the application of the ZOI method during mock-up walkdowns. The preliminary set of ZOI was developed through the conservative application of the NUREG-1805 Hand-Calculation toolset [5].

Uncertainties were found in the calculation of the Hot Gas Layer ZOI for Task 8. At present, the proposed concept is to develop a conservative lookup table to establish an appropriate Hot Gas Layer temperature based on the room size and general characteristics. The estimated duration of the fire affects the HGL results, and thus an appropriate set of characteristics for the purposes of Task 8 – HGL is still under development.

The calculation of the local effect ZOI such as flame height, plume temperature, and radiant heat flux also present areas of uncertainty with respect to the selection of conservative modeling inputs suitable for the screening fire scenarios in Task 8. Work continues in this area to understand modeling sensitivities and limitations with respect to the scope of work in Task 8.

3.9. Fire PSA Task 9 through 14

These tasks are not underway as they depend on inputs not yet provided by preceding tasks.

4. FLOOD PSA PROGRESS REPORT

The Internal Flooding PSA (IFPSA) is conceptually similar to that for Fire-PSA (both are common cause events). The G-2 methodology is mainly based on EPRI-1019194 Guidelines for Internal Flooding Probabilistic Risk Assessments [2]. The process layout and some of the tasks described for G-2 are based or inspired by the NUREG/CR-6850 [1] The IFPSA process includes the tasks shown in Figure 5.

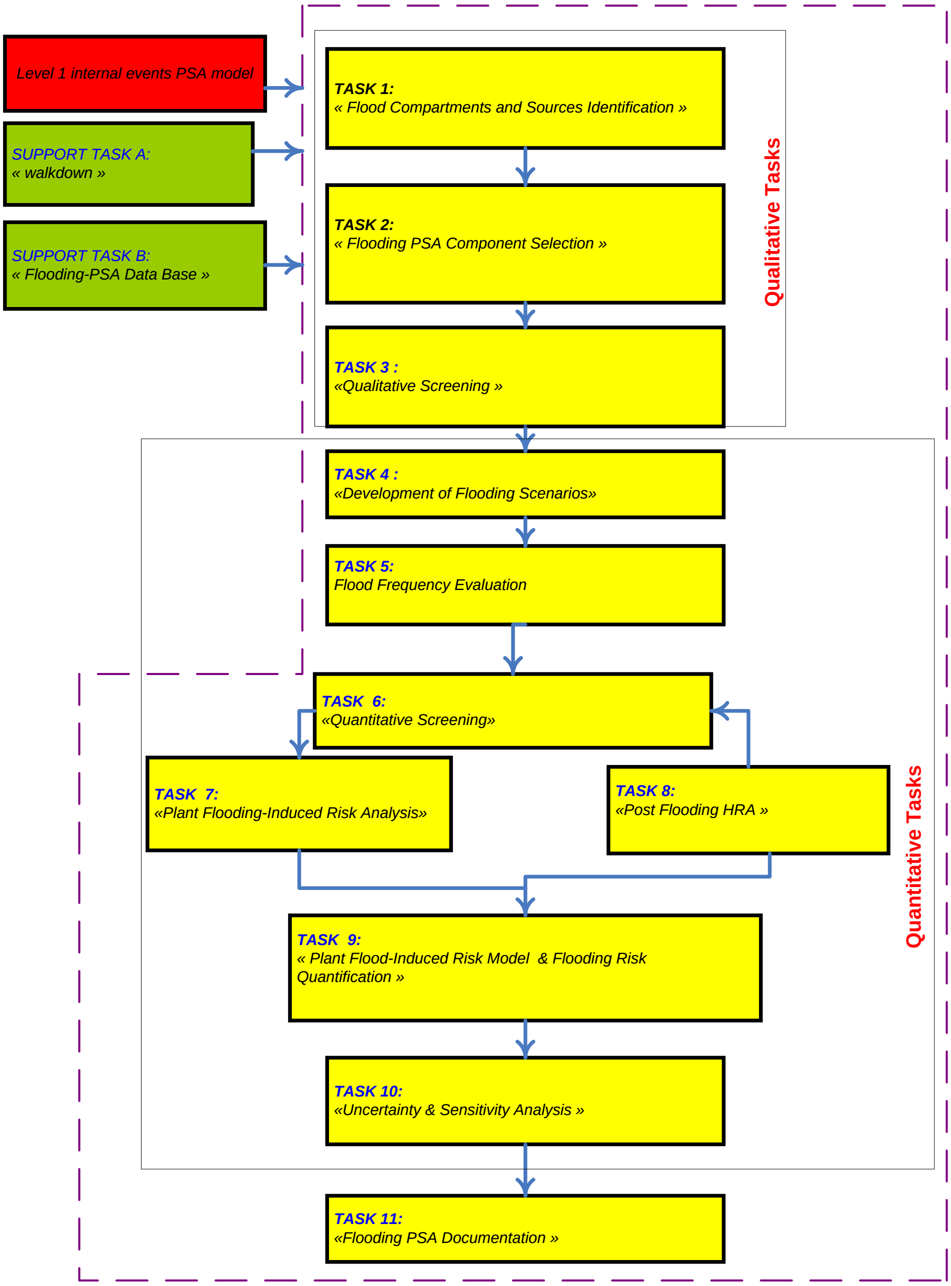

Figure 5 Internal Flooding PSA Process

4.1. Task 1 – Plant Partitioning for G-2 IFPSA

The global plant partitioning task identifies the G-2 buildings of potential interest to the IFPSA. Unimportant areas with respect to flood induced core damage within this boundary are identified and screened out. Plant buildings are retained for further analysis if they meet one of these two conditions, as in the Fire PSA:

1. Building that contain Level 1 PSA equipments with internal flooding potential;
2. Adjacent buildings to those identified in step 1 and that pose flood propagation potential.

Flooding sources inside the primary containment (i.e., LOCA and other pipe breaks inside the Reactor Building) are excluded from this IFPSA. The impact of these events including the flooding consequences on the mitigation functions will be addressed in the Internal Events PSA.

In general, the compartment delimitations follow the physical room boundaries except for open areas such as those found in the Turbine Building. The compartments were defined based on the following criteria:

1. Closed rooms are defined as single compartments;
2. open areas and communicating rooms are grouped with lower level areas for submergence analysis. However, for spraying analysis they are defined in separate compartments as in the drawings in order to better define the zone of influence of the spraying effect.

All water (heavy and light water) sources outside of the containment structure that have a potential to cause flooding impacts are considered in this IFPSA. The list of sources was established after reviewing all G-2 systems. Figure 6 illustrates the potential open-ended and closed circuit flood sources at G-2.

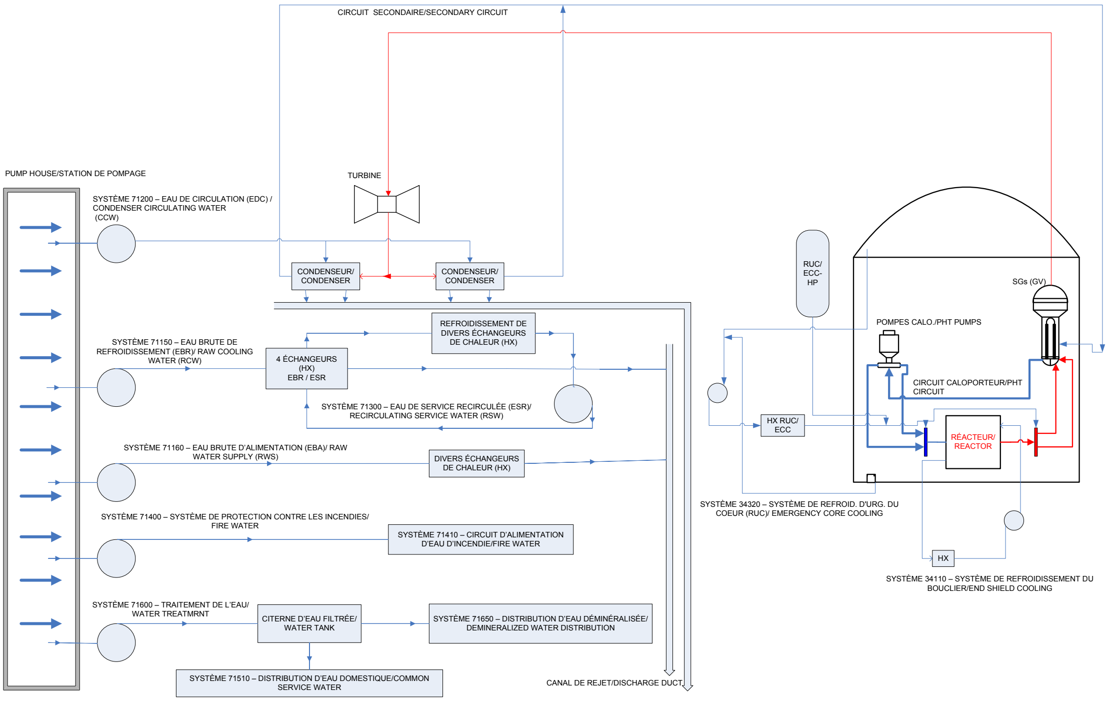

Figure 6 Potential Flooding Sources

4.2. Task 2: IFPSA Components Selection

Given that the G-2 Internal Events PSA development overlaps that of the Fire and Flood PSAs, preliminary versions of the Level 1 PSA have been used to establish a working list of Flood PSA components. This poses a configuration management challenge as each revision of the PSA represents additional data mapping and impacts parallel work in other Flood PSA tasks. The same list for fire and flood is used with a vulnerability identifier (see section 3.2).

As the junction boxes (JBs) are not part of the Internal Events PSA the cable routing database CARD-G2 will be used to identify critical JBs (see section 3.3 for the Fire PSA). However, the vulnerability of the JBs to spray and submergence should be evaluated.

4.3. Task 3: IFPSA Qualitative Screening

The following qualitative criteria have been considered:

- Criterion #1 - Flood sources, critical Systems, Structures, and Components (SSCs) and propagation paths.

- Criterion #2 - Flood induced initiating events (IEs) or need for manual reactor trip.
- Criterion #3 - Flood potential impact on critical SSCs.

The process is based on the guidelines contained in the IFPSA EPRI-1019194 [2] and is depicted in Figure 7.

As a general rule, if a flood initiator causes the loss of a single PSA component, it is assumed that this is captured by Internal Events PSA analysis (part of the component random failure). However, in a case of the loss of two or more PSA components, a manual reactor trip is conservatively assumed even though this limiting condition of operation might warrant such a trip after a certain delay of, for example, 8 hours or more. Furthermore, if the flood initiator induces a loss of a system considered as an Internal Event IE with no further impact on mitigation functions (systems and operator actions), this would be part of the Internal Event PSA and would not be analyzed with the IFPSA.

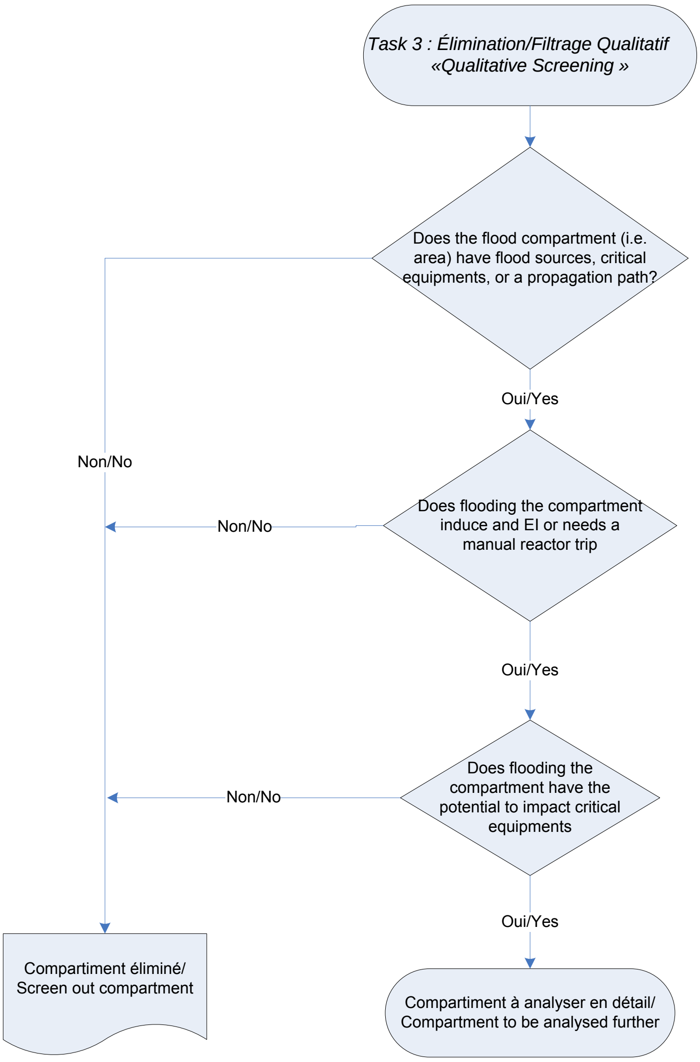

Figure 7 IFPSA Qualitative Screening Process

4.4. Task 4: IFPSA Development of Flood Scenarios

The purpose of the development of flood scenarios is to characterize the flood and to be able to group flood damage states (FDSs) in the case the effects of the scenarios are similar or can be bounded by a set of conditions. Figure 8 is an illustration of the development of a flood scenario for the battery room.

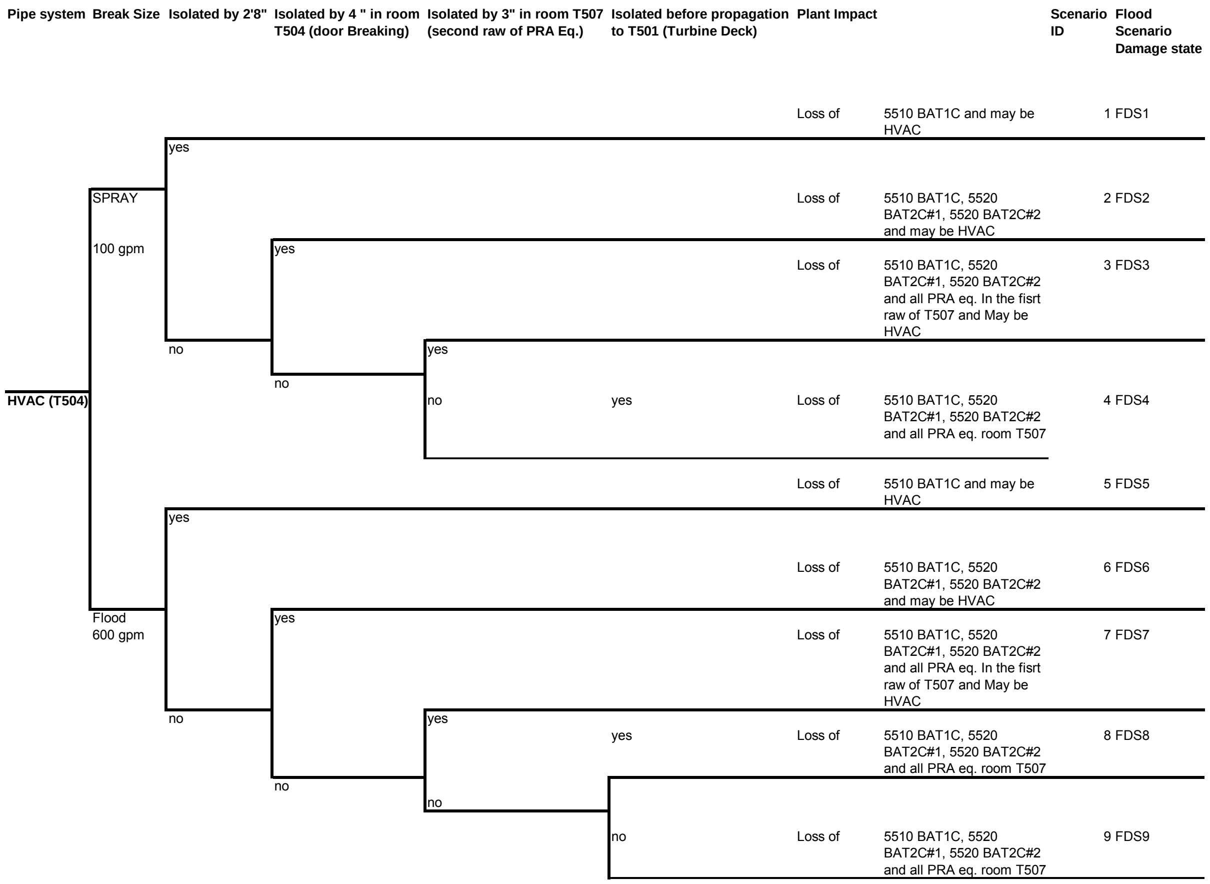

Figure 8 Flood Scenarios Development for the Battery Room

4.5. Task 5: Flood Frequency Evaluation

The pipe failure rates used in this IFPSA are based on data obtained for pressurized water reactors (PWR), and documented in Reference [6]. Because this IFPSA deals with a CANDU reactor, a system correspondence list between the two reactor technologies is established. Table 3 presents a limited correspondence between systems at G-2 (see Figure 6) and Reference [6]. This mapping will be performed for all retained flood sources.

Table 3 Correspondence between EPRI 1013141 [6].and G-2 Flood Sources

EPRI 1013141 [6].	**Equivalent G-2 system**	
	USI	**Description G-2**
SW - Service Water Systems (for River Water)	71150	Eau Brute de Refroidissement (EBR)
	71160	Eau brute d'alimentation (EBA)
	34610	Système d’eau d’urgence (SEU)
Circulating water system	71200	Eau de circulation (EDC)
CCW - Component Cooling Water System or other closed clean water low energy piping system	71300	Eau de service recirculée (ESR)
Fire Protection	71400	Eau d’incendie
SIR[1] outside containment or drywell	34320	Refroidissement d’urgence du Cœur (RUC)
FW- Feedwater		Eau d’alimentation

[1] Includes HPSI, LPSI, HPCS, LPCS, and RHR piping located outside the containment in PWRs and BWRs and taking suction from ECCS storage tanks or suppression pool. Small bore pipe (<2”) is excluded.

EPRI 1013141 [6].	**Equivalent G-2 system**	
	USI	**Description G-2**
CND-Condensate System		Système de vapeur et de condensât

4.6. Fire PSA Task 7 through 11

These tasks are not underway as they depend on inputs not yet provided by preceding tasks. This includes external inputs such as the Internal Event PSA Model.

5. CONCLUSION

This paper presents a summary of work performed to date on the Level 1 Internal Fire and Flood PSA for the Hydro-Québec Gentilly-2 CANDU Nuclear Power Plant. The overview will present findings, observations, challenges, and solutions that have been developed to supplement the NUREG/CR-6850 and EPRI-1019194 methodologies.

6. REFERENCES

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