GRA MODEL DEVELOPMENT AT BRUCE POWER

R. Parmar[1], K. Ngo[1] and I. Cruchley[2]
[1] AMEC NSS Limited, Toronto, Ontario, Canada
[2] Bruce Power, Tiverton, Ontario, Canada

Abstract

In 2007, Bruce Power undertook a project, in partnership with AMEC NSS Limited, to develop a Generation Risk Assessment (GRA) model for its Bruce B Nuclear Generating Station. The model is intended to be used as a decision-making tool in support of plant operations. Bruce Power has recognized the strategic importance of GRA in the plant decision-making process and is currently implementing a pilot GRA application. The objective of this paper is to present the scope of the GRA model development project, methodology employed, and the results and path forward for the model implementation at Bruce Power.

The required work was split into three phases. Phase 1 involved development of GRA models for the twelve systems most important to electricity production. Ten systems were added to the model during each of the next two phases. The GRA model development process consists of developing system Failure Modes and Effects Analyses (FMEA) to identify the components critical to the plant reliability and determine their impact on electricity production. The FMEAs were then used to develop the logic for system fault tree (FT) GRA models. The models were solved and post-processed to provide model outputs to the plant staff in a user-friendly format. The outputs consisted of the ranking of components based on their production impact expressed in terms of lost megawatt hours (LMWH). Another key model output was the estimation of the predicted Forced Loss Rate (FLR).

Key Words: Generation Risk Assessment (GRA), Fault Tree (FT), Lost Megawatt Hours (LMWH), Force Loss Rate (FLR)

1. Introduction

Currently, Bruce B Nuclear Generating Station (NGS) does not have a systematic process in place to prioritize and evaluate plant improvement and maintenance options with respect to their impact on plant reliability, safety and profitability. As a result, plant investment/improvement and maintenance decisions are based on approximate methods that do not take into full consideration the dependencies among plant reliability, safety and direct operating and maintenance (O&M) costs. Bruce Power, therefore, initiated in 2007 a project to develop a Generation Risk Assessment (GRA) model and a prototype Risk Informed Asset Management (RIAM) model. The RIAM model combines the results of GRA and Probabilistic Risk Assessment (PRA) models to estimate the overall costs associated with the production and safety-related failures. In addition to being a key part of the RIAM model, the GRA model, by itself, can be used as plant production risk monitoring and mitigation tool.

In order to keep scope of the GRA model development manageable, it was decided to develop the GRA model in multiple phases. The first phase was initiated in 2007 and consisted of the twelve most dominant contributing systems to historical production losses at Bruce Power. Completion of the first phase was delayed in 2007 due to difficulties in arranging and concluding system model review meetings with all the Responsible System Engineers (RSEs). The work on the first phase of the GRA model development resumed in January 2009 and was completed in July 2009 with all the RSE review meetings concluded and the RSE comments incorporated into the system models.

The second phase was completed in December 2009 and consisted of the next top ten contributing systems to system unreliability as determined via a review of the production loss history at Bruce B NGS. The final phase was completed in October 2010 and consisted of additional ten systems related to electricity production.

2. Methodology

The methodology employed to develop the GRA models consists of the following steps:

a) Candidate Systems Identification

b) Component Identification via System Failure Modes and Effects Analysis (FMEA)

c) FT Logic Development

d) Component Data Assignment

e) FT Post Processing

These steps are described in detail in the following sections.

2.1 Candidate systems identification

In order to keep the scope of GRA model development manageable, it was decided to develop the model in multiple phases. At the start of this project, production loss history for the previous five years was obtained from Bruce Power. A review of the production history led to the identification of the twelve systems as the top contributors to the production loss, those systems were included in the first phase. After the conclusion of the first phase, additional ten systems were selected for the next phase. Similarly, ten more systems were chosen for the final phase. The systems for each of these GRA model development phases are listed below in Table 1.

Phase 1 GRA Systems	Phase 2 GRA Systems	Phase 3 GRA Systems
Boiler Feed Water (BFW)	Class III Electrical (CL III)	Annulus Gas System (AGS)
Digital Computer Control (DCC)	Class IV Electrical (CL IV)	Class I Electrical (CL I)
Fuel Handling (FH)	Emergency Power System (EPS)	Class II Electrical (CL II)
Generator (GEN)	Standby Generator System (SGS)	Common Service Water (CSW)
Heat Transport System (HTS)	Liquid Zone Control (LZC)	End Shield Cooling (ESC)
Moderator (MOD)	Stepback (STPBK)	Setback (SETBK)
Main Power Output (MPO)	Instrument Air (IA)	Water Treatment Plant (WTP)
Shutdown System 1 (SDS1)	Emergency Coolant Injection (ECI)	Maintenance Cooling System (MCS)
Shutdown System 2 (SDS2)	High Pressure Recirculating Service Water (HPRSW)	Negative Pressure Containment (NPC)
Low Pressure Service Water (LPSW)	Heating, Ventilation, and Air Conditioning (HVAC)	Reactor Regulating System Poison Addition (RRSPA)
Switchyard (SYD)	-	-
Turbine (TURB)	-	-

Table 1: Bruce B GRA Systems

2.2 GRA component identification via FMEAs

The objective of a system FMEA is to identify components that are critical to plant reliability and assess the impact of their failures on plant reliability. The system FMEAs were carried out via the following methodology.

a) For each system, conducted a review of system information such as flow sheets and design manuals, and identified all the components and the associated failure modes and their impact on production in terms of power loss states (e.g., trip or a de-rate level).

b) Based on the information above, developed the system FMEA tables. The FMEA development included any special conditions/configurations and the relevant failure criteria. For example, failure criteria for LPSW pumps during summer are different from winter.

c) Reviewed plant production loss operating experience to ensure that all the significant components failures are captured in the FMEAs.

d) RSE review of the FMEA tables and incorporation of their comments.

Table 2 shows an example of a system FMEA table.

#	Component	Failure Modes	Power Loss	Comment
1	Condensate Extraction Pumps (CEP) **6-4321-P1/2/3**	Failure mode for running component (P1 and P2): ▪ **FO:** Pump trip or running failures. Failure mode for standby pump (P3): ▪ **RF:** Pump trip when brought in service ▪ **MO:** Maintenance outage	100% & 40%	Condensate Extraction Pumps (CEP), extract the steam condensate cooled by the main condensers (4211-CD1/2/3) and pump it through LP and HP heaters and then to the deaerator. Once a CEP pump trips, the condensate supply can be interrupted. The failure criteria are as follow: (3x50% pumps) one standby and two operating. Failure modes are different for standby and running pumps. 1/3 (Normal Operation) No impact 2/3 Results in 40% power reduction 3/3 Results in 100% power loss **Assumptions:** ▪ Assume P3 is on standby.

Table 2: Example of a FMEA table

2.3 Fault tree development

The system FMEA tables were used to create GRA models in the Fault Tree (FT) format using an EPRI tool called CAFTA. The following steps were performed to develop FT logic for each system.

a) Using the system FMEA tables, develop FT logic for each system. The system FT logic includes a separate branch for each power loss state. Any support systems such as electrical power and instrument air are included in the FTs where applicable, but their probability contribution to the supported system is set at zero as the support systems are considered outside the supported system's boundary. However, for developing an overall plant model, complete FT logic for the interfacing systems is substituted.

b) Conduct a walkthrough of each system FT model, assumptions, and the failure data with RSEs via RSE review meetings. The objective of the walkthroughs is to explain to the RSEs the purpose and application of the GRA models, have the FT logic reviewed by the RSEs for accuracy and completeness, and obtain RSE inputs on component failure rates, test intervals, restoration times, and maintenance data.

c) Revise GRA FT logic and component reliability data to incorporate RSE feedback received in the review meetings.

d) Assign component failure data - see Section 2.4 below for details.

Each system FT model consists of a top event representing the generation loss due to that system failure. For each system, generation losses are categorized according to the possible power loss states for that system as identified in the corresponding FMEA table. The applicable power loss states are incorporated in each system GRA model via an appropriate flag event. In addition to the flags used to represent various states, each system FT also contains a system flag to mark component failures from that system. This is done to identify the component failures by the related system in the power loss equation if there is a need to integrate and evaluate the component failures from more than one system. The FT logic is arranged for each system such that the termination point is the component failures. An illustrative example of GRA FT logic is shown below in Figure 1.

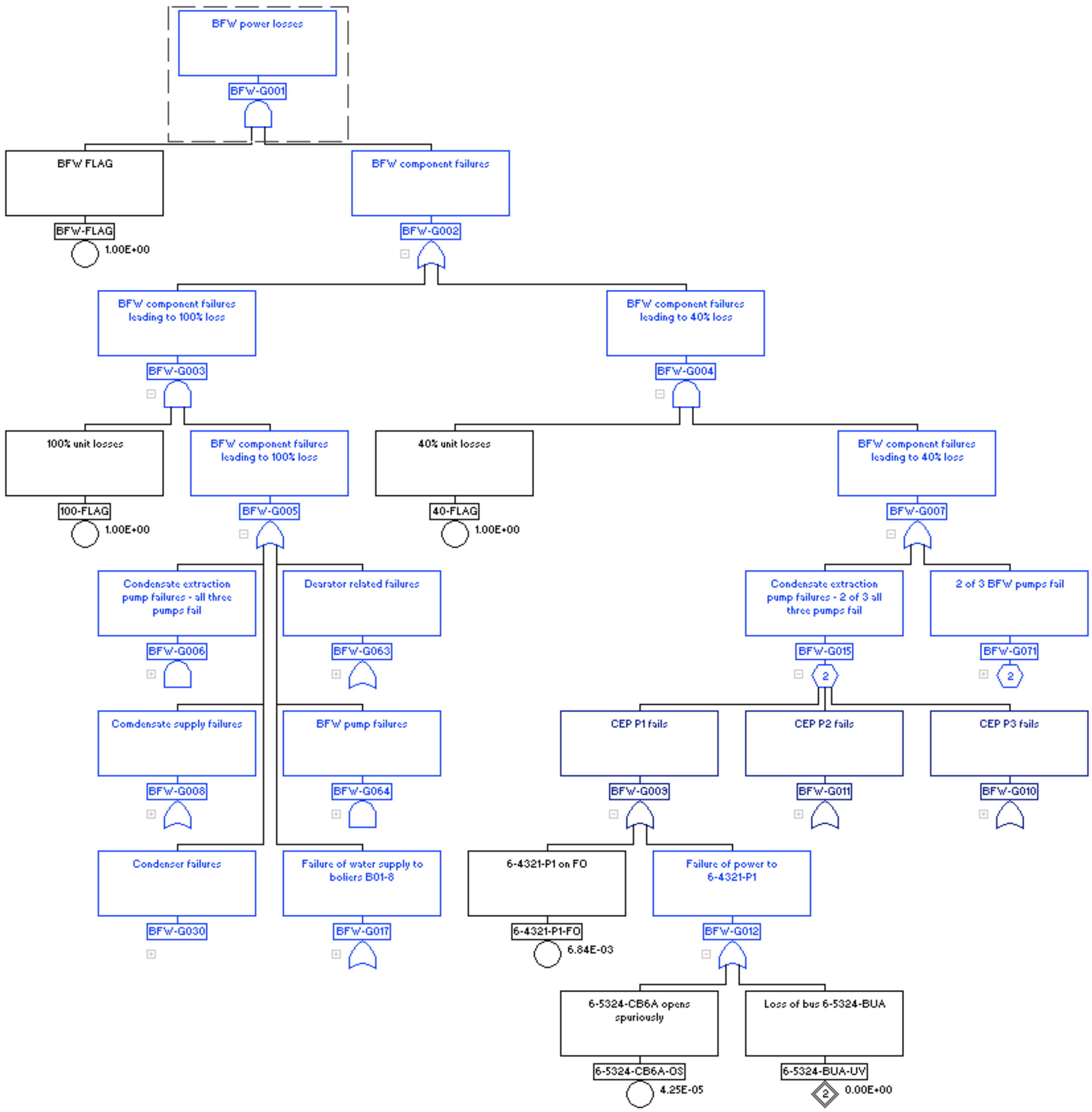

Figure 1: Example of a GRA fault tree

2.4 Component data assignment

There are two main data elements needed for the GRA model, component failure rates and the corresponding restoration times. In additional to these, in some cases, test intervals (TI) of dormant components and the maintenance outage data (i.e., duration and frequency) are also needed.

The sources of the failure rates used in this work comprise production loss history, failure data from the Bruce B Risk Assessment (BBRA) to the extent applicable, expert judgment (i.e., inputs received from the RSEs during review meetings or senior AMEC NSS staff inputs) and generic databases used by other utilities [1, 2] in support of GRA and PRA models. The GRA models were reviewed by experienced NSS staff to detect any data outliers and the data was modified as needed. The RSE judgment on the validity of the assigned data was sought during the RSE review meetings and in a number of instances, revisions were made to the assigned generic data. Due to the limited resources, however, the systematic review of in-plant data sources was not conducted and data assignment was in general based on the expert judgment, BBRA database and the generic data.

The restoration times assigned to the component failures were mainly based on the expert judgment, i.e., inputs from RSEs and the experienced AMEC NSS staff. For the dormant components failures, test intervals were based on the RSE inputs or the Safety System Test (SST) listings. If specific information was not available, test intervals were assumed to be 30 months (i.e., components were assumed to be tested every scheduled outage). The data on maintenance outage duration and frequency were obtained from the RSEs during the review meetings. Used data sources were noted in the CAFTA database and the RSE data inputs were also recorded in the minutes of the RSE review meetings.

2.5 Fault tree post processing

After the FT models were finalized for each system, they were solved using the EPRI tool CAFTA at a truncation level of zero in most cases. Note that for some systems (e.g., SDS1, CSW, WTP, etc.), a higher truncation level (i.e., 1.0E-12) was used due to the large number of insignificant terms (i.e., component failure combinations also known as cutsets) in the CAFTA output files – these files are called cutset files.

The cutset files required some processing as they contained some illegitimate cutsets such as the simultaneous removal from service (for maintenance) of more than one major component. In practice, maintenance does not happen simultaneously on more than one major component. However, in CAFTA, the failure logic for each major component such as a pump has contribution from the maintenance term and the solution of the failure logic leads to terms or cutsets containing maintenance outage of two pumps, which is an illegitimate cutset. The illegitimate cutsets were removed by using the “delete term” feature of the CAFTA tool.

The next step was to remove the redundant cutsets. Redundant cutsets are the component failure combinations that appear more than once in a cutset file but are associated with different power loss states or impairment levels. For example in safety related system, an unrecovered closed failure of either of the two motorized valves leads to a Level 3 impairment of the system thereby leading to a mandatory requirement to reduce unit output. However, closed failure of both MV35 and MV37 results in Level 1 impairment, which, if not recovered within an allowable time, results in the need to trip the reactor as per the licensing requirement. As these motorized valves are normally closed and are supplied from the same power supply, failure of the power supply will fail both valves and thus results in both Level 1 and Level 3 impairments. The cutset with less severe consequence was considered as the redundant cutset hence the power supply failure was removed as a contributor to the power loss state associated with an unrecovered Level 3 impairment. Such redundant cutsets were identified via an MS EXCEL macro and removed by using a CAFTA cutset utility.

3. Model outputs

3.1 GRA model interrogation tool

Using the GRA model, an application tool was created to allow plant staff such as responsible system engineers (RSEs) to use the tool as an aid in making decisions related to plant operation and improvements. The tool was created in MS EXCEL environment and allows users to perform "what if" assessments by changing any of the model input parameters such as component failure rates, restoration times, and maintenance outage duration/frequencies. These assessments can be used in the following applications: prioritizing maintenance activities, assessment of system improvement options, and performing cost benefit assessments in support of project prioritization. The tool allows the end users to quickly assess the impact of any changes in the component reliability/availability on the power output (as measured by the power loss state frequencies and the associated expected lost megawatt hours). A sample output from the tool, as shown below in Table 3, includes listings of the component failure combinations (that result in a power loss state), their frequencies, durations, and the associated power losses expressed in lost megawatt hours.

Frequency	Power Flag	Event 1	Event 2	Duration (hours)	Power Loss Factor	Loss MWH/Yr
Unit Capacity = 825 Megawatts						
7.00E-03	100-FLAG	6-4102-P4-FO		168	1.00	970.07
7.00E-03	100-FLAG	6-4102-P5-FO		168	1.00	970.07
2.75E-02	40-FLAG	6-7121-SC1-FO	SUMMER	48	0.40	435.23
2.75E-02	40-FLAG	6-7121-SC2-FO	SUMMER	48	0.40	435.23
2.75E-02	40-FLAG	6-7121-SC3-FO	SUMMER	48	0.40	435.23
3.33E-03	100-FLAG	6-4115-RV1-OS		120	1.00	329.86
3.33E-03	100-FLAG	6-4115-RV2-OS		120	1.00	329.86
9.59E-02	3-FLAG	6-7121-P1-FO	SUMMER	130	0.03	308.70
9.59E-02	3-FLAG	6-7121-P2-FO	SUMMER	130	0.03	308.70
9.59E-02	3-FLAG	6-7121-P3-FO	SUMMER	130	0.03	308.70

Table 3: Sample Output from GRA Interrogation Tool

The fields from the output file are defined below:

Frequency: Represents cutset frequency or the frequency of combination of component failures that can lead to a power loss state.

Power Flag: Indicates the power loss associated with the cutset.

Event 1, Event 2, …: Represent the component failures in a given cutset.

Duration (hours): Represents the duration of the failed component(s) in hours.

Power Loss Factor: Represents the level of power loss. A value of 1 represents the unit trip and a value of 0.xx represents xx% reduction in the unit output.

Lost MWH/Yr: Represents the expected lost megawatt hours per year.

The tool allows the users to change reliability/availability parameters pertaining to any of the components in the GRA model via a user friendly interface in MS EXCEL format. The results of those changes on the output parameters is recalculated by the tool and presented in the format as shown in Table 3.

3.2 Forced loss rate (FLR) calculation

The Force Loss Rate (FLR) is an important output from the GRA model as it can be used for the planning and power marketing operations. FLR is defined as the ratio of all unplanned forced energy losses during a given period of time to the reference energy generation minus energy generation losses corresponding to planned outages and any unplanned outage extensions of planned outages, during the same period, expressed as a percentage.

Thus, the FLR is calculated as

$$\text{FLR Value for a unit (\%)} = \frac{FEL}{REG-(PEL+OEL)}\times 100\% \tag{1}$$

where FEL = unplanned forced energy losses
REG = reference energy generation
PEL = planned energy losses
OEL = unplanned outage extension energy losses value for the industry
= median of the unit values

FEL, expressed as lost megawatt hours, is obtained from the GRA model.

For Bruce NGS B, one unit energy production is 825 MW, and thus for a given year period, the reference energy generation is:

REG = 825 MW × (8760 H/yr) = 7.227E+6 MWH/yr.

Assuming that the planned outage plus the unplanned outage extension is combined to 15 days per year, the term PEL+OEL is equal to:

PEL+OEL = 825 MW × 15 D × (24 H/D) = 2.97E+5 MWH.

Using the results above, FLR can be easily calculated by running the baseline GRA model and summing the power loss contributions for the plant as estimated by the GRA Model Interrogation Tool discussed above in Section 3.1.

4. Future activities

Bruce Power is planning to implement GRA as a decision making tool. 2011 GRA implementation activities include a pilot implementation of GRA via the use of a dedicated GRA specialist at the Bruce B station. The GRA specialist will identify and implement the GRA model changes and the related post-processing necessary for the real time production risk monitoring at Bruce B. This work will also involve developing appropriate indicators for the production risk monitoring. Another key GRA implementation activity will be to identify the plant interfaces with the GRA model to allow its use as a decision making tool and then develop specifications for the tools needed to integrate those interfaces with the model.

5. Conclusion

Bruce Power along with South Texas Project has taken the lead in developing and using GRA model in support of plant decision making. Although, Bruce B model development activity is essentially complete, a lot of work still needs to be done to establish GRA as a decision making tool. If the pilot GRA pilot implementation is successful, it is expected that GRA will become an integral part of decision-making at Bruce Power in the next few years.

6. References

[1] U.S. Nuclear Regulatory Commission, “Industry-Average Performance for Components and Initiating Events at U.S. Commercial Nuclear Power Plants”, File # NUREG/CR-6928, Feb. 2007.

[2] Westinghouse Savannah River Company, “Savannah River Site Generic Data Base Development”, File # WSRC-TR-93-262, Rev. 1, May 1998.