Canada Deuterium Uranium Updated Fire Probabilistic Risk Assessment Model for Canadian Nuclear Plants

Hossam Shalabi, George Hadjisophocleous

Abstract**—**The Canadian Nuclear Power Plants (NPPs) use some portions of NUREG/CR-6850 in carrying out Fire Probabilistic Risk Assessment (PRA). An assessment for the applicability of NUREG/CR-6850 to CANDU reactors was performed and a CANDU Fire PRA was introduced. There are 19 operating CANDU reactors in Canada at five sites (Bruce A, Bruce B, Darlington, Pickering and Point Lepreau). A fire load density survey was done for all Fire Safe Shutdown Analysis (FSSA) fire zones in all CANDU sites in Canada. National Fire Protection Association (NFPA) Standard 557 proposes that a fire load survey must be conducted by either the weighing method or the inventory method or a combination of both. The combination method results in the most accurate values for fire loads. An updated CANDU Fire PRA model is demonstrated in this paper that includes the fuel survey in all Canadian CANDU stations. A qualitative screening step for the CANDU fire PRA is illustrated in this paper to include any fire events that can damage any part of the emergency power supply in addition to FSSA cables.

Keywords**—**Fire safety, CANDU, nuclear, fuel densities, FDS, qualitative analysis, fire probabilistic risk assessment.

I. Introduction

THE fire data for the U.S. experience is presented in NUREG/CR 6850 [1]. A Canadian Fire Database for CANDU reactors was built [2]. There are differences in systems, structures, and components when comparing CANDU reactors (Pressurized Heavy water reactor) to U.S. reactors (Light water reactor). For example, some fires that are negligible in light water reactors and are screened out by NUREG/CR-6850 may have consequences that are more significant in CANDU reactors. CANDU uses a heavy water moderator and heavy water coolant, whereas the U.S. reactors mainly use light water [3].

A CANDU fire PRA model was partially developed and discussed in [4]. The CANDU fire PRA model is an analysis method, which can quantitatively evaluate plant damage states including core damage frequency. The model would provide support to fire engineers performing CANDU fire PRAs, by recognizing vulnerabilities related to internal fires and furthermore would contribute to further improvement of the Canadian NPPs' safety.

The Nuclear Energy Agency (NEA) is a specialized agency within the Organization for Economic Co-operation and Development (OECD). The FIRE Database project was created to support the collection and analysis of fire events data in all participating OECD NPPs. Most values are less or equal to 2, except for three consecutive periods between 1997 and 2004 (i.e. the 1st and 2nd periods) where the number of events were 20 between 1997 and 2000 and 39 between 2001 and 2004. After 2008, the number of events per period went back to a level lower or equal to 2. There is no obvious reason or explanation for the spike in the number of fires between 1997 and 2004 [2]. However, the first CSA N293 standard (Fire Protection for CANDU NPPs) was developed in 1995 and approved for publication in February 1997 [5]. CSA N293 was then added to the Canadian NPPs license conditions handbook (LCH). CSA N293 provides the minimum fire protection requirements for the design, construction, commissioning, operation, and decommissioning of CANDU NPPs, including structures, systems, and components (SSCs) that directly support the plant and the protected areas. CSA N293 also states fire protection requirements for Canadian NPPs. Some of these requirements are for NPPs to have a fire protection program, perform fire protection assessments (Code Compliance Review, Fire Hazard Analysis and FSSA). CSA N293 also defines the design and installation requirements of fire protection systems. CSA N293 requires a lot of effort, workforce, expertise and time to adopt and mature. This might be an explanation for the decrease in the number of fires after 2004.

TABLE I
NUMBER OF FIRES REPORTED IN CANADA [2]

Period	Years	Number of Fires Reported in Canada
1	1997-2000	20
2	2001-2004	39
3	2005-2008	6
4	2009-2012	0
5	2013-2016	2
6	2017-2020	?

II. CANDU Fuel Survey

There are 19 operating CANDU reactors in Canada at five sites (Bruce A, Bruce B, Darlington, Pickering and Point Lepreau). The fire load density surveys were carried out for all FSSA fire zones in all five sites and the average for all fire zones is presented. The fire load density surveys include floor areas/ceiling heights, ceiling/walls/floor constructions, available suppression and/or detection systems, accessible fire

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hose and/or portable extinguishers, available ventilation and/or penetration, the potential for High Energy Arcing Faults (HEAF), all potential ignition sources and the types and quantities of combustibles [6].

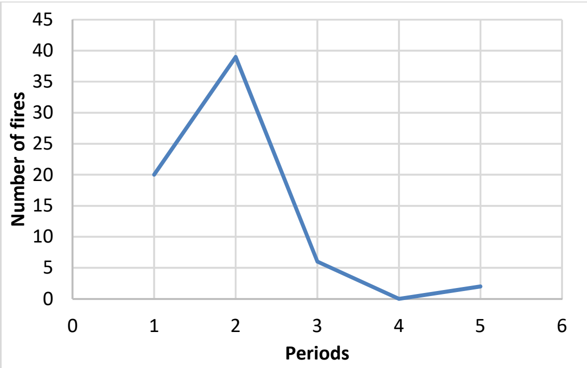

Fig. 1 Distribution of Fires Reported in Canada

CSA N293-12 [7] defines the FSSA as an evaluator of the capability to safely shut down and maintain the reactor in the shutdown state with respect to postulated fire damage. FSSA fire zones are defined as the fire zones that contain FSSA equipment and/or cables where one or more of the fire safe shutdown performance goals cannot be met if all of the FSSA equipment and/or cable located in the fire zone are assumed unavailable. The fuel survey was carried out only in fire zones that contain FSSA equipment. CSA N293-12 defines FSSA as an evaluator of the capability to safely shut down and maintain the reactor in the shutdown state with respect to postulated fire damage. There are 1,230 FSSA fire zones in all Canadian NPPs.

A fuel load survey was carried out using NFPA 557 [8] combination method. The combination method combines the use of the direct weighing method and the inventory method. This can include pre-weighed combustibles, inventory of calculated masses based on direct measurement of volume and material densities. Using the inventory or direct weighing method alone has several disadvantages that may obstruct the progress of the survey and negatively affect the survey results. This has resulted in the use of both methods for a number of surveys in the past [9]-[13].

The total fire load in a compartment is calculated using (1):

$$Q = \Sigma\, k_i\, m_i\, h_{ci} \tag{1}$$

where, Q = total fire load in a compartment (MJ), k_i = proportion of content or building component i that can burn, m_i = mass of item i (kg), and h_{ci} = calorific value of item i (MJ/kg).

The total fire load per unit area in a compartment is calculated using (2):

$$Q'' = Q / A \tag{2}$$

where, Q'' = Fire load per unit area (MJ/m^2), and A = Floor surface area of a compartment (m^2).

The survey included multiple similar compartments; hence, the average and standard deviations of the fire loads are also computed.

The standard deviation is calculated using (3):

$$\sigma = (\Sigma\, (x_i - x)^2 / N)^{1/2} \tag{3}$$

where, σ = standard deviation; x_i = fire load from ith sample; x = average of all fire load samples; N = number of fire load samples.

As per NFPA 557, 99% confidence interval should be used [8], which can then be calculated as:

$$x = \pm\, z\, \sigma / (N)^{1/2} \tag{4}$$

where, z = 2.57 for a 99 percent confidence interval.

Table II illustrates the typical combustibles in different fire zones, and Fig. 2 shows a linear relationship between areas and heights from 3.9 m^2 to ~ 1200 m^2.

TABLE II
TYPICAL COMBUSTIBLES IN FIRE ZONES [6]

Typical Combustibles in Fire Zones ~ 500 MJ	Miscellaneous Power Cable 25.00 Feet (~ 7.6 meter)
Typical Combustibles in Fire Zones ~ 5000 MJ	Miscellaneous Power Cable 30.00 Feet (~ 9.1 meter) Oil - Lube Oil 21.00 Gallon(s) (~ 95 liters)
Typical Combustibles in Fire Zones ~ 50000 MJ	Miscellaneous Power Cable 250.00 Feet (~ 76.2 meter) Plastic 200.00 Pound(s) (~ 45.4 kg)
Typical Combustibles in Fire Zones > 50000 MJ	Miscellaneous Power Cable 1,000.00 Feet (~ 304.8 meter) Oil - Lube Oil 2,500.00 Gallon(s) (~ 11365 liters) Plastic 100.00 Pound(s) (~ 90.7 kg)

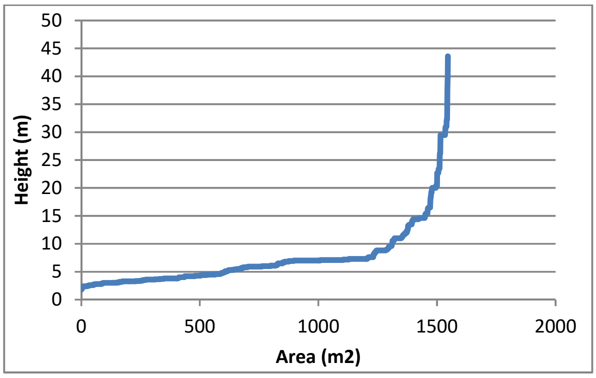

Fig. 2 Area - Ceiling Height relationship

A fire zone group list for all sites was developed to combine fire zones with similar functions and hence 38 fire zone groups were developed. Table III shows the average fuel load density and standard deviation for all 38 fire zone groups.

The average fire load density for all 1,230 fire zones is 170.1 MJ/m^2 and the average fuel load is 79183 MJ [6]. The maximum fire load density is 1319 MJ/m^2 and the maximum fire load is 2785404 MJ. HEAF risk was found in 254 fire zones out of the 1230 fire zones. Electric fault is the highest ignition source risk present in all 1,230 fire zones [6]. The maximum fuel load density is in the range of Group F, Division 2 occupancy as described in the National Building Code of Canada (NBCC) [14]. NBCC permits the fuel load to be averaged so that the occupancy calculation is based on the average fuel load and not the maximum fuel load density. As such, when averaged, NPPs are considered to contain a Group F, Division 3 major occupancy.

TABLE III
AVERAGE FUEL LOAD DENSITIES [6]

Fire Zone Group Name	Average fuel load density (MJ/m^2)	Standard Deviation
Access Area	120	98
Access way	130	123
Airlock & TC	60	56
Annulus Gas	77	47
Battery Room	459	296
Boiler Room	29	21
Cable Areas	249	223
Control Room	241	88
Decontamination Room	246	126
ECI Room	70	52
Electrical Room	89	52
End shield cooling	91	53
Equipment area	205	201
ERT Room	637	424
Fueling machine	226	137
Generator Room	577	523
Heat Transport	387	288
Instrument Room	57	47
Moderator Room	229	207
Monitoring Room	59	47
Motor Control	149	100
Nuclear Storage	78	64
Office/ Miscellaneous	223	212
Pump Room	109	88
Reactivity Mechanism	59	34
Reactor Vault	72	54
Relay Room	46	18
Shutdown	81	55
Steam	171	149
Storage Area	146	139
Switchgear Room	219	197
Transformer Room	416	153
Turbine Room	206	205
Valve Room	91	84
Ventilation & Air Equipment	129	121
Water System	102	73
Workshop	217	145
Zone Control	504	424

III. QUALITATIVE ANALYSIS SCREENING STEP

The qualitative screening step is used to separate fire scenarios in fire zones that need additional quantitative analysis from the ones that can just be screened out from further analysis. This step is very crucial in the fire PRA. There is more than one requirement that is used worldwide to define the qualitative screening criteria.

A new methodology for the qualitative screening step for CANDU reactors in Canada for performing Fire PRA was introduced in [15]. This qualitative screening step screens out fire zones that do not have ignition sources and/or combustibles, and considers all fire zones that have HEAF potential for further analysis. The qualitative screening step also defines three levels of hazards to qualitatively screen in or out potential fire scenarios [15].

Applying the NUREG/CR-6850 qualitative screening step to the Canadian (FSSA) fire zones identified in the fuel survey [6] will result in screening-in all 1,230 fire zones for further analysis. Applying the German criteria of 90 MJ/m² [16] [17] will result in screening out 594 fire zones from further analysis. Both methods' outcomes will result in inaccurate overall Fire PRA results.

A. Qualitative Screening Methodology [15]

Step1. FSSA Fuel Survey: Carry-out a full fuel survey for all FSSA fire zones in operating CANDU reactors in Canada at the 5 sites (Bruce A, Bruce B, Darlington, Pickering and Point Lepreau)

Step2. Area and height ranges: Divide all 1,230 FSSA fire zones into five categories by areas and heights. Identify the most common typical areas and heights for all five categories.

Step3. Combustible load ranges: Divide the combustible loads present in all 1,230 FSSA fire zones into four categories. Define the most common typical combustibles present in each category.

Step4. FSSA cables: Identify the most common distances between combustibles and FSSA cables. Identify the typical location of FSSA cables.

Step5. Fire Modelling: Model the worst-case fire scenario for each combination of the defined categories. Define all required assumptions to meet the worst-case fire scenarios.

Step6. Fire Model results & Sensitivity Analysis: Produce the results from step 5 and carryout a sensitivity analysis to account for potential errors in the fire model.

Step7. Qualitative screening matrix: Create the Qualitative-screening matrix by defining hazards levels.

FDS was used in this analysis for its ability to analyze very detailed scenarios, in complex geometric domains. FDS takes into consideration aspects such as turbulence description, reaction kinetics, radiation transport and pyrolysis. FDS also permits the users to model the interactions, which happen simultaneously in a fire accident, helping to evaluate the effect of different parameters on the event progression. FDS has been subject to a series of validation tests over different configurations, thus it is considered appropriate for complex geometries description. This Validation & Verification project began using Version 4.05 of FDS. As part of the V&V process, several improvements were made and a minor bug was corrected in this version. The final version of FDS used in this study is Version 4.06 and includes the changes described above. The mathematical and numerical robustness of FDS has been verified in accordance with the general criteria listed in ASTM E 1355: Analytical Tests, Code Checking and Numerical Tests. NUREG/CR-6850 uses FDS as its main fire-modeling tool [1]. FDS can reliably predict gas temperatures, major gas species concentrations, compartment pressures to within about 15%, and heat fluxes and surface temperatures to within about 25% [18].

Table IV summarizes all 14-fire scenarios inputs that were modelled using FDS and [15]. Table V summarizes all FDS outputs for the 14-fire scenarios including maximum temperatures and maximum heat fluxes after performing sensitivity analysis [15] using 25% error margin [18].

TABLE IV
SUMMARY OF THE 14 FIRE SCENARIOS INPUTS

Simulation Number	Area (meter^2)/ Height (meter)	FSSA cable distance from fire (meter)	Combustible Load MJ
1	26.0 / 4.2	2	~ 500
2	26.0 /4.2	5	~ 500
3	74.0 / 5.3	2	~ 500
4	187.7 / 6.1	2	~ 500
5	571.0 / 7.0	2	~ 500
6	26.0 / 4.2	5	~ 5000
7	74.0 / 5.3	7	~ 5000
8	187.7 / 6.1	7	~ 5000
9	571.0 / 7.0	7	~ 5000
10	74.0 / 5.3	7	~ 50000
11	187.7 / 6.1	7	~ 50000
12	571.0 / 7.0	7	~ 50000
13	187.7 / 6.1	7	> 50000
14	571.0 / 7.0	7	> 50000

TABLE V
SUMMARY OF THE 14 FIRE SCENARIOS OUTPUTS

Simulation Number	Max. Temperature °C	Max. Heat Flux, kW/m^2	Error Analysis Maximum Temperature °C	Error Analysis Maximum Heat Flux kW/m^2
1	189.0	2.7	236.3	3.4
2	153.0	2.6	191.3	3.3
3	131.0	2.6	163.8	3.3
4	78.0	2.5	97.5	3.1
5	90.0	1.2	112.5	1.5
6	640.0	28.2	800.0	35.3
7	532.0	16.8	665.0	21.0
8	636.0	25.3	795.0	31.6
9	588.0	55.9	735.0	69.9
10	722.0	52.9	902.5	66.1
11	795.0	70.5	993.8	88.1
12	670.0	38.2	837.5	47.8
13	901.0	98.5	1126.3	123.1
14	745.0	57.1	931.3	71.4

B. Qualitative Step Matrix [15]

The following is the description of the full qualitative step matrix:

- Quantify all fire zones that have potential HEAF incidents,
- Screen-out any fire zone that does not have ignition sources and/or combustibles, and
- Follow Table VI in assessing potential fires for screening out fire scenarios.

Damage threshold temperature for IEEE-383 qualified cables is 330 ºC and for nonqualified cables is 205 ºC. Damage threshold heat flux for IEEE-383 qualified cables [19] is 11 KW/m^2 and for nonqualified cables is 6 KW/m^2 [1], [19], [20].

Based on the results of the maximum temperatures and maximum heat fluxes after performing the sensitivity analysis for the 14-fire scenario FDS models in Tables IV and V; simulation numbers 1- 6 had the same combustible load of ~ 500 MJ with different areas/heights and different distance between the FSSA cable and the design fires. In simulation numbers 2, 3, 4 and 5, both the maximum temperatures and the maximum heat fluxes did not exceed the threshold temperature of 205 ºC and the threshold heat flux of 6 KW/m^2 for IEEE-383 unqualified cables. However, for simulation number 1 the maximum temperature and the maximum heat flux exceeded both threshold for IEEE-383 unqualified cables, but did not exceed the threshold IEEE-383 qualified cables. For the rest nine simulations (simulation numbers 6, 7, 8, 9, 10, 11, 12, 13 and 14), the maximum temperature and the maximum heat flux exceeded both threshold for IEEE-383 unqualified cables and qualified cables [15].

The limits for the hazard levels (Low, Medium and High) in table 6 were based on thresholds for IEEE-383 unqualified cables and qualified cables [1], [19], [20]. The definitions for the three hazards levels are based on area of fire zones, distance of designed fires, FSSA cables, and the results of the maximum temperatures and maximum heat fluxes for the 14-fire scenario FDS models in Tables IV and V [15].

TABLE VI
HAZARD LEVEL THRESHOLDS [15]

Low	Medium	High
Target < 205 ºC and/or < 6 KW/m^2	> 205 ºC & < 330 ºC > 6 KW/m^2 & < 11 KW/m^2	Target > 330 ºC and/or > 11 KW/m^2

Low Hazard Level: Fire zones that are < 500 MJ and with an area between range of between 26 m^2 and 571 m^2 where, also the potential fire is at a distance of more than 2 meters away from the FSSA cable can be screened out from further analysis (where the FSSA cable is not IEEE-383 qualified).

Medium Hazard Level: Fire zones that are < 500 MJ and with an area between range of between 26 m^2 and 571 m^2 where, also the potential fire is at a distance of more than 2 meters away from the FSSA cable can be screened out from further analysis (where the FSSA cable is IEEE-383 qualified).

High Hazard Level: Any other fire that is not listed in Low Hazard Level and/or Medium Hazard Level should be screened in for further analysis.

IV. CANDU FIRE PRA MODEL

Below is a high-level summary of the updated CANDU Fire PRA methodology [3]:

- **Task 1: Plant Boundary Description:** This is to divide the plant into fire zones and compartments, while classifying the plant boundaries.
- **Task 2: Selection of Fire PRA Cable & Components:** Selection of target components includes vulnerable components that can get involved in fire which can cause

damage to FSSA cables or any emergency power supply.

- **Task 3: Qualitative Screening [15]:** Any fire zone that has HEAF potential must be quantitatively analyzed, screen-out any fire zone that does not have ignition sources and/or combustibles, and follow Table VI in assessing potential fires for screening out fire scenarios.
- **Task 4: Frequency of Fire Occurring & Modeling the Fire Assessment:** The expected ignition frequency for all CANDU reactors in Canada is estimated to be 2 fire events between 2017 and 2020 and hence the annual ignition frequency is 0.5 fire/year [3].
- **Task 5: Circuit Failure Analysis & Fire Modeling:** The purpose of this task is to determine the response of the components in each fire as a way to filter out cables that have no impact on the operation of the component.
- **Task 6: Human Reliability Analysis (HRA) for Post-Fires:** This is a three-step task as follows:

1) Step 1: Modifying and adding human failure events to the models;
2) Step 2: Assigning quantitative screening human error probabilities and performing detailed best-estimate analyses of the important HFEs and;
3) Step 3: documenting the HRA.

- **Task 7: Fire Risk Quantification:** This task comprises of creating a faults tress and event trees to further analyze the selected fire scenarios to calculate the residual risk.
- **Task 8: Sensitivity Analysis & Uncertainty:** This task includes the methodology for identifying the uncertainties throughout the Fire PRA process, and developing approaches to address these uncertainties.

V. CONCLUSION

The paper summarized all the work that has been done to develop CANDU Fire PRA. This work includes CANDU Fire PRA, CANDU fuel survey, CANDU Fire PRA qualitative analysis and the updated CANDU Fire PRA.

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