Development of Probabilistic Safety Assessment Methodology

for

Fire Events in CANDU Plants

by
G. How Pak Hing and A. Stretch

Presented by G. How Pak Hing at:

International Workshop on Fire Risk Assessment
OECD Nuclear Energy Agency (NEA),
Committee on the Safety of Nuclear Installations (CSNI),
Principal Working Group No. 5 (PWG5) - Risk Assessment
June 29 to July 01, 1999, Helsinki, Finland.

DEVELOPMENT OF PROBABILISTIC SAFETY ASSESSMENT METHODOLOGY FOR FIRE EVENTS IN CANDU PLANTS

G. How Pak Hing and A.H. Stretch

Atomic Energy of Canada Limited
2251 Speakman Drive, Mississauga
Ontario, Canada, L5K 1B2

ABSTRACT

Atomic Energy of Canada Limited (AECL) initiated a Generic Probabilistic Safety Assessment (PSA) program in 1998, with the mandate to upgrade the expertise and technology base to support the CANDU products in the future. It expands the scope of earlier PSA work to include external events, detailed human reliability analysis, common cause failure analysis. This paper describes the development of a PSA methodology for fire events in CANDU plants, as part of the overall Generic PSA program, which will be applied to current and future CANDU designs. The methodology was selected to be internationally acceptable and with the flexibility to accommodate changes in design and equipment.

The elements of the Fire PSA include the following:

- *Development of fire initiating event frequencies*
- *Identification of plant characteristic relevant to fire events*
- *Fire scenario analysis, including qualitative and quantitative screening*
- *Quantification of the fire risk in terms of severe core damage frequency (SCDF)*
- *Recommendations for design changes to satisfy PSA objectives.*

With the assistance of experienced external consultants, AECL has built a generic experience based CANDU fire events database to estimate initiating event frequencies. The database consists of fire events from US Light Water Reactors, as well as fire events that have occurred in CANDU plants, screened for applicability to the current CANDU design. The data related to plant systems, including the safety related and PSA credited equipment, cables, and their locations, has been assembled in a comprehensive reference CANDU 6 plant characteristics database. As part on the ongoing acquisition of the methodology and technology phase, a one-week fire PSA walkdown training exercise was conducted at a CANDU plant.

The fire vulnerability analysis for the CANDU 6 design will be started in early 1999, using information gathered up to this point, including the fire initiating event frequencies, the fire zone data, the lists of equipment and fire hazards, and the walkdown information. This activity involves the identification of fire scenarios for each room and/or area, qualitative and quantitative screening of each area, and the calculation of plant damage and core damage frequencies using modified system models for internal events. The COMPBRN code will be used to model fires in selected areas, and determine their impact on PSA credited systems and components.

1. INTRODUCTION

The probabilistic design approach has long been a feature of CANDU plants, since reliability targets for the Special Safety Systems (two shutdown systems, emergency core cooling, and containment) were set by the Canadian regulatory authority in the mid-1960s, in conjunction with different dose limits for accidents involving loss of one of the Special Safety Systems. During the 1970s, an analytical technique was developed called "Safety Design Matrices", which used event trees and fault trees to evaluate safety support systems. This technique was the forerunner of the Probabilistic Safety Assessment (PSA) methodology used for recent CANDU plants, which applies current risk assessment methods and computer codes to an extensive range of internal events.

Last year, Atomic Energy of Canada Ltd (AECL) embarked on a program to upgrade the PSA capability to include the latest methods to address external events (fire, seismic, and flooding), common cause events, human reliability, and severe accident modeling. This program is called the Generic CANDU Probabilistic Safety Assessment Program [1].

This paper outlines the development of the PSA methodology for fire events, as part of the Generic CANDU Probabilistic Safety Assessment Program at AECL.

2. DEVELOPMENT OF CANDU FIRE PSA METHODOLOGY

The overall objectives for the selection of the methodology for the fire events PSA was that it must be internationally acceptable (as CANDU plants are being marketed globally), able to accommodate the expert judgment of analysts and designers, and flexible enough to easily deal with changes in design and improvements in methodology. In addition, the documentation produced must be easily auditable by clients and regulators, generally following the approach outlined by the International Atomic Energy Agency in Safety Series No. 50-P-4 [2].

The development of the methodology consisted of a planning phase, a methodology development phase, and then a trial application to typical CANDU designs. The initial planning phase included preparation of budgets and schedules for a three year program, the selection of experienced consultants to provide training and expertise, and the staffing of the fire PSA team. The definition of the fire PSA program included a decision to follow a comprehensive risk assessment approach (i.e. based on event trees and fault trees) rather than using a more deterministic approach, such as the EPRI Fire Induced Vulnerability Evaluation (FIVE) technique. To assist in the efficient acquisition of the basic fire PSA techniques and tools, several consultants experienced in the US Individual Plant Examination of External Events (IPEEE) were interviewed. The consultant with the expertise and risk assessment tools and approach felt to be most compatible with the objective of the CANDU fire PSA program was selected. This consultant provided the initial training for the fire PSA team (as well as for a number of other related resource staff), the fire events database for US plants, ongoing assistance with the application of the tools, and a peer review of the methodology documents.

The methodology was developed in parallel with its trial use on a typical CANDU 6 plant design, which provided a "hands-on" aspect to the development process. The methodology and preliminary design assessment phase, shown in Figure 1, will be followed by a detailed analysis and final design assessment phase. Problems encountered during the application of the methods and computer tools were resolved and factored into the methodology documentation. The methodology development process consisted of the following basic elements:

- Calculation of fire event frequencies for typical plant locations and equipment types
- Identification of plant characteristics relevant to fire events
- Development of a plant walkdown process to confirm plant characteristics
- Fire scenario analysis, including qualitative and quantitative screening
- Quantification of the fire risk in terms of severe core damage frequency.

3. FIRE INITIATING EVENT FREQUENCIES

The frequency with which fires occur in a nuclear power plant is a key parameter for the analysis. To ensure that the methodology is conservative and internationally acceptable, it was decided that the fire initiating event frequencies should include experience beyond that of Canadian operating experience, so a database of US PWR and BWR fire events was acquired. The events were screened for applicability to

CANDU plants, and entered into a generic CANDU Fire Initiating Events Database. Events occurring in the CANDU plants operated in Canada were then added to the database, and fire frequencies were calculated.

Definition of Fire Events

Fire events were defined as those characterized by the presence of flame, burning, or smoldering which has the potential for growth and propagation to cause a reactor trip and/or damage to safety related or PSA credited equipment. In selecting events for the database, the potential impact of the event on plant safety during reactor operation and the relevance of an event to a CANDU plant were considered. Generally, events with smoke and no fire were not included, as well as those involving arcing, sparking, explosions and other short bursts of energy failing to result in ignition. Such events were carefully considered, however, and if it was obvious that the event could have led to a fire if not detected in time, then it was included. Explosion events involving mechanical effects but no fire were not included.

Frequency of Fire Induced Initiating Events

To establish fire initiating event frequencies for PSA purposes, the specific plant operating history (on power and shutdown durations) is required, and the fire initiating events must have been consistently reported throughout that period. This information was available for US and Canadian plants, but was not available to us for off-shore plants, so only North American experience was used to calculate frequencies.

The data for CANDU fire events was extracted from the CANDU Owners Group (COG) Significant Event Report Exchange database. Data for the US fire events was purchased from the fire PSA consultant. The US LWR events were considered applicable to CANDU if they involve similar types of equipment in systems providing functions similar to those in CANDU plants. The information was assembled in the CANDU Fire Initiating Events Database.

It was recognized that there is variability among the different plants in areas such as specific design, layout, maintenance procedures and practices, safety culture and fire protection features. However, the general level of technical standards for component manufacturing, safety regulations and requirements, personnel training, plant maintenance practices, etc. are not vastly different for the nuclear industry in North America. Moreover, fire events are evaluated individually at the component/equipment level, minimizing the impact of different plant designs. Therefore it was considered appropriate to use US LWR data for the CANDU fire events database.

Categories of Fire Initiating Event Sources

The fire initiating events in the CANDU Events Database are assigned to a number of categories, based on component types (e.g. cables, motors, pumps, etc.), areas in the plant with common characteristics for several plants (e.g. main control room), and transient fires (e.g. fires caused by welding and cutting, transient combustible materials, human errors)

Table 2 shows the list of twenty-five categories chosen to represent fire event sources contributing to fire risk for CANDU plants, and the numbers of events identified for each category, in both the operating and the shutdown plant state. The definition of these categories is tailored according to specific assumptions, as follows:

a) Category 4 (Main Control Room) relates to all fires occurring in the MCR, regardless the cause and/or equipment involved (transient fires, fires in control panels, cabinets, etc.). This approach avoids the need to comprehensively list and sum the individual fire initiation frequencies for all fire sources for this area.
b) Category 5 and Category 8 refer to Digital Control Computers (DCC) and to D_2O Recovery Dryers respectively, which are specific to CANDU plants and are not present in US LWR

plants. Therefore, the calculation of fire frequency considers only the CANDU data and plant operating history.

c) Category 9 (Hydrogen fires) includes fire events associated with hydrogen vessels and supply systems, but excludes turbine-generator hydrogen fires.
d) Category 12 (Pumps) refers to fire events related to pumps only; fires occurring in pump motors are assigned to Category 14 (Motors).
e) Fires in Junction Boxes are included in Category 16 (Power and Control Cables).
f) Category 20 (Turbine-Generator) includes all the fire events related to the T/G group (i.e. T/G exciter, oil, hydrogen fires).
g) Category 23 (Human error) contains fires related to causes such as human error and transient combustibles.

In some cases, classification of an event in one or another category may not be obvious due to limited knowledge of the individual plant and/or limited or incomplete description of the event. This requires judgments and analysis of the event on a case by case basis.

Screening Criteria

Since LWR plants may contain systems which do not exist in CANDU plants, the events recorded in LWR plants are screened for applicability to CANDU plants. For example, fires in the following LWR systems are screened out: fires in equipment that does not exist in CANDU plants (e.g. turbine driven pumps), fires in facilities that do not exist in CANDU plants (e.g. fires in the standby gas treatment system in BWR plants, fire associated with the off gas system in the radwaste building).

Events are also screened out based the definition of fire events. This includes events with smoke and no flame (smoking bearings, belts, unless a detailed examination reveals that open flaming would likely occur if the event is allowed to progress), arcing, sparking, shorts and explosions that are short bursts of heat energy but fail to result in ignition (e.g. crankcase explosions in diesel generator sets, since they are contained and cannot propagate).

Events that involve components and systems that are not modeled in the PSA and are not located in areas that contain safety related or PSA credited equipment are screened out. As a result, the following categories of events are screened out: fires in administrative buildings, main entrance area, guard house, temporary buildings, trailers, and outside the fenced area (e.g. forest or grass fires, even if they result in failure of transmission lines, as these events would be captured in the loss of offsite power frequency).

The raw data obtained from the COG database also contains events that do not involve a fire, and are therefore screened out, such as fire code violations, false fire alarms and failures in fire fighting systems.

During the screening process, an evaluation is made about whether the fire can occur during reactor power operation and/or at shutdown. This is necessary because there may be significant differences between the plant on power and the plant at shutdown, in areas such as plant configuration, system operation, maintenance activities, personnel access to various areas in the plant. As a result, the frequency of the fire initiating events for the plant with reactor on power may be different than when the reactor is at shutdown.

Screening of LWR Fire Events

The US fire events database contained 783 fire event records spanning the period from January 1, 1964 to January 26, 1994. It provided station data on the date of first criticality, date of first commercial operation, average availability, unit years, total unit years for multi-unit stations, unit power years, and total power years for the multi-unit stations.

Following the Browns Ferry fire in 1975, there were a significant number of design upgrades carried out at the US LWRs, such as the use of better materials, improved physical separation and fire protection measures, changes in plant operating philosophy with strict administrative controls, and better defined event reporting requirements. For this reason, the records prior to January 1, 1980 were not considered relevant, and events prior to that date were screened out. For plants commissioned after that date, only events that occurred after the beginning of commercial operation were considered. A cut-off date of December 31, 1992 (or the date of termination of commercial operation, if this happened prior to December 31, 1992) was selected for the fire events considered in the study. Based on the period from 1980 to 1992, the US fire database was reduced to 487 records.

The results of the screening process are presented in Table 1. The breakdown of the 487 events in the US database for the 13 year period ending December 1992 is as follows: 124 are not fire events, 134 are screened out based on the screening criteria, and 229 are fire events.

Screening of CANDU Fire Events

The COG Significant Event Report Exchange database contains approximately 15,000 records, and is searchable by many different criteria. The query for fire events resulted in a collection of 337 events, but not all the events were true or actual fire events, since they also included fire code violations and equipment failures in fire protection systems. The CANDU plant sites that were considered were the single-unit CANDU 6 plants, (Point Lepreau and Gentilly 2), and the multi-unit Ontario Hydro stations (Pickering A, Pickering B, Bruce A, Bruce B and Darlington).

The results of the screening process are presented in Table 1. The breakdown of the 337 events from the COG database for the period from first commercial operation of each plant to December 1997 is as follows: 230 are not fire events, 33 are screened out based on the screening criteria, and 74 are fire events.

The calculation of operating years for CANDU plants for the fire frequency calculation was based on the cumulative gross capacity factor since in-service, which provides a conservative value of fire frequencies during on power operation. This will be upgraded later to consider the total inservice period less outage durations.

The fire events from the CANDU plants remaining after screening were added to the US LWR events remaining after screening to form the generic CANDU Fire Initiating Events Database. The database has a combined total of 303 fire events from both LWR plants and CANDU plants. The breakdown of the 303 Fire events is as follows: 20 Power Only events, 28 Shutdown Only events, and 255 Anytime events.

Calculation of Fire Initiating Events Frequencies

The determination of the generic fire frequency due to potential fire sources in a CANDU plant involves statistical processing of the information on fire events included in the CANDU Fire Initiating Events Database. The calculations are performed with data analysis software purchased from the US consultant, using the first stage of a Two Stage Bayesian Update option (the second stage would be used for the fire frequency analysis of a specific plant).

The fire events in the database represents US LWR operating experience from 70 plants with a cumulative service life of 1149 reactor years, and for the CANDU plants it represents 7 plants (22 units) with a cumulative service life of 332.7 reactor years. With the capacity factors or outage durations considered, a total of 1054.8 power operating years (814.4 for US LWR plants and 240.4 for CANDU plants) was used in the fire frequency calculation.

The resulting calculation provides the fire initiating event frequencies for a generic CANDU plant design. The mean frequency of the distribution for each category is given in Table 2. The generic fire frequency represents how often (events per year) a fire caused by each particular category occurs in the plant during one year of operation with the reactor on power.

4. PLANT CHARACTERISTICS DATABASE

The plant characteristics relevant to fire were assembled in a database consisting of linked tables using a modern database software that is widely available. The database includes fire zone data, a list of safety related and PSA credited equipment, and a list of fire hazards. The database tables are structured in such a way that they provide easy collection, organization, grouping, storage, and retrieval of data. The tables are kept to a reasonable size so the data can be easily managed and efficiently used.

Fire Zone Data

The fire characteristics of a CANDU plant are evaluated in terms of "fire zones", which are small sections of a plant that can be treated as a unit for evaluation purposes. A fire zone usually corresponds to a single room, but can consist of two or more rooms that are spatially linked. A fire zone is not necessarily bounded by physical barriers; spatial separation may be used between fire zones. A "fire area" is one or more fire zones contained within a defined set of fire barriers.

The data tables include the following types of information:

a) Rooms: The data includes the room number and plant building designation, a description of the room function, the location of the room (elevation), and the fire zone and fire area in which the room is located

b) Zone Exposure: The data includes the zone number, other zones to which the zone is exposed, the fire propagation pathway, and the fire barrier ratings.

c) Fire Detection and Suppression: The data includes a description of the devices in each room, the number of devices in the room, whether the device is automatically initiated, and the hazard category of the device (where the device may also be the source of a fire).

d) Fire Loading: The data includes the combustibles, heat load, fire hazards and ignition sources in each room.

e) Systems: The data includes a list of systems, their identification number (subject index), whether it is safety related or PSA credited, and its function.

f) Equipment: The data includes a list of equipment in each room, its identification number (subject index), tag number, description, hazard category, and a cable termination identifier.

g) Cables: The data includes the cables in each room, the cable identifier, the length of cable in the room, the raceway identifier (conduit, tray, etc.), and hazard category.

The data collection activity for the fire PSA is very time consuming, so existing databases for equipment, cables, electrical devices, etc. are used wherever possible. For future plants, engineering databases assembled during the design and procurement phases will be more compatible with the needs of the fire PSA, allowing linkages directly to the database containing the necessary information. For example, the cable routing database will include the room identification and cable lengths within the room, avoiding the manual collection of this data from cable tray routing drawings.

5. PLANT WALKDOWN

The walkdown is a very important activity to be undertaken by the fire PSA analyst. The walkdown is necessary to confirm the accuracy of the information assembled using design documentation, to obtain additional details about the plant (field installed equipment, maintenance practices, operating procedures, handling of transient combustibles), and to identify interactions between equipment and areas that may affect the propagation of a fire. This past year, a training exercise was held at an operating CANDU 6 plant. The team assembled for the exercise included an experienced trainer from the fire consultant, a team leader, team members including expertise in plant layout, electrical equipment, safety design, process system design, PSA analysts, and plant operations staff. The team visited all areas of the plant (except the reactor building), practicing note taking and discussing the relevant fire hazards and plant characteristics in each area. Notes were taken using a predetermined format, and a digital camera was used to record features of interest in each area, for later reference in the vulnerability analysis phase.

6. FIRE VULNERABILITY ANALYSIS

The fire vulnerability analysis, which has just started for the CANDU 6 generic design and will start later this year for the new CANDU 9 design, provides an understanding of the impact on plant safety from internal fire initiating events, and quantifies the risk in terms of severe core damage frequency. To calculate the core damage frequencies, the fire vulnerability analysis uses information on generic fire initiating event frequencies for the various categories of sources, plant layout (fire areas, fire zones, fire barriers), location and interaction of components and equipment in the plant, as well as modified internal event PSA plant models.

The fire vulnerability analysis consists of the following steps:

a) Determination of fire initiating event frequencies in each fire area.

b) Definition of fire scenarios in each fire area.

c) Qualitative screening of fire areas requiring no further consideration.

d) Quantitative screening of fire areas, and calculation of plant damage and core damage frequency using PSA system models

e) Refinement of the fire scenarios in areas having a significant impact on the SCDF, using a fire growth analysis computer code to obtain a more realistic evaluation of equipment damaged, and recalculation of plant damage and severe core damage frequency using PSA system models.

The qualitative and quantitative screening of the fire scenarios is performed in order to reduce the number of fire scenarios for which a detailed fire hazard analysis is performed. The screening analyses assume a worst case impact of fire in the areas to which it is applied. Scenarios which are not screened out are retained for detailed fire hazard analysis, which provides a more accurate determination of the impact of the fire on plant safety and severe core damage frequency. The COMPBRN IIIe computer code [3] will be used to calculate fire propagation and to determine the time interval between fire initiation and damage to critical equipment. The PSA plant modeling for both screening analysis and detailed analysis is based on the internal events PSA model, suitably modified to reflect systems and components damaged by the fire.

7. CONCLUSION

The Generic CANDU Fire PSA Program has completed its first phase, the development of the fire PSA methodology. The methodology is flexible, with the capability to be applied to any CANDU plant design, and structured so new information and changes can be easily incorporated. Training materials and documentation have been produced which will ensure that a consistent approach is taken on all plants to which it is applied. The methodology is ready to be applied to future CANDU plant designs.

8. REFERENCES

1. Bonechi, M. and Snell, V.G., CANDU Severe Accident Resistance, Paper M7-A6-CA, to be presented at the August 1999 SMiRT-15 Conference, Seoul, Korea.

2. IAEA, Procedures for Conducting Probabilistic Safety Assessments of Nuclear Power Plants, Level 1, Safety Series No. 50-P-4, 1992.

3. Ho, V., Chien, S. and Apostolakis, G., COMPBRN IIIe, An Interactive Computer Code for Fire Risk Analysis, University of California, Los Angeles, prepared for the Electric Power Research Institute, UCLA-ENG-9016, October 1990.

Figure 1: Generic CANDU PSA Program

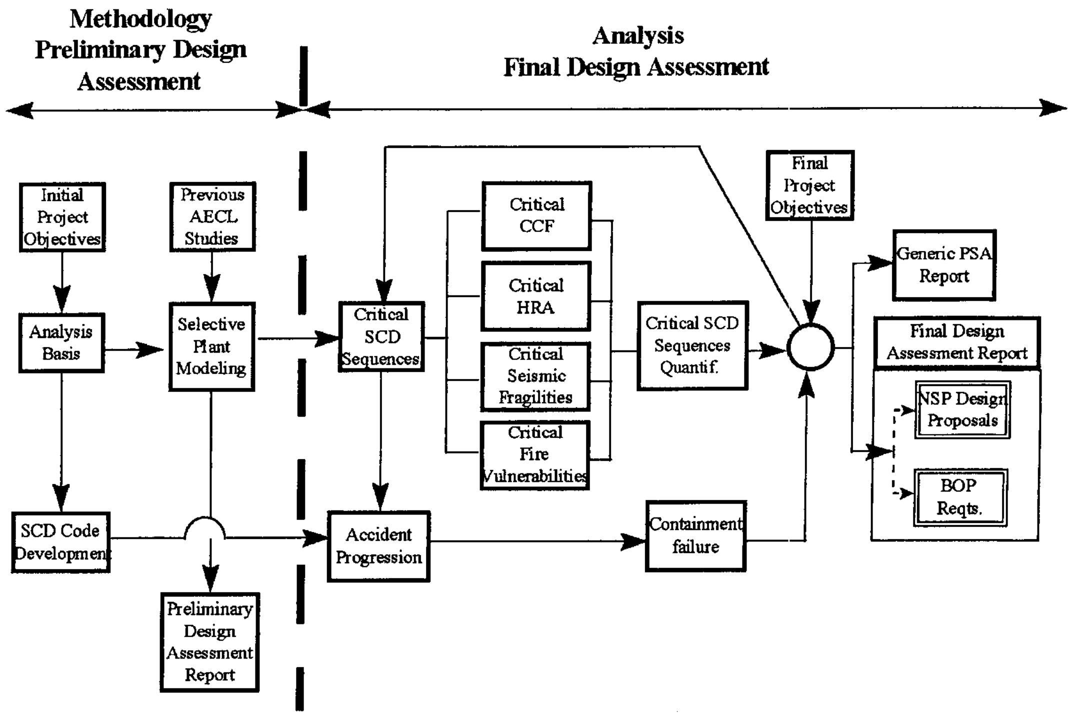

Table 1
Generic CANDU Fire Events

Event	US LWR Plants[1]	CANDU Plants[3]	Generic CANDU
Total	487[2]	337[4]	N.A.
Not a Fire	124	230	N.A.
Screened Out	134	33	N.A.
Power Only	17	3	20
Shutdown Only	21	7	28
Anytime	191	64	255

Note 1: Based on the US Fire Events Database

Note 2: For period between January 1, 1980 to December 31, 1992

Note 3: Based on raw data on search of the COG Database.

Note 4: For period from first commercial operation to December 31, 1997. It is noted that the raw data also contain events that do not involve a fire, e.g. fire code violations, false fire alarms, failure of fire fighting equipment, etc.

Table 2
Fire Frequencies for the Categories of Fire Event Sources

Category ID	Category Name	Mean Frequency (events / plant / year)
1	Battery	1.29E-03
2	Battery charger	2.35E-03
3	Inverters	1.01E-03
4	Main control room	3.06E-03
5	Digital control computers	4.15E-03
6	Diesel generator sets	2.25E-02
7	HVAC equipment	3.26E-03
8	Dryers	5.27E-03
9	Hydrogen fires	7.50E-03
10	Logic and protection cabinets	1.82E-02
11	PHTS pumps	3.88E-03
12	Pumps	1.17E-02
13	Motor control center	6.38E-03
14	Motors	1.06E-02
15	Motor generator sets	1.34E-03
16	Power and control cables	1.26E-02
17	Low voltage switchgear	7.40E-03
18	High voltage switchgear	1.21E-02
19	Standby generators	1.29E-02
20	Turbine-generator	2.57E-02
21	Main unit transformer	1.15E-02
22	Transformers	1.23E-02
23	Human error	1.89E-02
24	Cable fires caused by welding and cutting	1.71E-03
25	Transient fires caused by welding and cutting	2.92E-02