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Third Party Review of PRAISE-CANDU Probabilistic Fracture Mechanics Code

Martec Technical Report #TR-15-09
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EXECUTIVE SUMMARY

The report is a review of the documents generated as part of a probabilistic fracture mechanics code and is entitled "Third Party Review of PRAISE-CANDU Probabilistic Fracture Mechanics Code" by Lloyds Register Martec for the Canadian Nuclear Safety Commission. The objective of the work is to provide an independent third-party evaluation of the PRAISE-CANDU Probabilistic Fracture Mechanics (PFM) code development process carried out for the Composite Analytical Approach to address Large Break Loss of Coolant Accident safety margins. The scope of work involves technical evaluation of the CANDU Owner's Group (COG) reports on PRAISE-CANDU in order to address and offer recommendations on the suitability and adequacy of the PFM code degradation models, the validation and verification (V&V) and benchmarking activities and the probabilistic simulation and uncertainty analyses techniques. In addition, a literature review of the acceptance of PFM codes in regulatory decision making in other countries is covered.

An exhaustive literature review indicates that PFM is used to assess the structural integrity of two components, the reactor pressure vessels (RPV) and the piping systems, as a part of risk informed decision making (RIDM), along with expert opinions, engineering judgement and experience. The most active country at the regulatory and operational levels is the USA, with a large involvement of the United States Nuclear Safety Commission, (USNRC) and the US nuclear industry. In the area of piping systems, the literature review indicates that over the years, USNRC has sponsored the development of several PFM codes. Currently USNRC, along with industry partners is developing a PFM tool, xLPR that may be used to certify the leak before break (LBB) extremely low probability of failure of piping systems due to active corrosion damage, such as primary water stress corrosion cracking (PWSCC).

Regulators from two countries, USA and Sweden, responded to a questionnaire that was developed and administered on the application of PFM in NPP. Feedback from USNRC regulators indicate that there are two regulations that involve the use of probabilistic insights, four areas being investigated which could lead to the adoption or probabilistic insights into other regulations and eight licensing decisions based upon current regulations. The two regulations are 10CFR 50.61, titled "Fracture Toughness Requirements for Protection Against Pressurized Thermal Shock Events", and 10CFR 50.61a, titled "Alternate Fracture Toughness Requirements for Protection Against Pressurized Thermal Shock Events". These regulations were formulated using PFM as part of RIDM with input from expert opinion (acceptance criteria), engineering analyses and operational experience (PRA event sequence and thermal hydraulic analyses etc.). Two licensing decisions have been made in Sweden with probabilistic insights. Other countries are active on PFM in NPP, including Canada, Japan, UK, South Korea, Czech Republic and Spain. Several probabilistic fracture mechanics tools are identified and summarised.

Six COG reports on PRAISE-CANDU were reviewed individually, including the Specification, the Theory Manual, the Verification and Validation (V &V) and the Pilot Study reports. For ease of presentation, traceability and tracking each document was reviewed using its sectional outline. For a given section, an overview of the section, the strengths and suggestions for improving the report were summarised.

Based on our review, we conclude that the basic software plan is sound. The standard selected, CSA N286.7-99, when properly followed would lead to a great product. In addition, independence between the developer and the verifier is part of the plan and the software developer is familiar with both the nuclear industry and PFM. There is provision for tracking, documentation, verification and validation within the plan. It is recommended that a higher level of transparency needs to be in place for tracking and documenting errors during the software development.

The deterministic models –structural, loads, damage, strength- in PRAISE-CANDU are up to date, and should be adequate for assessing the structural integrity of most CANDU piping systems when the shortcomings identified in the report are adequately addressed. The damage models considered, fatigue and stress corrosion crack initiations and growth, and FAC, cover the major damage categories in CANDU piping systems. Nuclear piping loads modeling capability is broad and includes normal and transient service loads, deadweight, environmental loads, seismic, vibratory and weld residual stresses. In keeping with CSA- N286.7-99 requirements, most of the model assumptions, sources, methods, and limitations are identified and explained. The major deterministic modelling shortcomings that need addressing in the COG reports are completeness, documentation, justifications, explanations and guidance for users. Frequent reference made to information or models in WINPRAISE 07 without fleshing out the details in the COG reports need to be corrected. Because deterministic models have bias that could impact the accuracy of the results, discussions on bias need to be provided. There are many instances where the user is expected to stipulate parameters, to ensure consistent results from different users a guidance document needs to be developed. Several assumptions and default values need to be clearly defined and explained.

Detailed presentation need to be provided on several load related terms and their implementation, including primary loads, secondary loads, load combinations and load sequence for multiple loads to ensure consistent results. Distinction between secondary and primary loads and their implementations, load variables for dissimilar metals welds, E_{ab}, T_a, T_b, α_a, α_b, the accuracy of the residual stresses treatment for large diameter pipes need more detailed discussions. Diagram showing the weld configurations is needed to clarify the formula and symbols used to compute the peak stresses. Guidance need to be provided on the appropriate set of stress indices (Ci, Ki) in the ASME Equation used for the peak stresses. For consistency, detail definition of the stresses for initiation of fatigue crack, accounting for spatial variations and environmental differences between transient types, should be provided in the COG Theory Manual. Discussions should be given on the implications of ignoring residual stresses on crack opening areas.

Other deterministic modelling issues that need to be attended to are: the stress intensity factor solutions in API 579/ASME FFS-1 (2007) in PRAISE-CANDU are derived for values up to $\alpha = 0.8$. However in PRAISE-CANDU the stress intensity factor solutions at $\alpha = 0.8$ are used for $\alpha > 0.8$, justifications should be provided for using values of crack tip stress intensity factor beyond the limit of their intended application. Also, justification for adapting independent tensile and bending part-wall cracks solutions for combined tensile and bending situations, and the suitability of the Romberg-Osgood model when employed for dissimilar metal welds. Solutions for axial flaws are not modeled, but are possible, for example the transition of crack growth by PWSCC.

Guidance needs to be provided on the limit of application of the hard-wired, stipulated, fixed fatigue crack initiation models from Argonne National Laboratory to PRAISE-CANDU. The concepts of heat-to-heat and within-heat, which have a large influence on break probabilities, are introduced but not well explained. Other issues that need addressing include, inclusion of the bivariate interpolation scheme (equations) and the hard-wired tabular numbers for fatigue crack growth rate in the COG report, separate presentation on the stability criteria for part-through and through-wall cracks, documentation of the mathematical formulas (equations) associated with the net-section and tearing instability, guidance on the material properties used for dissimilar metal welds stability assessment. Guidelines should be provided on how to determine the appropriate thinning rates for FAC. Clarification should be given on the analysis sequence in cases of combined FAC, fatigue and stress corrosion cracking. Conservatism or lack therefore in the current FAC model (uniform thinning rate) vs localised model should be discussed.

The probabilistic models in PRAISE-CANDU are current and versatile and will be adequate for analysis provided the above deterministic shortcomings and the shortcomings identified with the probabilistic models are addressed. The main probabilistic features are the description of scatter in some input parameters as either aleatory or epistemic random variables (mean values, standard deviation, probability distribution), and the Monte Carlo simulation capability. The probability distributions are based on data, engineering judgement and/or experience. The contributors to randomness offer potential benefits when used in PFM. The epistemic uncertainty capability provides a rational and systematic basis for incorporating incomplete or inadequate knowledge. The statistics of failure probabilities (mean, standard deviation, median, and quartile) derived from epistemic runs allows for introduction of a graded scale of conservatism into the decision making process. The probabilistic modelling issues that need to be tackled in PRAISE-CANDU deal with completeness, documentation, justifications and explanations. From a review of the COG reports, it is not clear how model uncertainties, that arise from the use of simplified models to speed up computation, and could result in deterministic predictions that are slightly different from the more elaborate models or experimental tests or operational results, are handled. The rational for limiting the number of probability distributions to two-six parameters distribution and correlation to only normal and lognormal distributions, should be provided. In addition, other probabilistic model issues that need addressing are: the provisions for calibrating distributed parameters based on measured in-service or experimental data and determining the most suitable distributions for parameters among several alternative distributions based on measured in-service or experimental data; the minimum number of data points needed to consider a parameter a random variable. Because a user specified cut-off below which life time calculation should not be performed has the potential to influence the results of analyses and the distinction between the within-heat and heat-to-heat has a strong influence on the results, detailed discussions and models on the scheme for speeding up calculations on break probabilities for cases with multiple initiating cracks and the variances of heat-to-heat and within-heat should be provided to ensure consistency of results from multiple users.

Verification and validation activities are used to demonstrate that the as-built software meets its requirements, as described in the theory manual and user's guide. Verification is essentially an error check to see if the right equation is solved in the computer code. Validation is used to checks if the model equation is an accurate representation of the real system. The standards used for the verification and validation exercise, CSA N286.7-99 and CANDU Energy Standard Quality Assurance, are of high quality and when correctly implemented can result in a great product. Sixteen broad tasks to be executed for verification and validation are stipulated in the Specification report. Most of the tasks were carried out and documented to some extent in the Verification and Validation report. Documentations and/or executions on a few tasks are missing, including the load module verification on transformation of bending moments, pressures and temperatures to stresses; the multi-dimensional interpolation and the tables for the crack-tip stress intensity factor; the check on the tearing instability for part-through and through-wall cracks and net section stress; and the unit verification using both SI units and customary Imperials units. With regard to the implementation of verification and validation plan, the independence of the developers and the verifiers should be addressed because it is difficult to judge from a review of the COG V & V reports.

A review of the Verification and Validation report shows that the adequacy and completeness of the both the verification and validation exercises, especially the documentation, have major shortcomings that need to be addressed. The definition of the acceptance criteria and the four-step approach for documenting the verification and validation activities, test plan, test implementation, test results and summary, are reasonable. However, detailed discussion on test implementation is incomplete for most test cases. The level of detail provided will not allow for an independent exercise to be carried out. In some cases, the main information offered is a reference to verification and validation file folder packages where inputs and results are stored. Many test plans do not have clear statements, define too many models, and do not identify the means or tools for verification. Many test implementations and results do not provide problem statements, method used, the input parameters, assumptions, even the results, and the discussions of the result.

The items that need to be included in the validation and verification report documentation to improve its quality are: (i) the write-up in each test case should focus on only one model, analytical equation, logic, etc. Putting multiple models into one test case creates difficulty with assessing the item being verified; (ii) a clear written statement of the test plan should be included and in cases where more than one model is tested the test plan for each model should be clearly stated; (iii) for each test case, a clear definition of the problem statement or objective, the section of the theory manual and the equations being verified, the tool/s used for testing or verification, the acceptance criteria, a description of the input parameters (for example list of parameters and units), a brief description and discussion of the results/outputs (for example list or plots etc.), need to be presented in the validation and verification report itself, in addition to information that can be used to identify file folders and tags where additional information can be obtained; (iv) Since PRAISE CANDU 1.0 covers both imperial and SI unit, for completeness, the test cases involving equations should include both units; (v) a brief discussion should be provided for each test case to justify the correctness or lack thereof of the test results; (vi) cases where the results are not correct should be documented within the COG V & V report for tracking of corrections in future versions of the software; and (vii) whenever possible, to minimise verification error more than one independent verifier should be used to create, verify and compare the results of the models verification.

The validation documentation, centered on using benchmarking exercises to compare PRAISE-CANDU results to other similar PFM tools and operating experience, do not have enough information for a meaningful assessment. Several benchmark case studies, executed using PRAISE-CANDU, documented in other reports, need to be included in the COG V & V report. PRAISE-CANDU results when compared with other NURBM tools are not bounding for large pipes. As this is the target application, it requires explanation. The section on validation that compares PRAISE-CANDU with operating experience is incomplete. Along with detailed documentation of reported work, the test plans on Canadian OPEX that were deemed essential but no carried out due to budget and scheduled constraint should be executed. It is not obvious how one can claim that "*PRAISE - CANDU 1.0 meets the V&V requirements*" when only one OPEX case was assessed. The scope of the validation exercises needs to be expanded to include other databases, such as Pipe fracture database, IPIRG database and OPDE database.

A more complete pilot report that covers all the damage models in PRAISE-CANDU should be executed. For completeness, extensive sensitivity studies have to be a part of the COG Pilot study to strengthen the conclusions that are drawn. This is especially true since some of the uncertainties and models are not directly derived from the CANDU plants at Pickering. Because there are many instances where the user is expected to stipulate parameters, a guidance document for the end-users needs to be developed.

A review of industry responses to CNSC staff comments and questions concerning PRAISE-CANDU development activities, which were raised prior to the preparation of the final PRAISE-CANDU documentation, indicated that the follow-up and conclusions were reasonable. A few shortcomings in the COG answers that need to be addressed are identified.

Using extensive literature review of international studies, the COG recommends break opening models for axial and circumferential flaws in large-diameter CANDU PHTS piping. For axial breaks, it is recommended that the initial break develops to a size of 7% of the flow area of the pipe in 5 ms. The recommendation for circumferential breaks is that the initial break develops to a size of 3.5% of the flow area of the pipe in 5 ms, followed by an increase in the size of the break to 200% of the flow area of the pipe in an unspecified long-length of time that would depend on the dynamics of the piping system but that would be in excess of 2.5 s. The proposed models, which are based mostly on literature review of studies that do not involve large CANDU PHTS piping directly, deviate from international practice and do not have precedence. They will involve significant changes in break-opening time philosophy for large CANDU PHTS piping. To ensure safety, the proposed models need to be justified and substantiated through detailed studies of typical CANDU plants. Conclusions based solely on literature review are not adequate.

It is recommended that the CNSC should initiate independent PFM studies, starting with some of the models in PRAISE-CANDU and others, so that it can be better prepared if/when it has to make licencing and regulatory decisions on the subject.

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1.0 INTRODUCTION

1.1 INTRODUCTION AND MOTIVATION FOR THE STUDY

Nuclear power plant (NPP) owners and operators are granted operating licences for a finite period of time. The Canadian Nuclear Safety Commission (CNSC), which is the nuclear regulatory body in Canada, makes decisions to grant licences based, among other things, on the satisfaction that licensees' operations are safe and are in conformity with set regulations, design codes and standards of practice. In order for the CNSC to make rational and consistent decisions regarding the fitness-for-service and life extension of existing NPPs without compromising safety and without imposing undue risk to the health, safety and security of Canadians and the environment, it is essential that formal procedures and guidelines be developed in aiding the decision process licensee submissions be reviewed carefully to confirm adequacy and completeness.

The CANDU industry has asserted that small safety margins associated with the analysis of a Large Break Loss of Coolant Accident (LBLOCA) as a Design Basis Accident (DBA) can be attributed to excess conservatism in the Traditional Safety Analysis (TSA) evaluation procedure. In the traditional approach, it is assumed that pipe breaks develop instantaneously irrespective of the break size or discharge area, and that the maximum break discharge area is twice the pipe cross-sectional area. Industry has presented its case that the expected frequency of large pipe breaks is much lower than the assumed frequency attributed to DBAs. To support its position, industry undertook a CANDU Owners Group (COG) project to develop a Composite Analytical Approach (CAA) to characterize, demonstrate and reduce conservatism in TSA for LBLOCA scenarios.

One element of the CAA involved the development of a Probabilistic Fracture Mechanics (PFM) code, PRAISE-CANDU, to generate estimates of the frequency of primary system pipe failures which would lead to LOCAs. One of the intended functions of this code is to provide estimates of failure frequencies for piping of different sizes to identify which failures are expected to occur at frequencies lower than $1x10^{-5}$ per year, which would support their reclassification to Beyond Design Basis Accidents (BDBAs). In theory a double-ended guillotine failure of large diameter piping, which would stress safety systems and challenge post-accident fuel cooling, is far less probable than the failure of small diameter piping.

The concept of PFM is not new, but its application to nuclear piping systems has been approached with caution. The level of uncertainty associated with modelling parameters, lack of documentation, quality assurance control during software development and the variability in results achieved from different PFM codes have resulted in limited acceptance of PFM codes for regulatory decision making. There is an inherent difficulty in acceptance of PFM code given the complexity of some of the piping degradation mechanisms which may lead to a LOCA and the fact that no operational data exists for these low frequency events, thereby, making validation of code results difficult.

1.2 OBJECTIVES AND SCOPE OF PROPOSED STUDY

The objective of the study is to obtain an independent third-party evaluation of the PRAISE-CANDU Probabilistic Fracture Mechanics code development process carried out for the Composite Analytical Approach to address Large Break Loss of Coolant Accident safety margins.

The scope of work involves technical evaluation of the CANDU Owner's Group (COG) reports prepared during the development of PRAISE-CANDU to provide an independent evaluation of:

- the suitability of the PFM code degradation models to assess pipe failure frequencies due to plausible CANDU specific degradation mechanisms;
- a comparison of the PRAISE-CANDU validation and verification (V&V) and benchmarking activities to public domain information describing validation and verification and benchmarking of other PFM codes, for example (but not necessarily limited to) PRO-LOCA, PASCAL, NURBIT, ProSACC, PRODIGAL and PROST;
- the extent to which PFM codes have been accepted in regulatory decision making in the United States, Europe and Japan;
- limitations of the probabilistic simulation techniques within PRAISE-CANDU; and

- limitations of the uncertainty analysis techniques used for PRAISE-CANDU.

The four tasks defined, to achieve the objectives and the scope of work, are:

- A literature review on current level of acceptance of PFM codes in nuclear regulatory decisions;
- A review of the COG Reports generated during the development of the PRAISE-CANDU code;
- A review of CNSC staff comments on the development of PRAISE-CANDU code and the adequacy of developer response; and
- Identification of potential gaps in the code verification, validation and benchmarking activities

1.3 ORGANIZATION OF THIS DOCUMENT

The remainder of this document is organized as follows:

- Chapter 2 presents the literature search methodology employed and a review of existing probabilistic fracture mechanics models for nuclear power plants components
- Chapter 3 provides the positions of various countries on the use of probabilistic fracture mechanics models for nuclear power plant regulatory decisions;
- The basic issues considered when reviewing the six COG reports and a summary of the findings are presented in Chapter 4 and Chapter 5, respectively.
- Detailed review of the COG Reports generated during the development of the PRAISE-CANDU code is given in Chapter 6 to Chapter 11;
- Chapter 12 summarizes a review of the CNSC staff comments on the development of PRAISE-CANDU code and the adequacy of developer' response; and
- Summaries, conclusions and recommendations are discussed in Chapter 13.

2.0 LITERATURE REVIEW ON PROBABILISTIC FRACTURE MECHANICS CODES

2.1 INTRODUCTION AND METHODOLOGY

Research, development and regulations relevant to the structural integrity of nuclear power plants and components have been taking place since the advent of nuclear facilities. Activities include programs at nuclear laboratories, material laboratories and regulatory agencies in many countries worldwide. These have resulted in the publication of numerous literature in various journals, conferences and internal reports. While some of these publications are proprietary and not publicly available, others are electronically listed in various comprehensive bibliographic databases such as COMPENDEX and Applied Science, Technology Index, National Technical Information Service (NTIS) and the NRC ADAMS Public Records System and Public Legacy Databases.

An exhaustive search on studies, articles, reports, documents and publications on applications and regulations of probabilistic fracture mechanics, (PFM), and structural reliability methods (SRM), to nuclear power plants, (NPP), was conducted using keywords, search engines and databases. Internet search engines such as Google, Yahoo, and MSN, along with Dalhousie University databases such as Science Direct, COMPENDEX, and Applied Science and Technology Index were used to collect information on related work in other countries and organizations. Relevant documents and reports were downloaded from the web sites of several nuclear regulatory safety and research organizations, including Canadian Nuclear Safety Commission (CNSC), International Atomic Energy Agency (IAEA), United States Nuclear Regulatory Commission (USNRC), Atomic Energy Canada Limited (AECL), NEA, NEI, EPRI, and European Commission Joint Research Center (JRC). Journal and conference articles were obtained through/from Dalhousie University library. Search was also conducted on the NRC ADAMS Public Records System.

Many keywords, phrases and combinations were used in the search process including the following:

- Probabilistic fracture mechanics and NPP

- Structural reliability analysis and NPP
- Risk informed methods and NPP
- Risk informed regulations and NPP
- Probabilistic methods and NPP
- Probabilistic safety analysis and NPP
- Nuclear regulations on risk informed inspections
- Nuclear regulations on leak before break
- Probabilistic leak before break
- Nuclear regulations on reactor pressure vessels and piping systems

A large number of publications were identified with the open literature search. The publications that are referenced in the report are listed in the reference section and a bibliography on other related materials, which are not necessarily cited in the body of the report, is included. We browsed through all the documents and reviewed in detail the reports and articles that are most relevant to the current literature review.

A questionnaire was developed and administered. The findings from the survey are incorporated into the review.

The search results have revealed that in nuclear power plant operations and regulations, probabilistic fracture mechanics is used to assess the structural integrity of two main systems, the reactor pressure vessels (RPV), under the pressurized thermal shocks (PTS), and the piping system to ensure that existing degradation, if any, is acceptable for continued operation or leak before break.

Based on a workshop conducted on structural reliability and probabilistic fracture mechanics in the nuclear industry (NEA, 2008), the most active country in the area of probabilistic fracture mechanics, at both regulatory and operational level, is the USA, with a large involvement of USNRC in research and US nuclear industry. Therefore, it is expected that USNRC will also have the most tools and regulations relevant to the application of probabilistic fracture mechanics. A few other countries are also active in this area, including

Sweden, Canada, Japan, UK, South Korea, Czech Republic and Spain. A summary is presented of the probabilistic fracture mechanics tools that have been developed and applied in the nuclear industry.

2.2 PRESSURE VESSEL TOOLS

The integrity of the reactor pressure vessel has to be maintained throughout the plant life since there are no feasible provisions which would mitigate a catastrophic vessel failure. The reactor pressure vessel integrity is ensured by a margin between its load bearing capacity, given by vessel design and material properties, and the acting loads, which could occur during the plant operation. The material properties are subject to degradation during operation by neutron irradiation, fatigue, thermal ageing and other mechanisms, which reduce the resistance of the vessel against brittle fracture. The load normally considered in the vessel integrity assessment is from the pressurized thermal shock (PTS), characterized by rapid cool-down in the primary coolant system usually with high level of primary system pressure. A list of pressure vessel tools by country of origin is given in Table 1. Brief summaries of these probabilistic fracture mechanics tools are presented below.

Table 1: Summary of Some PFM Pressure Vessel Codes

Software	Country	PFM-Method	References
FAVOR	USA	Monte Carlo Simulation	William et al., 2012, Dickson et al, 2012, 2004; EricksonKirk et al. 2007, 2010, Erikson and Dickson, 2010, Simonen et al., 2013
VISA-II	USA	Monte Carlo Simulation	Simonen et al, 1986
OCA-P	USA	Monte Carlo Simulation	Cheverton and Ball, 1984
VIPER	USA	Monte Carlo Simulation	Tang et al., 1999
PASCAL	JAPAN	Importance Sampling, Stratified Monte Carlo Simulation	Onizawa and Itoh, 2009

2.2.1 Pressure Vessel Tools in USA

Several pressure vessel tools have been developed by the USNRC. The discussion in this section begins with the most recent tool followed by the predecessors.

2.2.1.1 FAVOR

FAVOR, **F**racture **A**nalysis of **V**essels **– O**ak **R**idge is a probabilistic fracture mechanics code for structural integrity of a nuclear reactor pressure vessel (RPV) subjected to a range of thermal-hydraulic events. FAVOR combines and improves on the features of earlier codes, OCA-P and VISA-II. It was developed for the beltline region of the RPV wall and can be used to analyse pressurized-thermal shock (PTS) events and normal planned reactor operational transients, such as start-up, and cool-down. Over the years, various versions of FAVOR have been developed and the current version is 12.1. Some of the major features of FAVOR include: detailed flaw-characterization distributions, neutron fluence maps, warm-prestressing effects, temperature-dependencies in the thermo-elastic properties of base and cladding, crack-face pressure loading for internal surface-breaking flaws, ductile-fracture model simulating stable and unstable ductile tearing, embrittlement trend correlations, incorporation of multiple transients, fracture-toughness models based on extended databases and improved statistical distributions. FAVOR uses Monte Carlo Simulation (MCS) techniques for its PFM.

2.2.1.2 VISA-II

VISA-II (**V**essel **I**ntegrity **S**imulation **A**nalysis) is an earlier PFM tool that was developed by the USNRC to estimate the failure probability of failure of nuclear reactor pressure vessels under pressurized thermal shock conditions. It has both deterministic and probabilistic capabilities. The deterministic portion of the code has capability for heat transfer, stress, and fracture mechanics calculations for a vessel subjected to a user-specified temperature and pressure transient. VISA-II uses Monte Carlo simulation for the probabilistic assessment. The random variable parameters include initial crack size and position, copper and nickel content, fluence, and the fracture toughness values for crack initiation and arrest. Like OCA-P, linear elastic fracture mechanics methods are used to model crack initiation and growth.

2.2.1.3 OCA-P

OCA-P is also an earlier PFM tool that was developed by USNRC specifically for evaluating the integrity of pressurized-water reactor vessels subjected to overcooling-accident loading conditions. It uses linear-elastic fracture mechanics and has two- and limited three-dimensional flaw capabilities. Both deterministic and probabilistic analyses can be performed with OCA-P. For deterministic analysis, OCA-P can be used to determine critical values of the fluence and the nil-ductility reference temperature corresponding to incipient initiation of the initial flaw. The probabilistic portion of OCA-P uses Monte Carlo techniques, and simulated parameters include fluence, flaw depth, fracture toughness, nil-ductility reference temperature, and concentrations of copper, nickel, and phosphorous. Plotting capabilities include the construction of critical-crack-depth diagrams (deterministic analysis) and a variety of histograms (probabilistic analysis). OAC-P accepts as input the reactor primary system pressure and the reactor pressure-vessel downcomer coolant temperature, as functions of time in the specified transient.

2.2.1.4 VIPER

Another probabilistic fracture mechanics code, VIPER, was developed to address issues specifically related to welds in boiling water reactor vessels. This code also uses Monte Carlo approach and the fracture mechanics model is similar to those used in the VISA-II and FAVOR codes. VIPER has modelling features for weld residual stresses, crack initiation and growth by stress corrosion mechanisms.

2.2.2 Pressure Vessel Tools in Other Countries

2.2.2.1 PASCAL

PASCAL, (**P**robabilistic **A**nalysis of **S**tructural **C**omponents in **A**ging **L**WR), is a PFM code for evaluating the failure probability of aged pressure components. It is developed as a part of the Japan Atomic Energy Agency, JAERI's, research program on aging and structural integrity of Light Water Reactors (LWR) components. PASCAL can be used for PFM analysis of RPV as well as other components. PASCAL features include elasto-plastic fracture and fracture transition from brittle to ductile tearing analysis based on R6 method. The program has capability for analyzing the initial flaw of an infinite edge crack and a semi-elliptical crack, an approximate method to evaluate the influence of overlay cladding, ability to evaluate the effect of WPS and capability to evaluate the effect of embrittlement recovery by thermal annealing of a vessel. PASCAL uses importance sampling and stratified sampling in the Monte Carlo simulation.

2.3 PIPING TOOLS

PFM tools have also been developed and used to assess the integrity of piping system in NPP. The two complementary objectives that are usually pursued in piping structural integrity assessment are:

- Risk Informed In-service Inspection; and
- Leak Before Break (including LBLOCA re-definition)

Table 2 is a summary of some of the publicly discussed PFM piping tools from various countries. A discussion of some of the tools is also given in this section.

Table 2: A Summary of Some PFM Piping Codes

PFM	Developer	Degradation Mechanism	Analysis Method	References
xLPR	USA	Fatigue, SCC	Monte Carlo Simulation	Kurth et al. (2012), Rudland and Harrington (2012)
NURBIT	Sweden	SCC, pre-existing crack (non-growing) in piping components,	Monte Carlo Simulation	Guedri et al (2012), Simola et al. (2009), Brickstad et al (2004), Brickstad and Zang (2001)
ProSACC	Sweden	SCC, Fatigue, pre-existing crack (non-growing) in general components	Monte Carlo Simulation	Simola et al. (2009), Dillström et al (2008), Dillstrom (2003), Brickstad et al (2004)
PRO-LOCA	USA	Fatigue, SCC	Monte Carlo Simulation	Kurth et al. (2012), Scott et al. (2010), NUREG/CR-6936 (2011), Rudland et al. (2002) , PNNL-16625 (2007),
PROST	Germany	Fatigue, cylindrical components	Monte Carlo Simulation	Brickstad et al (2004)
PRODIGAL	UK	Fatigue, or pre-existing cracks in different components	Monte Carlo Simulation	Bell and Chapman (2003), Brickstad et al (2004)
PRAISE WinPRAISE pcPRAISE	USA	Fatigue, SCC in piping	Monte Carlo Simulation	Guedri et al (2012), NUREG/CR-6936 (2011), Harris and Dedhia (1998), Scott et al. (2010) PNNL-16625 (2007)

PFM	Developer	Degradation Mechanism	Analysis Method	References
				(Harris et al. 1981, 1986; Harris and Dedhia 1992) (Harris and Dedhia 1992, 1998) (Khaleel et al. 2000) (Khaleel and Simonen 1994a, 1994b; Khaleel et al. 1995; Simonen et al. 1998; Simonen and Khaleel 1998a, 1998b, Khaleel et al. 2000). (Gosselin et al. 2005), (Khaleel and Simonen, 2009)
PASCAL-SP	Japan	SCC in piping	Monte Carlo Simulation	Itoh et al (2012), Maeda et al (2009)
PASCAL-SC, EQ, EC	Japan	SCC, Fatigue Crack, Wall Thinning	Monte Carlo Simulation	Maeda et al (2009)
PEPPER	Japan	Fatigue, SCC, Creep and Wall Thinning	Monte Carlo Simulation	Maeda et al (2009)
PRAISE-JNES	Japan	SCC in piping	Monte Carlo Simulation	Itoh et al (2012),
PINEP-PWSCC	South Korea	PWSCC	Monte Carlo Simulation	Hong et al. (21012)
SRRA	USA	Fatigue, SCC, FAC	Monte Carlo Simulation	Bishop, 1997, 1999, Cronvol et al, 2006
VTTBESIT	Finland	Fatigue, SCC	Monte Carlo Simulation	Simola et al (2009)
WinPRAISE07	Spain	PWSCC	Monte Carlo Simulation	Cueto-Felgueroso C, 2007

2.3.1 Piping Tools in USA

2.3.1.1 xLPR

xLPR (e**X**tremely **L**ow **P**robability of **R**upture), is a probabilistic fracture mechanics tool being developed by USNRC in conjunction with EPRI as a means of demonstrating compliance with 10 CFR50 Appendix A, General Design Criterion 4 (GDC-4) requirement that primary piping exhibit an extremely low probability of rupture. It has a modular architecture and relies on the physics and fracture mechanics models developed in several legacy codes, including PRAISE and PRO-LOCA. 10 CFR50, Appendix A, General Design Criteria (GDC) 4 states, in part, that the dynamic effects associated with postulated reactor coolant system pipe ruptures may be excluded from the design basis when analyses reviewed and approved by the NRC demonstrate that the probability of fluid system piping rupture is extremely low under conditions consistent with the design basis. The NRC Standard Review Plan (SRP) 3.6.3 NUREG-0800, (2007) describes deterministic LBB assessment procedures that have been used to demonstrate compliance with the GDC-4 requirement. However, SRP 3.6.3 does not allow for assessment of piping systems with active degradation mechanisms, such as primary water stress corrosion cracking, PWSCC, which is currently occurring in main coolant piping systems that have been granted LBB exemptions in many United States PWR (Pressurized Water Reactor) plants. The purpose of the xLPR project is to develop a qualified probabilistic assessment tool, i.e., PFM code xLPR, to quantitatively assess compliance to the requirements of GDC-4 for piping systems subject to PWSCC.

2.3.1.2 PRO-LOCA

The PFM based code, PRO-LOCA, is a tool for predicting break probabilities for loss-of-coolant-accidents (LOCAs) in NPP piping systems. The USNRC began the development of PRO-LOCA in 2003 so that they can adopt and apply advances in fracture mechanics models, and thereby provide a successor to the PRAISE code. The need for an improved probabilistic fracture mechanics code became evident during an expert elicitation process funded by the NRC (Tregoning et al. 2005) to establish estimates of LOCA frequencies along with quantification of the uncertainties in the estimates. The PRO-LOCA code addresses the failure mechanisms associated with both pre-existing cracks and service induced cracks. Fatigue, intergranular SCC (IGSCC) and primary water SCC (PWSCC) are incorporated into PRO-LOCA. Other capabilities are in the areas of leak rate predictions and the prediction of critical/unstable crack sizes. PRO-LOCA has also incorporated an improved basis for simulating weld residual stress (WRS) distributions.

The MERIT (Maximizing Enhancements in Risk-Informed Technology) program was a 3 year international collaborative research program whose main objective was the further development of the PRO-LOCA probabilistic fracture mechanics (PFM) code. The membership in MERIT included the USNRC, the Electric Power Research Institute (EPRI), SSM in Sweden, Rolls Royce in the United Kingdom, a consortium of interests in Canada, and a consortium of interests in South Korea. The PRO-LOCA PFM code was originally developed for the US NRC as part of their re-evaluation of the emergency core cooling system (ECCS) requirements in 10 CFR 50.46. It was envisioned that PRO-LOCA would be used by the NRC on a periodic basis (i.e., every 10 years) as a tool to re-evaluate the break frequency versus break size curves which formed the technical basis for the transition break size (TBS) definition in the proposed rule change to 50.46, i.e., 10 CFR 50.46a. The PRO-LOCA code can be used to predict the leak or break frequency from crack initiation, subcritical crack growth till wall penetration and leakage, and instability of the through-wall crack (pipe rupture). The results obtained with the PRO-LOCA code are a sequence of failure frequencies for the probability of a surface crack, through-wall crack, and six different sizes of crack opening areas corresponding to different leak flow rates or LOCA categories. Note that the level of quality assurance of the PRO-LOCA code is such that the code in its current state of development is considered to be more of a research code than a regulatory tool.

2.3.1.3 PRAISE

PRAISE (**P**iping **R**eliability **A**nalysis **I**ncluding **S**eismic **E**vents) is a PFM computer code for estimating probabilities of leaks and breaks in NPP piping systems. The code was originally developed by USNRC, at Lawrence Livermore National Laboratory (LLNL) for the assessment of seismic events on the failure probability of PWR piping. The original work was directed at fatigue failures of large-diameter reactor coolant piping due to the growth of weld fabrication flaws. It was later extended to address intergranular stress corrosion cracking, IGSCC, in BWR stainless steel piping welds. PRAISE has seen continued applications over the years with ongoing updates to include capabilities needed to address specific piping integrity issues, most notably the initiation of fatigue cracks. The enhanced version of PRAISE has allowed for crack initiation at multiple sites around the circumference of girth welds and the linking of adjacent cracks to form longer cracks more likely to cause large leaks and pipe ruptures. In the early 1990s with the evolution of computer technology a version of PRAISE was developed to run on personal computers. Pacific North National Laboratory (PNNL) has performed numerous calculations with PRAISE that applied probabilistic fracture mechanics to examine how different in-service inspection strategies could improve component reliability. These studies evaluated changes in failure probabilities when changes to in-service inspection requirements are implemented at operating nuclear power plants. PRAISE was used also to develop the technical basis for changes to Appendix L of the ASME Code Section XI that addresses fatigue critical locations in pressure boundary components. Updated versions of PRAISE include Pc-PRAISE and WinPRAISE.

2.3.1.4 SRRA

SRRA (The **S**tructural **R**eliability & **R**isk-**A**ssessment) is a PFM code developed by Westinghouse for assessing pipe component failure probabilities to support piping, risk-informed in-service inspection, (RI-ISI) analyses. Besides pipe components, SRRA can also be used for probabilistic integrity assessment of RPVs and RPV internals. It uses MCS to simulate the effect of time dependent degradation mechanisms and infrequent loading events and to derive the probability of piping failure for a variety of failure modes. In SRRA, the user is required to provide best estimate (median) values for various input parameters related to pipe material, geometry, operating conditions, NDE, service stresses and cycles. Each parameter is associated with a statistical distribution and standard deviation which are based on industry data and detailed analyses are not required to be entered by the user. Similarly, assumptions for initial flaw distributions are built-in to the program based on industry correlations with respect to weld geometry and pre-service inspection.

The SRRA code has the capability to simulate the effect of a variety of time dependant material degradation mechanisms for components of carbon steel and stainless steels including low-cycle fatigue crack growth of an existing (fabrication) flaw, crack growth of an existing flaw due to SCC, wall thinning due to material wastage (e.g. by FAC), high-cycle fatigue induced stresses exceeding the fatigue crack threshold. SRRA computes the lifetime failure probability for three different failure mode types concerning piping pressure boundary: small leak (i.e. through-wall flaw with minor leakage), large leak (i.e. a through-wall flaw that leads to leakage beyond a user defined value), and full break (i.e. complete severance of the pipe cross-section).

2.3.2 Piping Tools in Other Countries

2.3.2.1 PASCAL-SP and Other Japanese Tools

PASCAL-SP is a PFM tool developed by Japan Atomic Energy Agency for assessing the structural integrity of piping joints and core shrouds made of austenitic stainless steel in BWR (Onizawa and Itoh, 2009). It uses Monte Carlo Simulation to evaluate the probabilities of leakage and rupture of piping of the pipes. The code conforms to regulations of Nuclear and Industrial Safety Agency (NISA) and the Codes for Nuclear Power Generation Facilities – Rules on Fitness-for-Service for Nuclear Power Plants of the Japan Society of Mechanical Engineers (JSME). The focus of PASCAL-SP is on the effects of in-service inspection and welding residual stress distribution. Accuracy of flaw detection and sizing error for in-service inspection are modelled by the data from Japanese national research projects such as Ultrasonic Test & Evaluation for Maintenance Standards (UTS).

Other PFM PASCAL series codes have been developed in Japan, including PASCAL-SC for stress corrosion cracking, PASCAL-EQ for fatigue cracks and, PASCAL-EC for wall thinning. All the PASCAL PFM programs use Monte Carlo Simulation techniques and have capabilities for assessing the effects of seismic loads.

Other PFM codes developed in Japan are REAL-P, PEPPER and PLEAS-SP. REAL-P is developed by the Japan Nuclear Cycle Development Institute, PEPPER, (**P**robabilistic **E**valuation **P**rogram for **P**ipe aiming **E**conomical and **R**eliable design) is developed by Tepco Systems Corporation and PLEAS-PP is developed by Kawasaki Heavy Industries ((Maeda et al., 2009)

REAL-P can be used to estimate the creep fatigue and ductile facture failure probabilities in weld joints subjected to the internal pressure and thermal transients. PEPPER and PLES-SP can be used for reliability assessment of piping subject to fatigue, SCC, creep and wall thinning. All the tools use Monte Carlo Simulation techniques.

Additionally, PEPPER adopts the stratified Monte Carlo sampling method for crack sizes and the weighted Monte Carlo sampling method for seismic loads whose frequency of occurrence is very low.

2.3.2.2 NURBIT

NURBIT is a Swedish PFM tool for assessing piping in NPP (Brickstad and Zang, 2004). Within NURBIT, there is a program called PIFRAP (PIpe FRActure Probabilities) that can be used for probabilistic assessment (Simola et al 2002). PIFRAP is linked with two deterministic programs, LBBPIPE and SQUIRT for the evaluation of crack growth and leak rates frequencies respectively. PIFRAP uses Monte Carlo Simulation. PIFRAP can be used to calculate the failure probability of a specific pipe cross section with a certain stress state that contains a growing circumferential crack due to IGSCC. Both deterministic and probabilistic input parameters are available in PIFRAP. The deterministic parameters are pipe geometry, loading conditions, material properties stress, and the initial crack depth and the initial crack length is assumed to be a random variable.

2.3.2.3 ProSACC

ProSACC is another SWEDISH PFM Code. It has deterministic and probabilistic analysis capabilities. The deterministic part of the software ProSACC may be used both for assessment of detected cracks or crack like defects and for defect tolerance analysis. The procedure, which is based on the R6 Method (BE, 2001), could be used to calculate possible crack growth due to fatigue or stress corrosion and to calculate the reserve margin for failure due to fracture and plastic collapse. ProSACC also has an option for assessment of cracks in ferritic pressure vessels, austenitic piping and ferritic piping according to the 1995 edition of the ASME Boiler and Pressure Vessel Code, Section XI Appendices A, C and H. ProSACC can be used to calculate the probability of failure when the defect size is detected or not detected by NDT/NDE. It uses Monte Carlos Simulation (Simola et al. 2009, Cronvall et al. 2009).

2.3.2.4 Probabilistic VTTBESIT

VTTBESIT is a Finnish PFM tool that has both deterministic and probabilistic analysis capabilities (Simola et al. 2009, Cronvall et al. 2009). It can be used to analyse fatigue and SCC. Both cracks caused by fabrication and those induced by service are considered. The input random variables in VTTBESIT include the depth of initial cracks, length of initial cracks and frequency of load cycle occurrence. Other crack growth analysis input data parameters are considered to have single deterministic values. It uses Monte Carlo Simulation technique. VTTBESIT also has capability for reliability assessment based on Markov process which is a stochastic method in which the probability distribution of the current state is conditionally independent of the path of past states. In the VTTBESIT, the states of the Markov process correspond to crack penetration depths through component wall, and the transition probabilities from a lower state to higher states (deeper cracks). The effects of inspections and POD are included in the model as it transitions from one state to another.

2.3.2.5 PRODIGAL

PRODIGAL is a British PFM tool developed by Rolls-Royce (Chapman and Simonen, 1998 Chapman, 2003). It has three main subprograms, DANCER, ISIBREAK and SNOWBREAK. DANCER and ISIBREAK evaluate the probability of failure of a welded joint, whilst SNOWBREAK evaluates the probability of failure for an area, such as an area of stress concentration, which includes a period of defect initiation prior to crack growth to failure. DANCER is used to simulate the number and size of defects generated during the welding process. Its output is a histogram or frequency plot of the defects that may form during the normal build of a weld. Different defects that may initiate in weld beads are handled in DANCER including center cracks, lack of fusion, slag, pores with tails and cracks in heat affected zones. DANCER does not use MCS to obtain the failure probability. Instead, since the failure criteria are deterministic, a conditional probability of failure follows directly from the distributions of Paris-Erdogan crack growth rate equation parameters. Thus, a set of conditional failures can be determined and hence the distribution of the conditional failure probabilities over the range of initial defects is determined. ISIBREAK is used to estimate the conditional probability of failure for defects of varying size and position within a weld. The degradation mechanism considered is fatigue induced crack growth. The applied failure criteria are based on procedures in the R6 Method. SNOWBREAK is used to estimate the probability of failure from non-weld areas.

2.3.2.6 PROST

PROST (**PRO**babilistic **ST**ructure Analysis), is a European PFM analysis software for evaluating leak and break probabilities of piping systems in nuclear power plants (Schimpfke, 2003). The leak and break probabilities can be estimated for a pre-existing semi elliptical shaped inner surface cracks. It uses deterministic fracture mechanics principles. The probabilistic nature is determined by the uncertainties of the input data entering the deterministic routines including geometry, material properties and initial crack size. Two different types of loading conditions are considered in PROST. The first are cyclic loads which represent fatigue problems and the second are stochastic load sets, like seismic events or transients. User defined weld residual stresses can be included as well. The program uses both plain and a stratified MCS.

2.3.2.7 PROPSE

PROPSE (**PRO**babilistic **P**rogram for **S**afety **E**valuation) is a European PFM software for computation of probability of failure when the NDT/NDE have found/missed a defect in NPP piping system inspections (Dillström, 2003). PROPSE has capability for both First Order Reliability Method (FORM) and Monte Carlo Simulation (MCS) methods that can be to calculate the probability of failure. In PROPSE, it is assumed that the crack depth is log-normally distributed, fracture toughness is normally distributed and the crack aspect ratio is assumed to be constant. Furthermore, the material yield strength is assumed as normally distributed, and covariance for tensile strength is assumed to be the same as for the yield stress.

2.3.2.8 BRT-CICERO

Electricité de France (EDF) has developed software BRT-CICERO for both deterministic and probabilistic evaluation of pipe wall thinning due to flow accelerated corrosion (FAC) (Ardillon, 1997). It has been in use in every French NPP unit since 1994. Because BRT-CICERO is proprietary, not much information is available in the public domain (Smith et al., 2001).

2.3.2.9 WinPRAISE 07

WinPRAISE 07 is a Spanish PFM tool (Cueto-Felgueroso C, 2007). It is based on the original PRAISE code developed in the US. In 2005, a research and development program was launched in Spain aimed at obtaining an enhanced Structural Reliability Model (SRM) to be used in the development of Risk-Informed In-Service Inspection applications for piping. The program was funded by the CSN, Tecnatom and UNESA. The result of the program was a new version of the WinPRAISE code, named WinPRAISE 07, which incorporates several new capabilities. One of these features is a module for calculating failure probabilities in Alloy 182/82 welds in PWR plants. The probabilistic treatment of initiation of PWSCC cracks in WinPRAISE07 is similar to that for IGSCC in austenitic materials in pcPRAISE and previous versions of the PRAISE code.

2.3.2.10 PRAISE-CANDU

A brief description of the features of PRAISE-CANDU is presented here for completeness. PRAISE-CANDU stands for Piping Reliability Analysis Including Seismic Events for CANada Deuterium Uranium reactor. It is a probabilistic fracture mechanics software for CANDU piping systems. The probabilistic fracture mechanics features of PRAISE - CANDU incorporate elastic and elastic plastic fracture mechanics deterministic models. Probabilistic theory is used to characterise the uncertainty and Monte Carlo Simulation is used to generate failure probabilities. The fracture mechanics models in PRAISE - CANDU covers the full spectrum of as fabricated, crack initiation, crack growth and coalescence, stable crack growth, and through-wall cracks. Uncertainties in the parameters can be modelled as aleatoric, epistemic or mixed aleatoric and epistemic. Three piping system degradation mechanisms are considered: general FAC, fatigue and primary water stress corrosion cracking (PWSCC). These failure modes can be considered simultaneously in an analysis. The five time-dependent parameters used to simulate ageing in PRAISE - CANDU are yield strength, Ramberg-Osgood coefficient, flow strength, wall thinning rate and tearing curve coefficients. The six statistical distributions in PRAISE-CANDU are normal, lognormal, weibull, triangular, uniform and tabular. PRAISE-CANDU has eleven modules: crack initiation, crack placement, crack coalescence, loads, stress intensity factor solutions, crack growth, J-integral solutions, crack opening displacement, inspection, net section stress crack stability and J-integral tearing instability. There are 14 analysis options and US customary and SI units are the two systems of consistent units in PRAISE - CANDU.

2.3.2.11 CANTIA

CANTIA is the Canadian CNSC tool for probabilistic assessment of inspection strategies for steam generator tubes (Revankar et al. 2008). CANTIA uses Monte Carlo techniques to determine approximate probabilities of steam generator tube failures under accident conditions and primary to secondary leak rates under normal and accident conditions at future points in time. It also determines approximate future flaw distributions and non-destructive examination results from the input data. The probabilities of failure and leak rates and the future flaw distributions can be influenced by performing inspections of the steam generator tubes at some future points in time, and removing defective tubes from the population. The effect of different inspection and maintenance strategies can therefore be determined as a direct effect on the probability of tube failure and the primary to secondary leak rate.

2.3.2.12 PINEP-PWSCC

PINEP-PWSCC (Probabilistic INtegrity Evaluation for nuclear Piping-PWSCC) is a South Korean PFM code for evaluation of the failure probabilities of Ni-base alloy components by PWSCC in a primary coolant piping system (Hong et al, 2012, Hong and Jian, 2010). The code uses the most recent research results and advanced models in calculation modules such as PWSCC crack initiation and growth models, and performance-based probability of detection (POD) model for Ni-base alloy welds, and so on. The development of PWSCC initiation model is based on the correlation with laboratory test data and field data of Alloy 182 butt welds failure in PWR. In the model, effects of material variability and water chemistry were incorporated. In PWSCC crack growth model, the effects of dissolved hydrogen and crack orientation as well as temperature were considered. The code uses Monte Carlo Simulation technique.

2.4 GENERAL PURPOSE RELIABILITY TOOLS

2.4.1.1 CALREL

CALREL (CALibration of RELiability) is a general purpose structural reliability analysis program developed by the University of Berkeley, California (Liu et al., 1989). The code is designed to work on its own or to operate as a shell program in conjunction with other structural analysis programs. Structural failure criteria are defined in terms of one or more limit state functions. CALREL can be used to compute the reliability of structural components as well as systems. Specific macro commands are available for first-order component reliability analysis, second-order component reliability analysis by both curvature fitting and point fitting methods, first-order reliability bounds for series systems, first-order reliability sensitivity analysis for independent and dependent variables with respect to distribution and limit state function parameters, directional simulation for components and general systems, employing first or second-order fittings of the limit state surfaces, and MCS for components and general systems.

2.4.1.2 COMPASS

COMPASS (acronym for Computer Methods for Probabilistic Analysis of Structures and Systems), is a general purpose reliability analysis tool developed in Canada by Martec Limited. It has capabilities for probabilistic analysis of structures and systems, probabilistic data characterization (including random field modelling), stochastic finite element modelling and analysis, and probabilistic risk-based inspection and maintenance planning methodologies. The main features of COMPASS include: A library of 16 probability distributions, including Gumbel, Weibull, Lognormal, Extreme Value, Exponential, Beta, and Gamma, to name a few; Robust Monte Carlo Simulation techniques, including direct MCS and adaptive importance sampling, which allows the user to generate a large number of samples (for a given random function) at any time; Component- and system-reliability analysis methods, including Monte Carlo Simulation (MCS), First Order Reliability Method (FORM), and Second Order Reliability Method (SORM); Built in-library of over 50 limit state functions; Ability to accept user-defined failure models (limit states); Confidence bounds on failure probabilities and reliability indices; Modeling random variables from measured data (statistical parameters, correlation and distribution types) using any of 16 built-in distributions; Goodness-of-Fit tests to discern the best distribution type for a given set of data; Modeling random fields (including spatial correlation structures) and random processes (including time-dependency); and Spatial-Time characterization (e.g., corrosion). COMPASS has been adapted for specialized application to structural integrity, inspection, and maintenance management of such structural including the following: **P**robabilistic **R**esidual **S**trength **A**ssessment of Damaged **P**ipelines, PRESAP; Probabilistic based cumulative fatigue and fracture damage tool for solid rocket missiles (ROCREL); and **PR**ob**A**bilistic **DA**ta **C**haracterization tool (PRADAC).

FORM is essentially a simplified method for estimating the failure probability. It involves first the transformation of the basic random variables, which defines the failure or performance or limit state function, into independent standard normal variables, and then estimating the failure probability by *linearizing* the failure function at the closest point to the origin in standard normal space. It is usually necessary to iterate to determine the closest point to the origin, and a number of iterative and optimisation techniques are available. Because the failure function are often nonlinear, SORM methods are used to improve the accuracy of first-order probability estimates by including curvature information at the failure point, and to approximating the failure function by a *quadratic* surface. The difference between the first- and second-order estimates of the probability gives an indication of the curvature of the failure surface. If there is a significant difference it suggests that perhaps Monte Carlo methods should be used to confirm the probability of failure estimate. For most practical reliability applications there is usually little difference between FORM and SORM estimates. Crude Monte Carlo simulation offers a direct method for estimating the failure probability. In essence, the technique involves sampling a set of values of the basic variables at random from the probability density function, and evaluating the failure function for the values to see if failure occurs. By generating a large number of samples, or trials, the probability density function is simulated, and the ratio of the number of trials leading to failure to the total number of trials tends to the exact probability of failure. The drawback with crude Monte Carlo simulation is the computational effort involved. To produce a reasonably accurate estimate of the failure probability at least 100/Pf, where Pf is the probability of failure, trials are required. For Pf of about 10^{-4} this requires that at least one million trials are generated.

2.4.1.3 NESSUS

NESSUS is a general purpose tool for computing the probabilistic response or reliability of structures. It was developed by Southwest Research Institute (SwRI) (Riha et al., 2000*)*. The framework of NESSUS allows the user to link traditional and advanced probabilistic algorithms with analytical equations, external computer programs including commercial finite element codes such as ABAQUS, NASTRAN and PRONTO. Also, NESSUS provides a built-in finite element structural modelling capability. It has several probabilistic algorithms including FORM, SORM and MCS.

2.4.1.4 STRUREL

STRUREL (STRUctural RELiability) is a general purpose reliability software series that has been developed in Germany (Das and Chryssanthopoulos, 2000). The program comprises several independent but interrelated programs: STATREL; statistical analysis of data, simulation, distribution fitting and analysis of time series; COMREL; time-invariant and time-variant analysis of component reliability; and SYSREL; reliability analysis of systems. The program has MC simulation, FORM and SORM methods.

2.4.1.5 PROBAN

PROBAN is a general purpose reliability analysis tool developed in Norway by DNV. PROBAN capabilities are similar to STRUREL, (Das and Chryssanthopoulos, 2000). It has capability for probabilistic analysis of structures.

2.4.1.6 ProSINTAP

ProSINTAP (PRObabilistic Structural INTegrity Assessment Procedure) is a probabilistic fracture mechanics tool, which uses SINTAP, (Structural INTegrity Assessment Procedures for European Industry), procedure (Dillstrom, 2000). It has both MCS and FORM capability and uses the failure assessment diagram in its limit state formulation. It can be applied to fracture and collapse failure modes. Five input data decks are listed, geometry, loading, material, NDE and analysis. The geometry section has stress intensity factor solutions for a range of plate and hollow cylinder geometries with surface and through-thickness cracks. The load module enables through thickness distributions of applied and welding residual stress to be incorporated. In the material module, yield strength, rupture stress and fracture toughness and their associated statistical distributions are input. This requires the mean and standard deviation of each parameter as defined by the normal, log-normal or Weibull distribution. The NDE module enables defect sizing as input data, but also allowing for treatment as an exponential distribution. The Analysis module enables the user to select MCS or FORM methods and to apply partial safety factors if required in order to achieve a specified target reliability method.

2.4.1.7 STAR 6

STAR 6 is a reliability analysis software developed by British Energy for automating reliability analyses of the fracture and collapse analysis procedures in R6 Method (Wilson, 1995). The tool has FORM and MCS and an extensive library of stress intensity factor solutions for different component geometries.

3.0 A REVIEW OF REGULATORY POSITIONS OF VARIOUS COUNTRIES ON PFM

3.1 INTRODUCTIONS

In most counties, the approach to NPP regulation is generally based on a deterministic viewpoint where a set of rules and requirements are defined with the objective of ensuring a high level of safety. Recently, a risk-informed approach to regulatory decision-making is gaining grounds. This effort, pioneered in the mid-nineties by the USA, is characterised by an approach, where insights from risk assessment are considered together with other factors to make decisions. It integrates information from service experience, plant and operating conditions, additional deterministic information, and risk insights. The risk-informed approach aims to integrate in a systematic manner quantitative and qualitative, deterministic and probabilistic safety considerations to obtain a balanced decision. In the risk informed framework, there is explicit consideration of both the chances or probability of an event and the potential consequences of the event. The probability of an event can be determined from service experience, expert opinion or by the use of a probabilistic fracture mechanic analytical tool. A probabilistic fracture mechanics analysis must be viewed in the context of probability of failure which has to be considered in the context of risk-informed decision. Therefore, any discussion on the regulatory position of a country on probabilistic fracture mechanics must be studied in the context of its regulatory position on risk-informed regulations.

In this chapter, a brief review of risk informed philosophy is presented along with methods that have been developed. The role of probabilistic fracture mechanics as a tool in risk informed decision is discussed. The position of various countries including the regulatory agencies on risk-informed regulation is also summarised. Practical applications of probabilistic fracture mechanics in formulating and revising regulations and developing technical specifications is also presented along with on-going work on probabilistic fracture mechanics that may lead to revision of existing regulations and technical specifications.

3.2 THE CONCEPT OF RISK-INFORMED DECISION

Risk is defined as the product of the consequences of a failure and the probability of that failure occurring:

Risk = {Probability of Failure} x {Consequence of that Failure}

In a NPP system, the failure of its structural component is an event involving leakage, rupture or any condition that would impact its ability to perform its intended safety function. For piping, failure usually involves a leak or a rupture, resulting in a reduction or loss of the pressure-retaining capability of the element in question. The probability of failure can be defined either in terms of failure frequencies or failure probabilities per demand. The precise definition of the consequence of failure is normally a matter of negotiation between the utility and the regulator. Whatever metric is chosen, it must be measured as an outcome that is conditional on the probability of failure.

There are three different approaches to risk-informed decisions, quantitative, semi-quantitative and qualitative. In a quantitative approach, numerical estimates are determined for probabilities of failures (Pf) and consequences of failures (COFs). The POFs can be estimated using a fully validated and verified probabilistic fracture mechanics model and plant specific safety assessment is used to calculate the COFs.

In a qualitative approach, both the POFs and COFs are characterised by qualitative terms, such as very low, low, high, etc. In this framework, expert elicitation is used to rank the POF and COF of individual components.

A semi-quantitative approach is one where the COFs are based on plant specific safety results, which may be expressed equally well in quantitative or qualitative terms. The failure probabilities may be partly evaluated using a fully validated and verified probabilistic fracture mechanics model, but partly also using experience data and expert elicitation.

In the nuclear industry, the risks are assessed by means of probabilistic safety assessment, PSA, which is an advanced quantitative approach. The use of PSA is the foundation of risk-informed approaches in the nuclear industry, and thus a purely qualitative approach to risk informed decision that does not make use of PSA insights would be difficult to justify. A qualitative analysis could be used to allow systems to be quickly prioritised for further detailed (quantitative) risk analysis. However, it is recognised that the current state of knowledge and understanding of some of the degradation mechanisms and the availability of the required plant data can be insufficient to accurately quantify the probability of failure. Likewise, many current PSA analyses may not be detailed enough and the consequence analysis must necessarily be complemented by some degree of qualitative assessment.

3.3 APPLICATION OF PFM IN RISK INFORMED REGULATORY DECISIONS IN USA

The USNRC has used PFM as a part of RIDM to define technical specifications on regulations. It has also accepted PFM results as a valid approach to satisfy regulatory requirements. It is currently supporting the development of a tool, xLPR, which may be used to meet the requirements of a regulation. In this section, a brief discussion is presented on how the US-NRC has used or accepted the use of PFM in pressure vessel regulations, leak before break and risk-informed in-service inspection of pipelines. The discussion is based on a review of several documents listed in the reference section, some of which are mentioned at the end of the relevant section.

3.3.1 Pressure Vessel Regulatory Decisions

In the early 1980s, the US nuclear operators and regulators focused attention on the possibility that PTS events could challenge the structural integrity of the RPV. This was brought on by the fact that operational experience suggested that overcooling events, while not common, did occur. The results of reactor materials surveillance programs also showed that the US nuclear power plants RPV steels and welds, particularly those having high copper content, experienced a loss of toughness with time due to neutron irradiation embrittlement. To ensure the safe operation of the plants, probabilistic fracture mechanics calculations were used as a part of a risk informed decision to develop the technical basis for the rules governing the integrity of RPV (10 CFR 50.61 (1984)).

Once the rules were developed and implemented, it became evident after several years of operation that the rules as implemented were conservative. This was due to inadequacy in the state of knowledge and data limitations at the time of implementation that necessitated conservative treatment of several key parameters and models used in the probabilistic calculations that provided the technical basis (SECY-82-465, 1982) of the PTS Rule (10 CFR 50.61 (1984)). The US-NRC then undertook the PTS re-evaluation project which was conducted between 1998 and 2009 by the USNRC ((Erickson et al., 2007a, 2007b). Assistance and data was provided by the commercial nuclear power industry operating under the auspices of the EPRI. The project findings were reviewed by the Advisory Committee on Reactor Safeguards (ACRS), the Nuclear Energy Institute (NEI), the public, and a panel of national and international experts. These reviews provided the basis for numerous model corrections and improvements. Based on the findings, the NRC initiated rulemaking as a voluntary alternate to 10 CFR 50.61 in SECY-06-0124 (2006). Rulemaking was completed on January 4, 2010 when the alternate rule 10 CFR 50.61a was published in the Federal Register (10 CFR 50.61a).

The basic approach that was used to derive the new fracture toughness requirement for the pressurised thermal shock, PTS, is shown in Figure 1. It involves the use of probabilistic fracture mechanics as a component of a risk-informed decision making (RIDM).

First, a PRA event sequence analysis was performed to postulate the sequences of events that may cause a PTS challenge to RPV integrity and to estimate the frequency with which such sequences might occur. The PRA event sequence analysis requires expert judgement, operating experience and data. The event sequence definitions were employed in a thermal hydraulic analysis model to obtain temperatures, pressure and heat transfer coefficient histories. The thermal hydraulic analysis does not require PFM, it involves the use of expert knowledge and deterministic models. These parameters along with other information and uncertainties on RPV design and construction materials, were then used in PFM models encapsulated in the software tool, FAVOR, to estimate the time-dependent “driving force to fracture” produced by a particular event sequence. The fracture-driving force was compared to the fracture toughness, or fracture resistance, of the RPV steel within a Monte Carlo framework and used to compute the probabilities that a crack could grow to sufficient size to penetrate all the way through the RPV wall. The final step in the analysis involved multiplication of the probability distribution of through-wall cracking (from the PFM analysis) with the distribution of frequencies at which a particular event sequence could occur (as defined by the PRA analysis). This product established an estimate of the distribution of the annual frequency of through-wall cracking that could occur at a particular plant after a particular period of operation when subjected to a particular sequence of events. The process was repeated for various operating conditions. The results were summed for all the event sequences to estimate the total annual frequency distribution of through-wall cracking for the vessel and used to establish the technical basis for a revised PTS Rule within an integrated system framework. The above discussion demonstrates the extent to which PFM has been employed as a part of a RIDM to derive fracture toughness requirement for the rector pressure vessel. More detailed discussion on this subject can be found in (Kirk, 2012, 2013 EricksonKirk et al. 2007, EricksonKirk and Dickson, 2010).

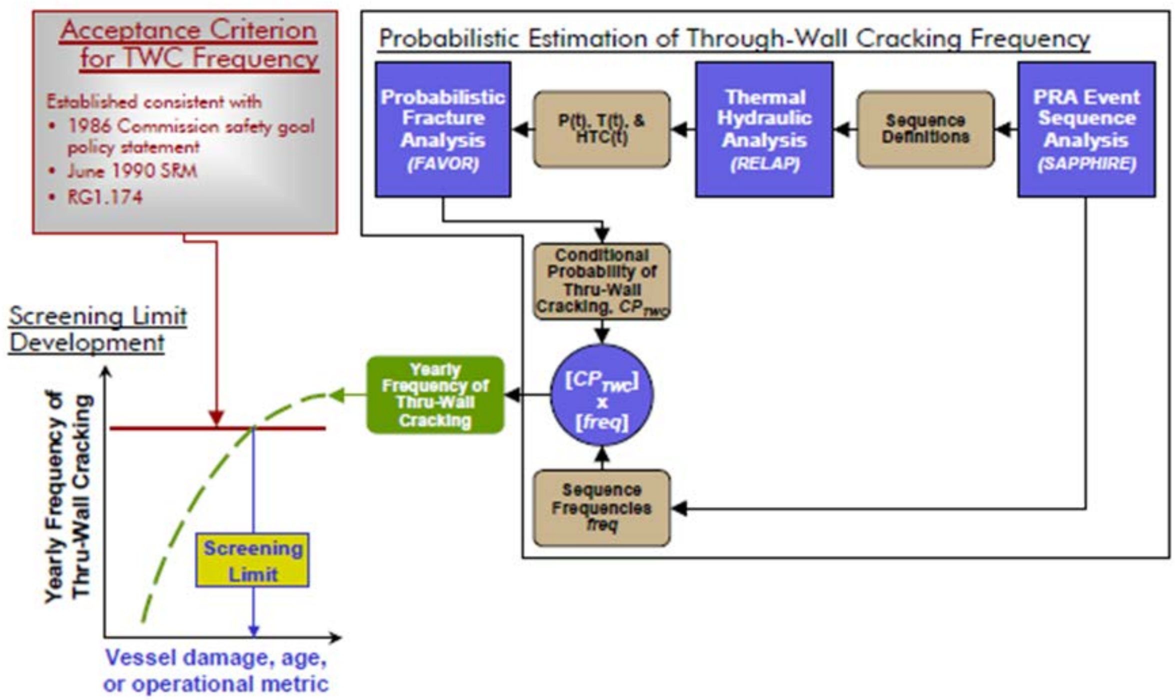


Figure 1 Approach for Deriving PTS Rules for RPV that Shows How PFM Analyses are Combined with Other Assessments with a RIDM Framework (Adapted from Kirk, 2012, 2013, EricksonKirk et al. 2007)

3.3.2 Piping LBB Regulatory Decisions

In the US, the section of the NRC regulation related to LBB is General Design Criterion 4 (Environmental and Dynamic Effects Design Bases) in Appendix A of Part 50 (Domestic Licensing of Production and Utilization Facilities) of Title 10 (Energy) of the Code of Federal Regulations (1OCFR50). It states that: "Structures, systems, and components important to safety shall be designed to accommodate the effects of and to be compatible with the environmental conditions associated with normal operation, maintenance, testing, and postulated accidents, including loss-of-coolant accidents. These structures, systems, and components shall be appropriately protected against dynamic effects, including the effects of missiles, pipe whipping, and discharging fluids, that may result from equipment failures and from events and conditions outside the nuclear power unit. However, dynamic effects associated with postulated pipe ruptures in nuclear power units may be excluded from the design basis when analyses reviewed and approved by the Commission demonstrate that the probability of fluid system piping rupture is extremely low under conditions consistent with the design basis for the piping."

Of particular interest to the subject of LBB, is the stipulation in GDC-4 that allows the use of "analyses reviewed and approved by the Commission" to eliminate from the design basis the dynamic effects of pipe ruptures. The Standard Review Plan (SRP) Section 3.6.3, which is a document prepared for the guidance of the Office of Nuclear Reactor Regulation (NRR) staff responsible for the review of applications to construct and operate nuclear power plants, describes the current methodology for LBB piping safety assessment. The LBB methodology as currently regulated and applied in the US is deterministic.

Based on the stipulation of GDC-4 and SRP 3.6.3 the USNRC used LBB analyses in the mid nineteen eighties, to grant exemptions to operators from the requirements of General Design Criterion -4 (GDC-4). However, in 1987, GDC-4 was revised to include the following statement “the leak-before-break approach should not be considered applicable to fluid system piping that operating experience has indicated is particularly susceptible to failure from the effects of corrosion.” This requirement is emphasised in the SRP for Leak-Before-Break Evaluation Procedures, where it is stated that “evaluations must demonstrate that these [corrosion] mechanisms are not potential sources of pipe rupture." However, since that time, operating experience has conclusively demonstrated that pressurized water reactor (PWR) reactor coolant pressure boundary (RCPB) components containing dissimilar metal (DM) welds fabricated from Alloy 82/182/600 are susceptible to primary water stress corrosion cracking (PWSCC).

Tregoining and Scott (2010) in their presentation, titled "Probabilistic Analysis as a Regulatory Tool for Risk-Informed Decision Guidance (PARTRIDGE)", noted that because PWSCC is occurring in systems that have been granted LBB exemptions, the systems no longer strictly satisfy SRP 3.6.3 which is a deterministic rule, yet 10CFR50 Appendix A, GDC-4 requires that an extremely low probability of failure should exist. However, there is currently no tool that can be used to validate the requirement of GDC-4 "extremely low probability of failure should exist" for an operating plant. The USNRC along with industry partners is now working on the development of probabilistic fracture mechanic tool that may be used to certify the extremely low probability of failure requirement. It is called xLPR.

The tool is being developed in three distinct versions. Version 1.0 was a pilot study to evaluate the feasibility of a code with a modular structure that can quantify uncertainties. Version 2.0 is being expanded to evaluate welds within primary system piping to provide a technical basis for LBB regulatory guidance. Phenomena to be addressed include fatigue, axial cracking, intergranular stress corrosion cracking (IGSCC), and transition from surface cracking to through wall cracking, and manufacturing defects. Version 3.0 will be applied to the entire reactor coolant pressure boundary including the piping, the reactor vessel, and the steam generator.

As in the previous section on the reactor pressure vessel, where PFM was used as a part of RIDM, the title of Tregoining and Scott presentation "Probabilistic Analysis as a Regulatory Tool for Risk-Informed Decision Guidance" again demonstrates the potential role of probabilistic fracture mechanics in regulatory guidance. The above discussion also illustrates the hands-on approach by the staff of US-NRC when it comes to the development, implementation and the potential for using PFM tools and models in regulatory decisions.

Additional materials on the above subject can be found in (Mattie et al, 2012, Tregoning, 2010, Rudland and Harrington 2012, 2013, Rudland, 2011a, b).

3.3.3 Piping RI-ISI Licensing Decisions

In the mid-nineties, the regulatory risk-informed approach was developed in the USA. The term “risk-informed” introduced by the U.S. Nuclear Regulatory Commission, characterises a technique, where insights from risk assessment are considered together with other factors to make integrated decisions. During the late 1990’s, significant advancements were made within the US to develop RI-ISI methods, industry consensus standards, and regulatory guidance. The NRC published the Regulatory Guide 1.178 titled “An Approach for the Plant-Specific, Risk-Informed Decision-making: ISI of Piping” and its companion Standard Review Plan, Section 3.9.8 of NUREG 0800. Methods for implementing the regulations were not prescribed by the NRC. The industry formulated and implemented methods which were certified and accepted by the NRC. Two primary RI-ISI methods were developed by the Electric Power Research Institute (EPRI) and the Westinghouse Owners Group (WOG).

EPRI and WOG methods use the concept of risk, which is the product of the probability of failure, POF, and the consequence of failure, COF. In NPP operations, the consequence of failure is generally estimated using PRA assessment. Three primary methods can be used to estimate the probability of failure. These are

- Probabilistic fracture mechanics and structural reliability method (SRM);
- Statistical models of pipe failure where available or qualitative results that includes the role and use of service experience data; and
- Expert judgment/expert elicitation.

A combination of these methods can also be used. PFM methods will yield quantitative data, while the other two methods will generally yield qualitative results.

The RI-ISI methodology implemented by WOG uses PFM to calculate the failure probabilities of piping segments. The SRRA PFM tool is used for this purpose. A discussion of this tool was presented in Section 2.3.1.4. PSA is used for quantitative assessment of the consequence of failure. The final safety significance category, "high" or "low", is determined by an expert panel.

The RI-ISI methodology developed by EPRI uses a qualitative approach from service experience and pipe failure data, to assign the susceptibility of piping segment to a certain degradation mechanism, and rupture potential category (high, medium, and low). It does not use probabilistic fracture mechanics. The consequence categorisation (high, medium, low, none) of each segment is based on the conditional core damage probability (CCDP) and conditional large early release probability (CLERP), connected with the segment's most severe postulated failure mode. The CCDP is estimated from the plant-specific PSA for initiating events and derived from general PSA-based rules for loss of mitigating system events. The risk categories are associated with three "risk regions", high, medium, and low.

These two methodologies, WOG and EPRI, along with the results from several plants were submitted to the NRC for review and approval. Most of these applications were found to satisfy the requirement of the Regulatory Guide 1.178 and its companion Standard Review Plan, Section 3.9.8.

In summary, methodologies for implementing RI-ISI regulations were developed by the NPP industry groups, Westinghouse Owners Group (WOG) and the Electric Power Research Institute (EPRI) and not the USNRC. The USNRC has reviewed and has approved application of these methodologies. Nearly all the nuclear power reactors in the USA have implemented one of the two methodologies for the risk-informed selection of components for inspections. The WOG methodology involves the use of PFM. The USNRC main role has been that of a reviewer and an approver of plant submissions that implements methods developed by the industry, one of which uses PFM, to ensure that the submissions meet the requirements NRC Regulatory Guide 1.178 and SRP 3.9.8. It should be emphasised that even when using the risk categorization method of EPRI or the WOG approaches, expert elicitation is required. The probabilistic methods are not used independently of expert elicitation. For Defence-in-Depth purposes for example:

- For ASME nuclear Class 1 components, even if the components are screened out based upon risk calculations, inspections of a sample of those components are required.
- 2) For Class 2 and 3 components, monitoring for leakage and pressure testing per ASME Section XI is required.

So, while PFM can be used to assess the risk of component failure, inspection programs are not defined based solely on the results of PFM. PFM must be used in the context of RIDM.

3.4 APPLICATION OF PFM IN RISK INFORMED REGULATORY DECISIONS IN OTHER COUNTRIES

3.4.1 Piping RI-ISI Regulatory Decisions

Table 3 summarises the position of various countries on RI-ISI. The methods used by the countries involve an adaptation of one of the two approaches for implementing RI-ISI developed by the US nuclear industry: the WOG approach, which involves the use of PFM and the EPRI approach. Some countries have also developed other qualitative approaches that do not involve PFM.

Table 3: Summary of Positions of Various Countries on RI-ISI (Adapted from, EUR NEA/CSNI/R(2005)9, 21320 EN (2004), ENIQ Report No 37, (2009), IAEA Nuclear Energy Series, (2010)

Country	RI-ISI Application			RI-ISI Pilot Study	
	Yes/No	*Regulation*	*Method Used*	*Yes/No*	*Method Used*
Germany	No			Yes	WOG
Spain	Yes	Yes	WOG	Yes	WOG
Bulgaria	Yes		WOG	Yes	WOG
Sweden	Yes	Yes	Modified WOG, Others	Yes	WOG, Others
Japan	No	No		Yes	EPRI WOG
Korea	Yes	Yes		Yes	WOG
Finland	Yes	Yes	Other	Yes	Other
France	No			Yes	Other
UK	No			No	
Hungary	No			No	
Belgium	No			No	
Czech Republic	No			No	
South Africa	No			Yes	EPRI

Mexico	No			Yes	EPRI
Switzerland	No			Yes	EPRI
Ukraine	No			Yes	EPRI

From Table 3 it is seen that most countries with NPP have not implemented RI-ISI regulations and only a few have undertaken pilot studies with PFM based WOG method. Only two countries Spain, Bulgaria, have RI-ISI regulations that use WOG PFM methods.

In Spain, the development in the USA towards RI-ISI was closely followed. A joint pilot project of regulator, CSN, and the Spanish utilities (UNESA) was carried out with the objective to develop and validate an application guide for RI-ISI of piping systems. This guide, issued in 2000, follows the principles established in the NRC Regulatory Guide 1.178. RI-ISI is not a regulatory requirement but an option. Assessment and approval of applications by CSN is required. Several licensee applications for RI-ISI programmes, using the WOG methodology, have already been approved by CSN.

Bulgaria also has a partial application of the WOG methodology.

In Sweden RI-ISI is mandatory. It involves the use of qualitative RI-ISI approach according to previous regulations and guidelines in SKIFS 1994:1 and a modified WOG methodology.

Pilot studies that involve the WOG approach have been performed in Germany and Sweden and other non-European countries such as Korea and Japan to test the method and to gain experience.

From the above discussion, it may be concluded that since most countries with NPP have not implemented RI-ISI, they most likely have not used PFM as a part of a regulatory tool. This conclusion will be verified and confirmed from results of the questionnaire administered to various nuclear regulatory bodies.

3.4.2 Pressure Vessel Regulatory Decisions

No documents on the use of PFM for pressure vessel regulatory decisions in other countries were found.

3.4.3 Piping LBB Regulatory Decisions

Some work has been done in other countries on probabilistic LBB. For example, in Sweden, Brickstad (2008) in a discussion titled "Regulatory Aspects on the Application of the LBB" noted that the Swedish Nuclear Power Inspectorate (SKI) funded a project called "ProLBB A Probabilistic Approach to Leak (Dillström and Zang, 2007)" where the deterministic criteria used in the current Swedish LBB guidelines (SKI regulation SKIFS 2004:2) were compared with a probabilistic analysis. ProLBB uses PFM approach. The purpose of the project was to evaluate leak and rupture probabilities for pipes of different sizes in Swedish BWR- and PWR-plants. The project was also designed to give information on which failure probability corresponds to a precise fulfilment of the deterministic LBB-criteria. Brickstad (2008), Dillström and Zang, (2007) noted that the results of the ProLBB project will be used by SKI staff in the reviews of applications from Swedish Nuclear Plants to use the LBB concept.

Apart from Sweden, regulators in most countries do not consider probabilistic-leak-before break for their piping systems. The reasons for this position are varied including potential threats to vital safety functions due to uncertainties in parameters and models used in the analyses, inadequate understanding of in-service degradations types, lack of knowledge of applicable loads, fear of unpredictable events leading to critical situations, and inadequate knowledge of the quality of construction material used (EUR 18549 EN (2000).

3.5 FEEDBACK FROM REGULATORS IN OTHER COUNTRIES ON APPLICATION OF PFM IN REGULATORY DECISIONS

A questionnaire was designed and sent to regulators in several countries. The questionnaire is shown in Appendix A. Regulators from two countries, USA and Sweden, responded to the questions. The thrust of the question was if their regulatory agency use PFM in regulatory and licensing decisions and a list of regulations/ licensing decisions that are based solely or partly on PFM. The response from the two countries are summarised in Table 4, where it is seen that in the, there are two regulations that involve the use of probabilistic insights and four areas being investigated which could lead to the adoption or probabilistic insights into other regulations. There are 8 licensing decisions that have been made in the US based upon current regulations and 2 licensing decisions in Sweden. The expert elicitation process used by US-

NRC in support of the pending regulatory decision regarding LLOCA redefinition for 10CFR50.46a, is summarised in Appendix B. (NUREG-1829, 2008)

Table 4: Summary of Regulation/Licensing Decisions in Other Countries Based Partly on PFM

Country	Regulation/Licensing Decision Based Partly on PFM
USA	**Regulations:** 1. 10CFR 50.61 2. 10CFR 50.61a **Licensing Decisions:** 1. Elimination of reactor vessel circumferential weld inspection for boiling water reactors (BWRs) 2. Reduction of inspection requirements for BWR reactor nozzle weld and blend radii 3. Risk-informed extension of the reactor vessel in service inspection intervals 4. Inspection intervals for RPV upper heads containing A600 nozzles 5. Risk-informed in service inspection of piping 6. Decision to maintain existing Cumulative Usage Factor calculation method for fatigue for license renewal 7. Evaluation of Davis-Besse RPV Head Degradation 8. In service inspection intervals for upper RPV heads **Pending Regulations/Licensing Decisions** 1. Large break LOCA redefinition (i.e., 10CFR 50.46a) 2. Resolution of GSI-191 using risk-informed approach (for certain plants). 3. Leak-before-break 4. 10CFR50 Appendix G
Sweden	**Licensing Decisions:** 1. Decision in 2008 to allow credit for LBB for the main coolant lines in the PWR-plant Ringhals unit 2. In part this decision was based on PFM for these lines which demonstrated very low risk of rupture. This meant that Ringhals 2 did not need to install pipe whip restraints in the main coolant lines. 2. Decision in 2006 to allow Ringhals units 2, 3 and 4 the use of a specific RI-ISI procedure for the selection of pipe welds for inspection. The RI-ISI procedure was the WOG-procedure developed by Westinghouse and published in WCAP-14572, Rev. 1-NP-A, 1999.

4.0 METHODOLOGY USED TO REVIEW THE COG REPORTS

4.1 INTRODUCTION

The six COG reports reviewed are:

1. COG-JP-4367-005, Revision 2, Specification for PRAISE-CANDU 1.0;
2. COG-JP-4367-011, Revision 0, Theory Manual for PRAISE-CANDU 1.0;
3. COG-JP-4367-046, Revision 0, PRAISE-CANDU Version 1.0 Pilot Study;
4. COG-JP-4367-026, Verification and Validation Report for PRAISE-CANDU 1.0.
5. COG-JP-4367-041-R0, FPBOC-WG Integrated Close-out Report; and
6. COG-11-2096, LOCA Break-Opening Characteristics for CANDU HTS Piping – Literature Review;

The goals of the review include a determination of the following:

- The applicability of degradation assessment models used in PRAISE-CANDU and the potential gaps in the models;
- The adequacy of the theory presented in PRAISE-CANDU to describe the basis for the selection of input parameters to ensure that consistent results would be generated by different users;
- The suitability of PRAISE-CANDU input parameters by answering whether the input parameters accurately describe the loading, environmental conditions which could lead to crack initiation and subsequent pipe breaks; and
- The suitability of the methodology used to address uncertainties in input and output.

4.2 BASIC METHODOLOGY

Four basic issues, summarised in Table 5, are used to review the documents

Table 5: Summary of Some Issues Used to Review COG Documents

	Issues	Brief Details
1.	Basic Software Quality	The software quality of PFM tool is central to the reliability of the output, the review examines the implementation of CSA N286.7-99 in PRAISE-CANDU and offers suggestions for improvement.
2.	Quality of the deterministic fracture	Central to PRAISE-CANDU outputs is the quality of the deterministic fracture mechanics models, which basically

	Issues	Brief Details
	mechanics models	reduce to elastic or/and elastic-plastic analytical, or experimentally calibrated models for crack initiation, crack growth and coalescence, stable crack growth, and through-wall stability. Some of issues examined in the review are: • The technical adequacy of the models; • Adequacy of models verification and validation; • Models range of applications; • The considerations given to alternative models; • The considerations given to model's capacity to handle combined damaged mechanisms; and • Impact of ageing on the models and parameters
3.	Adequacy of uncertainty representation and propagation	Uncertainty representation, aleatoric and epistemic, and the choice of a probabilistic distribution can influence the outcome of the probability analysis especially in cases where the failure probability is small. Some of issues examined in the review are: • The technical adequacy and sufficiency of the uncertainty representation and propagation; • Provision and basis for selecting appropriate representation for uncertain parameters; • Impact of ageing on uncertainty representation; • Definition of acceptance criteria for input, models and failure probability; • Treatment of model uncertainties; and • Provision and guidance for users
4.	Adequacy of verification and validation	Verification is the process of determining that a model implementation accurately represents the developer's conceptual description of the model and the solution to the model. Validation is the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model. The adequacy of both the verification and validation will be assessed.

4.3 ISSUES ADDRESSED BY THE COG REPORTS

Based on our review, four of the six documents under review deal directly with PRAISE-CANDU software development: COG-JP-4367-005, Revision 2, Specification for PRAISE-CANDU 1.0; COG-JP-4367-011, Revision 0, Theory Manual for PRAISE-CANDU 1.0; COG-JP-4367-046, Revision 0, PRAISE-CANDU Version 1.0 Pilot Study; and COG-JP-

4367-026, Verification and Validation Report for PRAISE-CANDU 1.0. The other two documents, COG-JP-4367-041-R0, FPBOC-WG Integrated Close-out Report and COG-11-2096; and LOCA Break-Opening Characteristics for CANDU HTS Piping – Literature Review, are focused on the arguments used by COG to support their request for changes to the existing regulations. A summary of the COG documents and the issues addressed by the documents based on our review is given in Table 6.

Table 6: Summary of COG Documents and Issues in the Documents

COG Document	Issues Addressed
COG-JP-4367-011, Revision 0, Theory Manual for PRAISE-CANDU 1.0;	• Quality of the deterministic fracture mechanics models • Adequacy of uncertainty representation and propagation
COG-JP-4367-005, Revision 2, Specification for PRAISE-CANDU 1.0	• Basic software quality • Quality of the deterministic fracture mechanics models • Adequacy of uncertainty representation and propagation • Adequacy of verification and validation
COG-JP-4367-046, Revision 0, PRAISE-CANDU Version 1.0 Pilot Study	• Quality of the deterministic fracture mechanics models • Adequacy of uncertainty representation and propagation • Adequacy of verification and validation
COG-JP-4367-026, Verification and Validation Report for PRAISE-CANDU 1.0.	• Adequacy of verification and validation • Quality of the deterministic fracture mechanics models • Adequacy of uncertainty representation and propagation
COG-11-2096, LOCA Break-Opening Characteristics for CANDU HTS Piping – Literature Review	• Arguments to justify request for change to existing regulation
COG-JP-4367-041-R0, FPBOC-WG Integrated Close-out Report.	• Summary report on previous documents and other activities in the Composite Analytic Approach

4.4 APPROACH USED TO REVIEW THE DOCUMENTS

The six documents are reviewed individually. Using Table 6 as a guide, the pertinent issues emphasised in each document are studied to determine the adequacy of PRAISE-CANDU Tool. For ease of presentation, traceability and tracking each document is reviewed using its sectional outline. For a given section, an overview of the section, the strengths and suggestions for improving the report are summarised. Before presenting the review of the individual document, summaries of the most important findings from the review are discussed in the next chapter.

5.0 SUMMARY OF FINDINGS FROM THE REVIEW OF THE COG DOCUMENTS

5.1 INTRODUCTION

The structural and the probabilistic models in PRAISE-CANDU are quite general, up to date, and based on our review, should be adequate for assessing the structural integrity of most CANDU piping when the issues summarised in the next sections are successfully addressed. The issues are discussed under six headings:

- Basic software development plan;
- Technical adequacy of the deterministic models;
- Technical adequacy of the probabilistic models;
- Adequacy of verification and validation exercises;
- Quality assurance and safeguards in place for users; and
- Adequacy of the pilot study

5.2 BASIC SOFTWARE DEVELOPMENT PLAN

The basic software plan, spelt out in the specification report, is sound. Independence between the developer and the verifier is in place as part of the plan. The software developer chosen is familiar with both the nuclear industry and probabilistic fracture mechanics. Furthermore, there is provision for tracking, documentation, verification and validation defined as part of the plan. CSA N286.7-99 standard is the chosen standard used to ensure quality, and when properly followed would lead to a great product.

We will suggest that the issue of tracking and documentation of errors need to be as transparent as possible.

5.3 TECHNICAL ADEQUACY OF THE DETERMINISTIC MODELS

The deterministic models implemented in PRAISE-CANDU are discussed mainly in four COG documents. The primary COG document is the Theory Manual (Sections 1-9). Other documents that present the deterministic models are the Specification Report (Section 5.11) and the Pilot Study (Section 3). Some considerations on the deterministic models are also presented in the Verification and Validation Report (Sections 3-5). In this section, the findings from the various reports are amalgamated and summarised.

The deterministic models in PRAISE-CANDU are used to represent the piping structure, material strengths, loading, damage initiation and progression. The models are for the crack tip stress intensity factor, the J-integral and crack opening areas, crack initiation and growth, crack stability, stresses and general flow acceleration. Damage modes that can be studied using the models are fatigue and stress corrosion crack initiations and growth and FAC. These are common damage mechanisms in CANDU piping. Nuclear piping loads that can be modeled in PRAISE-CANDU are broad, and include both normal and transient service loads, deadweight, environmental loads, seismic, vibratory and weld residual stresses. Most of the deterministic models are analytical equations derived from mechanics while few are empirical models based on calibrations from experiments or service data.

A review of the pilot study indicates that the input parameters for the deterministic models will come from various sources, including in-service experience, experimental data, nuclear databases, and advance numerical modelling tools, such as finite element analysis. Because a few of the models are still under development and evolving, it is expected that revised versions of the tool will incorporate new versions of the models. PRAISE-CANDU models in the theory manual are current and versatile but the documentation, justifications and explanations of assumptions need to be beefed up.

In keeping with CSA-requirements, most of the assumptions, sources, methods, limitations in PRAISE-CANDU are identified and explained. Given that this is the virgin version of the tool, there is room for improvement.

One major shortcoming, although not necessary technical (*difficult to determine*) is the frequent reference made to information or models in WINPRAISE 07 without presenting detailed discussions in the COG PRAISE-CANDU reports. Documentation of the deterministic models will be greatly enhanced if references to WINPRAISE 07 is minimised by providing the detailed information in PRAISE-CANDU reports or making the relevant

WINPRAISE 07 reports a part of PRAISE-CANDU reports in the form of an Appendix. As it stands, some of the major details in PRAISE-CANDU that need reviewing are buried in WINPRAISE 07 reports that are not accessible to the reviewers, making a fair assessment difficult.

Another major issue is the lack of discussion on bias or error in the deterministic models in PRAISE-CANDU. Deterministic models have bias that could impact the accuracy of the results. There is no mention in any of the COG reports, including the Verification and Validation report, on the treatment of bias determined from validation.

The number of user defined inputs puts intense emphasis on a Theory Manual and a User Manual providing a high level of guidance to the user. Assumptions and default values need to be clearly defined and explained.

A summary of the technical adequacy of the deterministic models based on the review of the COG documents is presented, starting with the loads on the structure. Attempts are made to summarize the content of the sections before highlighting the shortcomings.

5.3.1 Loads

One of the main drivers that affect the structural integrity of CANDU piping is the loads applied on the structure. These loads, which include environmental, operational and accidental, have to be adequately modeled if a credible structural integrity assessment is to be performed. The loads have to be translated to stresses and used to derive the appropriate stress intensity factors needed for crack initiation and growth. PRAISE-CANDU load representation is discussed in several COG documents that were reviewed. The primary document is the Theory Manual (Section 7 – Stresses). Other documents that discuss loads are the Specification Report (Section 5.11) and the Pilot Study (Section 3.3). From the Theory manual, five load categories, discussed under the topic stresses, can be discerned. These are: (i) Service Stresses (deadweight, normal operation, specified transient); (ii) Cyclic Stresses for fatigue initiation; (iii) Seismic Stresses; (iv) Residual Stresses; and (v) Vibratory Stresses. From the specification manual, six load groups are mentioned either under stress or load as (i)

Normal Operating Load (Pressure and bending moments due to deadweight and restraint of thermal expansion); (ii) Seismic Loads; (iii) Thermal Transient Loads (iv) Fatigue Initiation (v) Residual Stresses and (vi) Vibratory Stresses.

Based on the documentation, all the main load groups experienced by a typical NPP piping, including CANDU are discussed and these would be adequate for structural integrity assessment if they are correctly implemented. However, for clarity, the vocabulary and categorization used for loads need to be consistent across the documents. Furthermore, brief discussions on the various load categories before delving into their input format in PRAISE-CANDU will be helpful. In addition, several load related vocabularies used without definition or clarification, including primary loads, secondary, displacement controlled stress etc., need to be fleshed out for clarity.

Additional issues that need clarification are the load combination and the load sequence implemented in PRAISE-CANDU for damage initiation and growth when there are multiple loads. It is well known that the size of damage is influenced by how the loads are combined and which load is applied first. These issues need to be discussed and presented clearly. The distinction between secondary and primary loads and the implementation of the two loads type in PRAISE-CANDU also need to be clarified.

Other load related discussions are summarised using the load categorization in the Theory Manual.

5.3.1.1 Service Stresses

The main expression used to translate service loads, deadweight, normal operation, specified transient, to peak stresses in PRAISE-CANDU is a modified form of the ASME Boiler and Pressure Vessel Code Equation (11) of NB-3650 of Section III [42]. This is a standard model designed for NPP piping and should be sufficient for CANDU piping. This equation can be used to translate load, for example from deadweight, which are defined in PRAISE-CANDU as moments, pressure, temperature and forces, to stresses. Methods for handling transient loads and formulas for computing through-wall gradient of the service axial stresses are well laid out and clearly defined. However, the equation (Equation 7-1, Theory manual) also has variables, E_{ab}, T_a, T_b, α_a, α_b, which are not clearly defined or explained in PRAISE-CANDU. They are mentioned in the List of Symbols as Young's modulus at material discontinuity and temperatures and coefficients of thermal expansion in materials *a* and *b* of dissimilar metal weld. There are no discussions or mentions of dissimilar metal weld in the text describing the loads. For clarity, this needs to be added, and a diagram showing the weld configurations will definitely clarify the formula and symbols in the Equation (Equation 7-1, Theory manual).

Furthermore, the specification Manual states that appropriate set of stress indices (Ci, Ki) in the ASME Equation shall be defined by the user. Guidance will need to be given on this and a good starting place might be the use of the default values stipulated in the ASME manual as it is done in the pilot study.

5.3.1.2 Cyclic Stresses for Fatigue Initiation

In both the theory manual and the specification report it is noted that the definition of cyclic stresses for initiation of fatigue crack requires special consideration and PRAISE-CANDU has the ability to define these stresses taking into account the spatial variations and the differences in environments between transient types. However unlike the other load categories where descriptions of the load inputs are defined within PRAISE-CANDU Theory manual, there is none for cyclic stresses for fatigue. Instead the reader is referred to the USER manual for details, making it impossible to assess the cyclic stresses for fatigue initiation. For consistency and completeness, descriptions should be given on the stress details for cyclic stresses for fatigue crack initiation, or alternatively the user manual should be appended to the Theory manual.

5.3.1.3 Seismic Stresses

Seismic loads can be of high magnitude and failure can occur by a combination of overload and low cycle fatigue. A typical earthquake is a low frequency event, with maximum loads (variable amplitude) significantly higher than normal operating conditions.

In Section 7.3 of the Theory manual on Seismic Stresses, it is stated that “The inputs are in the form shown in Table 5. There are three lines of load input, one for loads…..” This is inconsistent with the format of Table 5 where each transient was represented by two lines of data and is not clear if seismic loads are defined before, after or in-between transients.

Also, two methods are provided to take into account the influence of the seismic stresses, one requires reset of the crack condition after the seismic event and the other allows the crack growth calculation to continue after the seismic event. These two methods will lead to different results that have practical implication. This should be addressed in the Theory manual.

5.3.1.4 Residual Stresses

Weld residual stresses can be influenced by material property variation, weld deposition sequence, repairs, weld process and inputs among others. Although residual stress is mentioned and some models are provided in several PRAISE-CANDU documents, not much discussion is given on the topic. For example, in the Theory manual the discussion is on three residual stress models implemented in PRAISE-CANDU: deterministically-defined, polynomial and linear, and circumferential variation. In the Specification Manual, it is noted that “the treatment of residual stresses in WINPRAISE 07 will be used in PRAISE-CANDU but the selection based on pipe size will be eliminated and the current default treatment for large diameter pipe will be reworked because it does not give an accurate representation of the data.” And the Pilot Study uses a residual stress model from R6, under the topic weld residual stress.

Several improvements can be made to the discussions on Weld Residual Stress (WRS) in PRAISE-CANDU, starting with a consistent acronym across the documents and followed with a more detailed discussion on WRS, especially for dissimilar metals, since WRS are known to drive PWSCC crack growth, which is one of the prime damage modes considered in the current tool.

Comments needs to be provided on the reworking of the default treatment for residual stress model from WINPRAISE 07 in PRAISE-CANDU since it was mentioned that the model is not accurate, and an explanation should be given on the implication, if any, of ignoring residual stresses on crack opening area as it is stipulated in the Theory manual, under the title of mid-life changes.

Also the introduction and use of R6 residual stress model in the pilot study, even though such a model was not mentioned in either the specification or the theory manual, needs clarification. Furthermore, within the pilot study, the uncertainty in WRS is assumed to be epistemic, a good assumption we believe, with a coefficient of variation of about 10%. The choice of COV of 10% and not a higher value needs to be justified given that nothing is known about the weld residual stress at the joint.

5.3.1.5 Vibratory Stresses

Vibratory stresses are discussed in the Theory manual. It is noted that these stresses can have a significant effect on fatigue crack growth. A description of what the PRAISE-CANDU tool does during crack growth analysis driven by high vibratory stresses is given, including several assumptions in terms of crack direction, breakthrough and checks made by the code. The user is expected to define the mean value and the standard deviations of the stresses, as well as, the values of the stress intensity factor at the high R-ratio.

Improvements that can be made to the discussion, to include a brief presentation on the sources of vibratory stresses in the context of CANDU piping and a description of how the stresses are derived. In addition, inclusion of a description of the input format structure for vibratory loads in the Theory Manual, similar to what is done for the other load types, will make for clarity and consistency of presentation.

5.3.2 Crack Tip Stress Intensity Factors

Crack tip stress intensity factors, which are the main driving force for crack growth and propagation, are discussed in three COG reports: The Theory Manual (Section 2, section 7.1.2), The Specification Report (Section 5.11.5) and The Verification and Validation Report

(Section 5.3). Two types of stress intensity factors, surface and through-wall are implemented in PRAISE-CANDU. Formulations and solutions for part-through wall stress intensity factors is derived from API 579/ASME FFS-1 (2007) while results from Takahashi (2002) is used for the through wall crack.

The stress intensity factors, K-solutions, used in PRAISE-CANDU are already developed and documented in the literature. They are for the idealised semi-elliptical cracks. These K-solutions, which are suitable for most applications, are derived for α values up to $\alpha = 0.8$. However, in PRAISE-CANDU the value of stress intensity factor at $\alpha = 0.8$ are also used for $\alpha > 0.8$ without justification. That is, the values of crack tip stress intensity factor are used beyond the limit of their intended application. This is a fundamental issue that needs to be addressed because such usage could undermine the accuracy of the crack initiation and propagation in the tool.

In PRAISE-CANDU the part through wall crack and the crack opening are assumed to have idealised semi-elliptical and elliptical shapes respectively. However, for some damaged scenarios, for example the transition of crack growth by PWSCC, the crack shapes may not take the idealised shapes implemented in PRAISE-CANDU. Axial flaws for example which are not modeled in PRAISE-CANDU are possible in these cases, bringing into question the adequacy of the K-solutions for those damage scenarios (USNRC and EPRI, 2011a). This is another issue that needs to be resolved.

In PRAISE-CANDU, it is assumed that when a semi-elliptical surface crack becomes a through wall it transitions to a straight crack with the same area. This assumption, although not necessarily true is all cases, is a conservative one that should be considered acceptable.

Since the choice of K-solution for the stress intensity factor can affect the accuracy of the results, as seen in Figure 12 (page 113 of Verification and Validation Report) where xLPR outputs are compared to PRAISE-CANDU outputs. It is imperative that justification be offered for the choice of the model in PRAISE-CANDU.

5.3.3 J-Integral and Crack Opening Area

J-integral and crack tip opening area are discussed in three documents: The Theory Manual (Section 3, Section 7.1.2), The Specification Report (Section 5.11.6) and the Verification and Validation Report (Section 5.2). The J integrals are used for stability analysis and one of the GE/EPRI methods is used in PRAISE-CANDU. With this method the total J-integral and the crack opening displacement are calculated as the sum of the elastic and plastic components. Fully plastic-J and total J are discussed for both part through-wall cracks and through-wall cracks. The Ramberg-Osgood stress strain characterization is adopted in PRAISE-CANDU. Several technical issues discussed below need to be addressed.

The part-wall and through-wall fully plastic J solutions in PRAISE-CANDU are from several literature publications. The **through-wall** plastic J-solutions are for **combined** bending and tensile loads. The J-solutions for the **part-wall** cracks are **not** for **combined** tensile and bending moment loads. As a result of this, several assumptions that appear questionable are made in PRAISE-CANDU (page 14 Theory Manual) to adapt the existing independent solutions for part-wall cracks for the combined case. Furthermore, assumptions are also made without justification that extend the application of the published results for α =0.8 to α > 0.8. These assumptions, which allow the J-integral solutions in PRAISE-CANDU to be used outside the limit of their intended application, have the potential to undermine the results and need to be justified.

Models are mentioned but not presented for the linear multidimensional interpolation scheme used in the J-solutions. These models need to be included in the Theory manual so that they can be verified and validated.

The crack opening area, COA is based on the crack opening displacement, an assumed elliptical break opening and a user specified shape factor, k, to account for opening area that are not elliptical. Guidance should be provided on appropriate value for k.

The Romberg-Osgood model used in the GE/EPRI model in PRAISE-CANDU has issues when employed to model dissimilar metal welds. Specifically, the problem is the ability of the model to accurately capture the measured stress-strain behavior (Brust, 1987; Gilles and Brust, 1991; Kim, et al., 2004; Chattopadhyay, 2006; Huh, et al. 2006). Huh, et al., 2006, discussed how the J estimates are sensitive to the accuracy of data fitting when the Ramberg-Osgood model is used. This issue needs to be addressed.

5.3.4 Crack Initiation

Three COG documents present the crack initiation models implemented in PRAISE-CANDU. These are the Theory Manual (Section 4), The Specification report (Section 5.11.13, 5.11.16) and the Verification and Validation Report (Section 4.1, 4.2, 5.1). Both fatigue crack (cycle dependent) and stress corrosion cracking (time-dependent) are discussed. The models are used to define the time to initiation at which a crack appears in a segment of the piping. The initiation time (cycles) is considered to be random but to depend on stress and service conditions. Under this topic, the concept of segments, within-heat, heat-to-heat and initiation size, which are used to translate the fatigue crack and stress cracking models developed from small size laboratory specimens, to reactor components that have much larger sizes, are also discussed. The fatigue crack initiation model in PRAISE-CANDU is based on fatigue life curves developed by Argonne National Laboratory (ANL). Two relations, power law and Garud, for defining the initiation time in PWSCC are presented.

Fatigue crack initiation models are an important driver to predicting probability of leak and rupture in piping systems. Flaws that can lead to leak or rupture can either initiate as a result of residual stresses, service loading or can grow from pre-existing flaws that are introduced during the fabrication and welding processes and associated imperfections (for example lack of fusion and porosity). The theory manual indicates that the fatigue crack initiation models in PRAISE-CANDU are hard-wired. As already noted, they are based on the probabilistic fatigue life curves developed by Argonne National Laboratory, calibrated from laboratory specimens of different piping material grades under different environmental conditions. The values of some model parameters are stipulated, fixed and cannot be changed. Because of these limitations and conditions, guidance and the limits of applications of these models to CANDU-piping should be discussed in detail. None of the reports reviewed discuss these issues.

Although the models for PWSCC initiation in PRAISE-CANDU are up to date, the issue of appropriate models for PWSCC initiation is still being debated and not yet resolved (USNRC and EPRI, 2011; NUREG-2110, 2012, Wang et al, 2011). This important point needs to be mentioned.

To convert laboratory models to actual rector components, the pipe circumference is divided into a user-defined number of segments of about 2 inches long and the crack initiation model is then applied to each of these segments. However, it is not clear if similar divisions are also made in the axial direction. It is noted in the Theory manual that within-heat and heat-to-heat variances have a large influence on break probabilities and that the user defined within-heat and heat-to-heat parameters, which is allowed in PRAISE-CANDU, can be additive or multiplicative. Clarifications and guidance are needed on the procedure for the axial variation of crack initiation, within-heat and heat to heat variances in CANDU piping.

5.3.5 Crack Growth

The crack growth models in PRAISE-CANDU are presented in three reports: The Theory Manual (Section 5); The Specification Report (Section 5.11.16, 5.11.17) and the Verification and Validation Report (Sections 4, 5). Both fatigue crack growth (cycle-dependent cracks) and stress corrosion crack growth (time dependent cracks), are discussed. Models are also presented on coalescence and placement, and crack transitioning. After the crack initiates, its growth is controlled by the crack-tip stress intensity factor. For a crack growing with both fatigue and stress corrosion cracking, the growth due to fatigue is performed before the growth due to stress corrosion. Cracks are grown in both the depth and the length directions. The fatigue crack growth rate is considered to depend on two factors, the cycle crack-tip stress intensity factor and the load ratio. Two forms of fatigue crack growth rate are implemented in PRAISE-CANDU, tabular and Equation 5-1 (from ASME Boiler and Pressure Code, 2010). Default tables for the rate of fatigue crack growth are provided for ferritic and stainless steel. The model for stress corrosion cracking employed in PRAISE-CANDU is based on the relation developed for Alloy 600 and related weld materials and can be found in Section XI of ASME Boiler and Pressure Vessel Code. Multiple cracks can initiate and grow in the segments that compose a given weldment and the crack linking criteria is based on Section XI of ASME Boiler and Pressure Code. A surface crack is considered to transition to through wall crack when the crack depth is 95% of the pipe thickness.

The availability of two models for fatigue crack growth, analytical and tabular is a very good idea because it broadens the scope of analysis that can be performed with the tool.

Assessment of fatigue damage growth in ferritic and stainless steel pipe will involve the use of default tables for fatigue crack growth rate, hard-wired into PRAISE-CANDU and derived from various sources. The bivariate interpolation model used to interpolate the results is mentioned, but the formula for the interpolation is not discussed in either the specification or the theory manual. A bivariate model implies there are at least two possible sequences of interpolation that should yield the same result, thus the need for verification. For testing and transparency and verification, the hard wired tables and the models for the interpolation need to be a part of the Theory or Specification Manual.

Several models for stress corrosion crack growth, which are likely to yield different results, are reported in the literature (White et al, (2005), Morton et al, (2005), Attanasio and Morton, (2003); Hong et al, (2002), Jenson et al., (2002); Eason, and Pathania, (2007)). The model implemented in PRAISE-CANDU is one among many and has a user specified crack growth random parameter, c_g, which is multiplicative and likely to greatly influence the crack growth. Given that there are so many models that can potentially be used a discussion is needed on the choice and suitability of the model in PRAISE-CANDU. Guidelines should be supplied on the appropriate values for c_g.

5.3.6 Crack Stability

A crack stability criterion, which can be through-wall or part-through wall, is a function of crack size (length and depth), materials property and applied load. A surface crack stability criterion is used to assess whether or not a surface cracked pipe transitions to a through-wall cracked pipe and a through-wall crack criterion is for evaluating transitioning a through-wall cracked pipe to a ruptured pipe. Two stability criteria, the net section stress and the tearing instability, implemented in PRAISE-CANDU, are discussed in several documents: Theory manual (Section 6); Specification document (Section 5.11.7); Verification and Validation (Section 5.2) and Pilot Study (Section 3.7). These criteria are not identified to be applicable to either through-wall or surface crack.

In PRAISE-CANDU, the stresses considered in the net section stress calculation are from global loading (pressure, deadweight, constrained thermal expansion and seismic). Only the pressure, deadweight and seismic loads, the so called load-controlled portion of stress, plus a user defined portion of the displacement stress (thermal expansion) is used in the net section calculations. The net section method computes the stability of a given set of cracks with a specified tension and bending loading. If the cracks are predicted to be unstable a complete pipe severance is considered to occur. In tearing instability analysis the applied value of the crack driving force, which is expressed in terms of J-integral, is computed using normal operating stress plus seismic and compared with the materials crack growth resistance. The material crack growth resistance is determined from test data.

Various improvements are needed in the stability criteria discussions. First, two separate discussions should be provided for surface crack and though-wall cracks because the stability criteria for the two types of cracks are not necessarily the same. Secondly, the models implemented, net-section and tearing instability, especially the net section, has mathematical formulas (equations) associated with them. These equations, which are not presented in any of the documents that were reviewed, should be added because they need to be verified and validated. Additional improvements are as follows.

In the description of the net section stress failure, the total stress is divided into a load-controlled portion and a displacement-controlled portion. The deadweight and pressure are considered as load-controlled, whereas the stresses from thermal expansion and seismic loads are grouped into the displacement-controlled portion. Justification and explanation need to be given for excluding the displacement-controlled stresses from net section stability analysis.

PRAISE-CANDU will be used to analyse cracks in the main piping as well as welds. The fracture properties of the base metal will usually be different from the weld. The question then becomes which strength properties should be used in the stability analysis. Guidance should be given on this issue.

5.3.7 General Flow Acceleration Corrosion

General flow acceleration corrosion is discussed in several documents: The Theory Manual (Section 8), The Specification Report (Section 5.11.25), The Pilot Study (Section 3.9), and The Verification and Validation Report (Section 5). In all the documents, the discussion on the subject is very brief. It is noted that the damage mechanism, which is common in carbon steel pipe, is mostly a localised phenomenon that results in the thinning of the pipe wall from the inside surface. Although the effect of FAC is a localised thinning of the pipe, the localised effect is not modelled in the current version of PRAISE-CANDU. It is designated as a task for future versions of the tool. In the current tool uniform thinning is used and the thinning rate is a user specified, random and time dependent variable. The combined effect of FAC and crack (initiation and growth) is treated in the conventional fashion for no thinning, with crack depth reduced by thinning while the circumferential extent of crack is not considered to be reduced by thinning. Although the wall thinning can impact the value of the crack tip intensity factor, its effect is neglected in the current version of PRAISE-CANDU. Also, the pressure, applied moments and forces are considered to be constant and the changes in stress as the wall thins are accounted for by changing the thickness in the formula for calculating the axial stress.
Some of the issues that need to be addressed are discussed below.

Unlike previous damage mechanism in PRAISE-CANDU where reference materials are provided to support the modelling strategy, no single reference is provided on the FAC modelling approach in PRAISE-CANDU. To strengthen the report and to support some of the assumptions that are made, relevant published material on the subject need to be included in the report.

Furthermore, the impact of simplifying assumptions, such as, “the effect of changes in R/h is not accounted for, it will be small for the wall thickness changes usually encountered”, have to be supported using references or studies.

Guidelines should be provided on how to determine the appropriate thinning rate, given that it is a user specified time dependent random variable. The analysis sequence needs to be clarified in cases of combined FAC, fatigue and stress corrosion cracking. Which is executed first, FAC, stress corrosion or fatigue and what impact if any does the analysis sequence have on the result?

Although FAC is a localised phenomenon, it is modelled as uniform thinning in the current version of PRAISE-CANDU. Based on the information in the specification document, two of the follow up efforts identified, local FAC and axial cracks with FAC, will involve improving the FAC modelling capability. In the meantime, the current PRAISE-CANDU tool has to be used to make safety, operational and regulatory decisions, some of which will involve FAC damage. It is not certain whether the results from the currently implemented FAC model in PRAISE-CANDU are conservative compared to results from the planned localised models. If an accurate result cannot be obtained from the current model, then to guarantee safety the output needs to be at least a more conservative one. In order to get a handle on the degree of conservatism in the current model if any, an independent deterministic investigation of both models should be undertaken.

5.4 TECHNICAL ADEQUACY OF PROBABILISTIC MODELS

The probabilistic models in PRAISE-CANDU are discussed mainly in four COG documents. The primary report is the Theory Manual (Sections 9-10). Other documents are the Specification Report (Section 5.11, 6.3.2) and the Pilot Study (Section 3). Some discussions on the probabilistic models are also presented in the Verification and Validation report (Sections 6-9). In this section, the findings from the various reports are amalgamated and summarised.

The two main probabilistic features of PRAISE-CANDU are provision for probabilistic description of the input parameters as random variables, with mean, standard deviations and correlation, and a Monte Carlo simulation capability, that allows for realization and propagation of values of the random variables through the various deterministic models. The probabilistic models are discussed in PRAISE-CANDU under two broad titles, general statistical consideration and PRAISE-CANDU statistical consideration. The models include the types of random variables in PRAISE-CANDU, Monte Carlo Simulation schemes and sources of uncertainty. As a probabilistic fracture mechanics tool PRAISE-CANDU uses deterministic models of damage initiation, namely crack initiation and growth, and FAC to compute the probability of leak opening areas of various sizes in a piping system. Although the models are deterministic, to reflect reality, many of the inputs to the models have inherent statistical scatter and uncertainty. The scatter is characterised by considering some of the inputs to be random variables, whose distributions are based on analysis of data or engineering judgement. These contributors to randomness are either aleatory or epistemic. Based on the pilot study, it can be concluded that the probabilistic descriptions of the input parameters, that is the statistics (mean, standard deviation, correlation) and the probability distributions of the input random variables, will be derived from various sources, including in-service experience, experimental data, nuclear databases and engineering judgement. The probabilistic models in PRAISE-CANDU are current and versatile but the documentation, justifications and explanations of assumptions needs to be strengthened.

Before discussion areas that need strengthening some of the potential benefits that can be derived from the probabilistic features in PRAISE-CANDU are presented.

The probabilistic framework in PRAISE-CANDU, both aleatory and epistemic, will enhance results from the tool. In general a probabilistic framework is designed to enhance deterministic results. It is not meant to compete with deterministic analysis, rather to add value to the deterministic analysis. Since probabilistic fracture mechanics tools rely on deterministic structural model, the soundness of the deterministic model is very essential for probabilistic analyses. Most deterministic structural integrity decision framework use factor of safety as a tool to make decisions and assume that most parameters are known constants. This assumption that most design parameters are known constants rather than statistical variables is in most cases a gross simplification. The use of factor of safety based on judgement is essentially an implicit acknowledgement of the existence of uncertainties though this is not always stated. A factor of safety attempts to lump all uncertainties, known and unknown, into one big number and has the potential to be conservative. However, not all uncertainties are unknown and a probabilistic framework seeks to exploit this information for decision making.

Unlike the deterministic framework where decisions are based on fixed values and safety factors, in the probabilistic framework, decisions are based on the statistics (average values, standard deviations) and probability distributions associated with the input parameters. PRAISE-CANDU has Monte Carlo framework for propagating the uncertainties through the various models. A single Monte Carlo run is essentially a single deterministic analysis. Multi Monte Carlo runs are multiple deterministic analyses with combinations of many possible input parameters. The beauty of the Monte Carlo simulation is that it allows possible deterministic results from all possible values of deterministic input parameters, which are usually ignored in a normal deterministic assessment, to be investigated. Results from Monte Carlo simulations are as good as the fidelity of the deterministic models and the input random parameters description. That is why extensive review was carried out in the previous section on the technical adequacy of the deterministic models. If the deterministic models are sound, there is at least an average chance that the probabilistic results will be sound, but if the deterministic models are flawed, no probabilistic analysis can compensate for those shortcomings. The best probabilistic results are obtained by using adequate deterministic models with proper descriptions of the input random parameters.

When PRAISE-CANDU is fully certified, its epistemic uncertainty capability will provide a rational and systematic basis for incorporating incomplete or inadequate knowledge and the ability to introduce a graded scale of conservatism into the decision making process. Since each individual epistemic probability analysis gives one failure probability, then the statistics of failure probabilities (mean, standard deviation, median, and quartile) can be derived from all the epistemic runs. These statistics, which can be used in decision making, allow for conservatism to be introduced to the desired level. For example safety decisions can be made using the median, the mean, or the quartiles of the failure probability. For example leak related decisions could be based on the median failure probability of leak, while rupture related decisions are based on 99% quartile statistic of probability of rupture, a graded scale that is only possible with a tool that has epistemic modelling capability. This is a very neat feature of PRAISE-CANDU which is very good and should be encouraged. It is also the reason why the US-NRC and EPRI are pursuing this approach in the development of the xLPR tool.

In keeping with CSA-requirements, most of the assumptions, sources, methods, limitations in PRAISE-CANDU are identified and explained. Given that this is the virgin version of the tool, there is room for improvement.

Again as in the previous section, one major shortcoming, although not necessary technical (*difficult to determine*) is the frequent reference made to information or models in WINPRAISE 07 without fleshing out the details in PRAISE-CANDU report. To make for a fair assessment, this problem needs to be fixed.

Another issue that needs clarification is the treatment of model uncertainty. Several models, which are simplified or idealised mathematical equations, are used in PRAISE-CANDU to predict responses of different quantities, including stress intensity factor, fatigue/crack initiation and growth, stresses in the structure etc. Probabilistic fracture mechanics uses Monte Carlo simulation that involves repeated calls to the deterministic models and this can be quite computationally expensive. Therefore, in practice to reduce the computational cost, complicated models that involve advance numerical tools, such as, finite element models, which may yield improved deterministic results, are avoided and simplified models, preferably analytical expressions, are used in most probabilistic fracture mechanics. Because the models have simplified assumptions they have model uncertainties. The uncertainties might be because the model predictions are slightly different from the more elaborate models or experimental tests or operational results. By its very nature, model uncertainty is very difficult to assess but it can have impact on the results and should not be ignored (HSE, 2001). Model uncertainty is often assessed on the basis of experimental test results and may be expressed in terms of the probability distribution of a variable X_m

$$X_m = \frac{\text{Actual/Measured Response}}{\text{Predicted/Model Response}}$$

It is not clear how model uncertainties are handled in PRAISE-CANDU. This needs to be explained. In the absence of better information on the model uncertainty for a deterministic model, at a minimum, model uncertainty could be introduced as a multiplicative random variable with a mean value of 1 and a small scatter or standard deviation to reflect the possibility that there may be slight variations in the model results from the "actual or measured" response. In the absence of model uncertainty, one can either conclude that the deterministic model used is either the best model representations for the phenomena under consideration or its shortcoming are not fully reflected.

A summary of the technical adequacy of the probabilistic models based on the review of the COG documents is presented. Attempts are made to summarize the content of the sections before highlighting the shortcomings.

5.4.1 General Statistical Considerations

The uncertainty in PRAISE-CANDU is characterised by modelling some of the inputs as random variables, whose distributions are based on analysis of data or engineering judgement. Five two-parameter probability distributions are available in PRAISE-CANDU, normal, lognormal, Weibull (exponential and Rayleigh as special case), symmetrical triangular and uniform. The tool also has a tabular distribution option. The random variables in PRAISE-CANDU are considered to be mostly independent. Any dependent random variables must have either normal or lognormal distributions and are treated using coefficient of linear correlation. Monte Carlo simulation technique, which employs Mersenne Twister random number generator, is used in PRAISE-CANDU to obtain the probabilistic results from underlying deterministic lifetime model.

The six probability distributions in PRAISE-CANDU are in keeping with the distributions used in the PRAISE tool and most of the other PFM tools developed in the USA for NPP applications, FAVOR, PRO-LOCA, SRRA etc. These two-parameter distributions, which are easy to calibrate (determine their statistics or distribution parameters), are adequate for most practical applications of PFM. Given that the results of very small probabilities of failures can be very sensitive to the distribution choice it should be explained, what impact if any, the unavailability of other probability distributions have on the results, and plans to mitigate such impact by using the six distributions.

Although the theory manual may not be the right document to address parameter specific questions that can be discussed in the user manual, since the user manual is not available for review, the following issues need to be addressed to improve the quality of the document.

1. What provisions are available in PRAISE-CANDU for calibrating distributed parameters based on measured in-service or experimental data?
2. What provisions will be used to determine the best distributions for parameters among several alternative distributions based on measured in-service or experimental data?
3. What guideline will be used to determine the minimum number of data points that is required to consider a parameter a random variable?
4. What are the rationales for limiting correlation to only normal and lognormal distributions?

5.4.2 PRAISE-CANDU Specific Statistical Considerations

Several topics are discussed under PRAISE-CANDU specific statistical considerations, including stratified sampling, selective lifetime calculation and, heat-to-heat versus within-heat scatter. The random variables in PRAISE-CANDU are independent, except two fatigue initiation random variables, four strength random variables, and two sizing random variables. All the random variables can assume any of the six distributions in PRAISE-CANDU except correlated variates, epistemic description of uncertainty, and fatigue initiation random variables which can only assume normal or lognormal descriptions. PRAISE-CANDU can be run in deterministic mode. Stratified sampling, which is essentially an approach that allows for samples of crack sizes to be drawn from the large-size tail of the distribution, is used to speed up calculation in the case of a single dominant pre-exiting crack. It cannot be used when there are multiple cracks. Selecting lifetime calculation approach is used in cases of multiple cracks that can easily combine into long cracks. Scatter in fatigue and stress corrosion crack initiation is considered to compose of heat-to-heat and within-heat contributions. The distinction between within-heat and heat-to-heat is very important when calculating probabilities of large crack opening areas.

A scheme for speeding up calculations on break probabilities for cases with multiple initiating cracks is developed and implemented in PRAISE-CNADU. But no discussion is given on the scheme in any of the documents that have been reviewed. For verification, testing and transparency, the models for the scheme and its implementation need to be in the Theory Manual.

The Theory manual states that a user specified cut-off below which life time calculation should not be performed has the potential to influence the results of analyses. The basis and practical sources of heat-to-heat and within-heat scatter, which are terms probably associated with welding etc., are not explained in any of the COG documents. However, it is noted in the reports that the distinction between the two has a strong influence on the results. Also how the variances in within-heat and heat-to-heat will be determined for CANDU piping is not discussed. Therefore for clarity and confidence in the output more detailed explanations need to be given on these concepts, practical implication and sources. Furthermore, guideline needs to be developed on how to determine within-heat and heat-to-heat scatter and the cut off for life time calculations.

5.5 ADEQUACY OF VERIFICATION AND VALIDATION EXERCISE

Verification and validation activities are used to demonstrate that the as-built software meets its requirements, as described in the theory manual and user's guide. They are the main tools used to prove that the computer program results are reasonable. Verification is used to check if we are solving the equations right in the computer code. It is essentially an error check: Verification answers the questions are the models implemented correctly in the computer, and are the input parameters and logical structure of the model correctly represented? Validation checks if we are using the right equations and if the model is an accurate representation of the real system. PRAISE-CANDU's verification and validation process are documented in two COG reports that were reviewed: The Specification Report (Section 6); and the Verification and the Validation Report.

The Specification report, states what will be done. From the report, the entire verification process consists of three items: (i) hardware/system test; (ii) user interface and input/output

(I/O) verification; and (iii) analysis validation. None of the reports that are reviewed has information on verification of hardware/system test, and user interface and input/output (I/O) for PRAISE-CANDU so we cannot comment on the execution of these items. However, it will be productive to know if the two related tasks, under Section 6.22 User Interface I/O Test and Section 6.2.3 File I/O Test, stated in Section 6.22 as " *….range checking of all the inputs and any dependencies with respect to the inputs will be verified*." and in Section 6.23 " *this set test consists of using text files will be used to repeat all the applicable verification performed in Section 6.2.2*", was executed, because this is a repeatability test.

Most of the sixteen tasks stipulated under analysis validation were executed and documented in the Verification and Validation report that was reviewed. Documentations on a few of the tasks are missing from the verification and validation report, and we are not sure if they were executed but not reported or if there were not executed, including the following:

1. Load Module Verification. "*load inputs will be in the form of bending moments, pressures and temperatures. Transformation of these loads to provide stresses used in the crack tip stress intensity factor and J-integral flaw models will be checked by independent calculations. Checks will also be made on the residual stress inputs to see if they are being implemented as intended*."
2. Crack-Tip Stress Intensity Factor Module Validation: "*……In cases where the K-solution is in terms of tabulated values, the tables will be checked. Multi-dimensional interpolation within such tables will be checked by independent calculations*."
3. Failure Criteria Module validation: "*…… Check on the tearing instability for part-through and through-wall cracks will be made, as well as check on net section stress.*"
4. Unit Verification: " *Comparison will be made between the results obtained using SI units (previously verified portion of PRAISE-CANDU program) and customary Imperials units*".

Although equations for stress transformation are presented in Section 7 of the Theory Manual, there is nothing in the Verification and validation report to indicate that these equations were verified. Multi-dimensional interpolation and net section collapse stress are both mentioned in the Theory manual, but their mathematical representations are not presented in any of the documents that were reviewed nor their verification, even though these items were designated for verification in the specification document. Also a review of the Verification report, shows that most of the analysis validation activities were executed using either the Imperial or the SI units, very few had both.

Based on these observations it can be concluded that analysis validation is incomplete from either lack of execution or documentation.

The Verification and Validation report on PRAISE-ACANDU is centered on the correct implementation of the models from the Theory manual into the computer tool. A review of the verification and validation report suggests that a lot of work was done. The report can be broadly divided into three main sections, introduction, verification, and validation.

The introduction deals with the quality standard used for the verification exercise, a definition of acceptance criteria and a summary of verification and validation packages. Several aspects of the Verification and Validation activities in PRAISE-CANDU are very good and commendable. The standards used for the verification and validation exercise, CSA N286.7-99 and CANDU Energy Standard Quality Assurance, are of high quality and if they are correctly implemented can result in a great product. The definition of the acceptance criteria is reasonable.

An issue that needs to be discussed in the Verification and Validation report is the independence of the developers and the verifiers. From the review of the Verification and Validation report, the level of independence between the code developer and the verifier is not clear. The tool was developed by the staff of SIA (Section 3.5 of Specification Report) and the majority of the verification packages, twenty five out of thirty, were prepared by the staff of SIA (Section 3 of the Verification and Validation Report). Was it the same or different staff that executed both activities? Since the SIA staff that carried out both tasks is/are not named, it is difficult to judge the independence of the activities, which is one of the ideas that was advanced in the Specification report to ensure the quality of the product.

A summary is presented of the adequacy of verification and validation documentation. More detailed discussion on these issues can be found in Chapter 9.

5.5.1 Adequacy of Verification

The verification section, which constitutes the bulk of the Verification and Validation Report (Chapters 4 to 11), is essentially an error check to ensure that formulas from the theory manual are implemented correctly in the PRAISE-CANDU tool. It covers several topics including, module verification, deterministic checks, random sampling checks, independent probabilistic verification and checks, trend and sensitivity studies and rank of importance random variables. The basic approach adopted for documenting the verification activities is the same for all the modules. It consists of four steps:

1 Definition of a Test plan;
2 Documentation of the Test implementation;
3 Test Results; and
4 Summary

The test plan states the plan to be carried out to verify a model or equation or module implemented in PRAISE-CANDU from the theory manual. An example test plan is "*perform a deterministic analysis, including fatigue crack initiation and observe initiation time. Compare the initiation time with hand calculation*." The statement highlights what model in PRAISE-CANDU is to be verified, the output from the model and the alternative calculations to be executed for verification. Some test plans in the verification and validation report are clearly defined, deal with one model at a time, and identify the output and the means/tool to be used for verification, which allows for easy and fair judgement on the test implementation and the tool capability. However, within the validation report there are many test plans that have various issues that need to be fixed, including a lack of statement of the plan, definition of too many models in one plan, and/or lack of identification of means/tools used for verification, making it difficult to assess the implementation or/and the documentation. One example is "*problems with one initiation and growth being the only random variable can be checked with simple independent calculation. The distribution of initiation time can be described in closed form in terms of the distribution of the initiation coefficient….*" This is not really a plan, it is a statement. Another one states "*.. stress intensity factors were checked by generating K versus* *a tables with PRAISE-CANDU and comparing results with independent calculations, using pc-CRACK[10] or SignalFFS[11]. J-solutions were checked using deterministic calculations for a specified load to obtain the applied value of J as a function of crack size A combination of tension and bending for both a surface crack and a through-wall crack were considered and results were compared with independent calculations. COD-solutions were checked using deterministic calculations for a specified load to obtain the opening displacement as a function of crack size. A combination of tension and bending for a through-wall crack were compared with independent calculation.",* which is also not a plan, but a statement of what was done.

A final example "*Perform a deterministic crack growth analysis with three transient types and check that loads are being properly used in the calculation of cyclic stress intensity factors. Include a deterministic fatigue crack growth problem that also include seismic event. Perform related analysis with FAC."* which has too many tasks, relating to too many models (fatigue, load check in cyclic stress factor, seismic check, FAC etc) in one plan and the means/tool to be used to execute the plan is not identified. These and similar problems are present in some of the test plans in the verification report. More problems of this type are highlighted in the detailed review of the documents, Chapter 9 of the current report. When the test plan is not clearly defined and/or loaded with too many models and/or not clearly documented, it is difficult to assess its execution and give a pass or fail grade to the verification exercise.

The test implementation and test results portion of the verification exercise are designed to flesh out the execution of the test plan. At a minimum a problem statement, method used, the input parameters, assumptions, the results and a brief discussion need to be presented in the test implementation documentation within the verification and validation report. This will allow for a fair assessment of the test implementation. Also, the level of details should be such that an independent verification can be carried out to arrive at the same or different outcome before consulting the results in the archives. A good example of typical items that need to be in the test implementation is an abbreviated version of the items in the example problem executed in the Pilot study. In addition a good record keeping where the above details, along with the test plan and summary are archived during the verification exercise is essential. Most of the test implementations in PRAISE-CANDU appear to have been archived well. These stored files, called V & V Packages along which with their extensions, are properly documented in the verification and validation report. This make for easy traceability

The level of detail on the test implementations documented in the verification and validation report is at best uneven, with most being very sparse or non-existent. This problem needs to be corrected because, it is difficult to assess the activities fairly without the documentation. An example on Random Sampling Check is presented below to highlight the problem. Detailed highlight of the issues with documentation of the verification exercise on the various sections of the Verification and Validation Report is presented in Chapter 9.

Section 6 of the verification and validation report which deals with Random Sampling Checks is used to illustrate the problem with the documentation in the Verification and validation report. Before discussing the issues we note that, Section 6 is the only chapter in the verification and validation report that deals exclusively with probabilistic or random testing. From this section we are supposed to draw conclusions on the fidelity of the random variables and Monte Carlo simulation capabilities in PRAISE-CANDU. Other sections of the report deal with either deterministic models or probabilistic fracture mechanics models that combine deterministic models with input random variables. One will expect that enough details are presented in this Chapter so that it is very obvious to a reviewer that the probabilistic portion of the code is working as intended. However, this is not the case as will be shown shortly.

The section has only one test plan that is supposed to capture all random sampling checks and it states "*checks are to be made to assure that the random Monte Carlo sampling is being performed properly. Define probabilistic runs with many random variables, and print out all sampled values of the random variables. Be sure to include at least one of each distribution type (plus tabular) included in Table 2-3 of the V&V Plan[2]. Compare sampled values with analytical expression representation of distribution, such as by computing mean, standard deviation and plotting cumulative probabilities. Include at least one run with correlated variables, and compute correlation coefficients to compare with inputs……*"

This test plan is loaded with too many tasks, but from this test plan one will expect that when it is implemented, there will be tables/figures/numerical numbers of random variables with mean values, standard deviation, plots of cumulative distribution of the random sample generated from PRAISE-CANDU against samples from some standard statistical packages, execution of goodness of fit test to ascertain that samples of random variables, such as a Weibull distribution, generated from PRAISE-CANDU matches up with similar samples from a standard statistical package etc. But this is not the case at least based on the documentation in the verification and validation report

In the Verification and Validation report the test implementation of the above plan is documented in two short paragraphs of ten lines each. There are no problem statements, no input parameters defined, no tool that was used for verification identified. The test implementation section starts as follows "*The PRAISE-CANDU 1.0 software was run with additional output box "random Samples" checked in the initial set up screen. Many runs were made so as to check all five distributions types described in Table 2-3 of V&V Plan[2]. Also, for selected random variables, random samples were checked by defining the random variable as either aleatory or epistemic or both. Correlation Coefficient were also checked for correlated random variables ……. Once it was observed that the sampling is correct for selected random variables a white box testing was performed by carefully looking into the code that sampling methods are called correctly for all the random variables… performed*."

The report on the test results has four sections. Each section has one paragraph of about 8 lines. There are no tables, figures, graphs or equation etc. to help the discussion. The entire tests plan, test implementation, test results and summary for Random Sampling Checks, which is supposed to be the only verification exercise for "the probabilistic portion" of PRAISE-CANDU, is presented in less than two and half pages. Therefore, there is not enough information for a third party or any other knowledgeable person that was not party to the implementation of the plan, to assess fairly the verification of random sampling capability in PRAISE-CANDU from this documentation.

Other sections of the verification and validation reports have similar documentation issues to varying degrees and these have to be addressed.

5.5.2 Adequacy of Validation

Validation is the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model. It provides evidence, or substantiation, for how accurately the computational model simulates the real world for the system responses of interest. Validation is meant to show that the output from the software is correct. In the context of probabilistic fracture mechanics, the main tool available for validation is benchmarking, where the results from the tool are compared either with results from other similar tools or with data from operating experience. Although benchmarking has its shortcomings, it is the only method that we know for validating a PFM tool. Unlike most deterministic outputs, for example stress response that can be measured experimentally, failure probabilities especially for large passive structural components like the piping in NPP, is not a measurable quantity, it is a derived quantity based on the frequency of occurrence of the failure event. A good benchmark must have a clear and precise definition and description of its purpose and a very good documentation of the exercise, including detailed description of the problem, the inputs, differences between the models, inputs and outputs between the tools, assumptions that are made to reconcile the differences between the tools, inputs, descriptions of the implications of the assumptions, and detailed discussions of the results.

The validation section (Chapter 11 and 12 of Verification and Validation Report), which is used to prove that PRAISE-CANDU results are reasonable, is centered on the use of benchmarking exercises to compare PRAISE-CANDU results to other similar PFM tools and operating experience. The documentation is similar to the one presented above for the verification exercise and consists of the four steps presented earlier: Definition of a Test plan; Documentation of the Test implementation; Test Results and Summary.

The test plan states the plan to be carried out to validate PRAISE-CANDU. Again, at a minimum, a problem statement, the method used, the input parameters, assumptions, the results and a brief discussion need to be presented on the test implementation within the verification and validation report. This will allow for a fair assessment of the test implementation and test result. Also, the level of details should be such that an independent validation exercise can be carried out to arrive at the same or different outcome before consulting the results in the archives. With regard to documentation, the problem with the validation of PRAISE-CANDU is similar to verification that was discussed in the previous section.

There is also an additional issue that makes proper documentation of validation activities crucial, the assumptions made during benchmarking. For example, when two similar tools are benchmarked, they do not necessary have exactly the same models. Assumptions have to be made during the benchmark exercise. These assumptions have to be properly documented in the validation report so that a fair assessment can be made by a third party concerning the results from the benchmarked tool.

The developers of PRAISE-CANDU recognise the importance of benchmarking the tool and have carried out several studies on it as documented in (Wang, 2012, Wang et al, 2013, Duan et al., 2013). One of the studies, Wang, 2012, is cited as a reference in the current COG V & V report. Twelve pages are devoted to documenting validation using benchmarking with other tools. The information provided in the twelve pages are mostly graphs of results and include the test plans (case titles), test implementations (two short paragraph with information on V & V file folder locators) and summaries (several plots that compare PRAISE-CANDU results to other tools). The section on validation with other tools as written does not have enough details for us to pass a valid judgement on the quality of the benchmarking exercises.

Some of the details provided in the other external documents will need to be included in the verification and validation report. For example in Wang et al, 2013, detailed description is given of the input parameters, and the differences between the input parameters used in xLPR and PRAISE CANDU. From Wang et al, 2013, for example, it is stated "*the temperature and pressure are considered to be random in xLPR while they are considered to be deterministic in PRAISE-CANDU*" and " *Note that the 10-based log term in f_{H2} was coded as natural* *logarithm in the Grower module source code of xLPR. This results in the growth rate being 30% lower and was taken into account in PRAISE-CANDU by adjusting other coefficients*". Such details and others are lacking in the current version of PRAISE-CANDU 1.0 V&V report and they have to be included to enhance the quality of the result and provide a basis for a fair assessment of the work.

5.6 QUALITY ASSURANCE AND SAFEGUARDS IN PLACE FOR USERS

The quality standard chosen for PRAISE-CANDU development, CSA N286.7-99, when fully followed, is a good one that can result in high quality software. For the most part, it appears the standard has been followed. Improvements that need to be made to fully execute the standard's verification and validation requirements in PRAISE-CANDU are already presented in the previous sections and will not be repeated here.

Other issues will be addressed in this section, including the User guide or manual. It is noted in Section 5.13 of the specification manual, "*the output of any software is only as good as the input. The limitations of this software are based on the values used for the inputs. If those values are incorrect then the outputs will be incorrect. Input values must be validated for each application.*" These sentences underscore the need for a good User manual that minimises the risk of input errors, output errors, result interpretations and that is validated to ensure that the tool has safeguards in place for users and cannot be used outside the limit of its applications. Items in the User manual should include flow charts that highlight the different paths that the user can take for different analyses, program flows, guidance on input data, defaults values that can be used for certain parameters that cannot be readily characterised etc. Therefore, verification and validation exercises should not only be performed to confirm the equations in the theory manual; they should also be extended to the User manual. An example is a test plan where two competent users are given the same analytical problem and tasked with coming up with the same results using PRAISE-CANDU tool and the User manual as a guide. This type of exercise should be executed and the outcome used to improve the User manual. It is well known that human errors/mistakes are a major cause of output errors. Clear, concise guidance is required. The goal of the User manual verification is to minimise human errors from wrong interpretation/understanding/application of the tool. Objective comments cannot be made on the safeguards in place for users because the User manual was not one of the documents we were tasked with reviewing. However, we suggest that this aspect should not be ignored. It needs to be looked into as well.

Based on the review of the Theory manual and the Specification document, there are many instances where the user is expected to stipulate parameters, the so called User defined parameters, without guidance. These have the potential to introduce errors or differences in the calculations. Most of these instances are documented in Chapters 6 and 7. A guidance document with justifications for the end users is very essential if the outputs from PRAISE-CANDU are to be reliable and repeatable.

5.7 QUALITY OF THE PILOT STUDY

The pilot study is used to demonstrate the capability of PRAISE-CANDU through an application of a problem of mechanical fatigue coupled with FAC degradation of the large diameters PHTS piping in Pickering NPP Unit 5-8. The goal of this study is to show how the PRAISE-CANDU tool can be applied to address a specific problem. The current pilot study, which has one example problem, is a good one but incomplete for several reasons.

As noted, the goal is to show how PRAISE-CANDU can be applied to address a specific problem and ultimately as an aid to the operators and the regulators in making decisions, that is, to showcase the capability of PRAISE-CANDU as a tool for decision making. Therefore, effort should be made to present a complete study that covers all the bases, including sensitivities analyses. In the pilot study only one example problem is solved but it is not completed because sensitivity analysis is slated for future work. Such an important aspect of the study should not be postponed because it could impact the outcome and conclusions from the study. For example, from the pilot study it is concluded "*…in theory more work could be done to reduce the uncertainty in the WRS; but considering the relative small uncertainty in the failure probabilities this additional effort may not be warranted*." In the absence of a complete study, that examines the impact of variability in both the standard deviation and the average value of the weld residual stresses and other parameters, this conclusion is at worst not valid or at best valid but premature.

Additional improvement in the Pilot study is on the models used. They should come from PRAISE-CANDU Theory manual and not outside sources because the pilot study is meant to show how PRAISE-CANDU tool is used to address a specific problem. Equations quoted in the Pilot study need to be equations from the Theory manual and emphasis should not be placed on other sources. Several references are made to ASME models in the current Pilot study, which is a good practice, without a corresponding emphasis on the models as implemented in PRAISE-CANDU. The primary reference for models, which can be quoted extensively, is PRAISE-CANDU Theory manual. Also, new models should not be introduced in the pilot study, as it is currently done, because it gives the impression that the PRAISE-CANDU models, presented in the Theory manual, are either not suitable or incomplete. In the Pilot study the weld residual stress used is a new model based on R6, which was not mentioned or discussed in the Theory manual. If the R6 equation is considered to be such an important model, that it merits application in the Pilot study, then for completeness of the PRAISE-CANDU tool, it needs to the added to the Theory manual.

Two of the three damage mechanisms in PRAISE-CANDU, fatigue and FAC are used in the Pilot Study. For completeness, a study that includes the third damage mode, PWSCC, needs to be investigated as well.

5.8 ADEQUACY OF PROPOSED BREAK OPENING CHARACTERISTIC MODELS

Using extensive literature review of international studies, the COG recommends break opening models for axial and circumferential flaws in large-diameter CANDU PHTS piping. For axial breaks, it is recommended that the initial break develops to a size of 7% of the flow area of the pipe in 5 ms. For circumferential breaks, it is recommended that the initial break develops to a size of 3.5% of the flow area of the pipe in 5 ms, followed by an increase in the size of the break to 200% of the flow area of the pipe in an unspecified long-length of time that would depend on the dynamics of the piping system but that would be in excess of 2.5 s.

The proposed models deviate from international practice and are based mostly on literature review of studies that do not involve large CANDU PHTS piping directly. They do not have precedence and will involve significant changes in break-opening time philosophy for large CANDU PHTS piping. To ensure safety, detailed studies of typical CANDU plants are needed to substantiate and justify the proposed models.

6.0 COG-JP-4367-005 REVISION 2: SPECIFICATION FOR PRAISE-CANDU 1.0

The specifications for PRAISE-CANDU 1.0 are discussed in the document. It is the main document that outlines the requirements that the software has to meet. There are six main sections: Introduction; Problem Definition; Development Plan; Theoretical Background; Requirement Specification; and; Preliminary Verification and Validation Plan. Each of the sections is reviewed and a summary of the most important issues is given at the end of the chapter.

6.1 INTRODUCTION

The introduction presents, the background, the purpose of the report, reason for choosing to work with Structural Integrity Associate (SIA), the quality assurance program and changes made from revision one. A joint Industry CNSC working group was established to find solutions for resolving the issue of positive Coolant Void Reactivity and Large Break Loss of Coolant Accident safety margins in existing Canadian CANDU reactors within a risk informed framework. One of the tasks of the working group is the development of a CANDU Probabilistic Fracture Mechanics (PFM) computer program for main circuit (primary heat transport system) piping in CANDU plants. The report is a quality assurance document that provides a description of the problem, development plan and the requirements that shall be met by the computer program. It is prepared in accordance with AECL SQA procedures, and CSA N286.7-99 software quality assurance standard. The initial version of PRAISE-CANDU will satisfy either the requirements of CSA N286.7-99 or 10CFR50, Appendix B.

6.2 PROBLEM DEFINITION

6.2.1 Overview and Strengths

PRAISE-CANDU 1.0 is intended to estimate the failure probability for a spectrum of break sizes of Primary Heat Transport System (PHTS) piping in CANDU plants. The results will be used to define the threshold break size. The plausible degradation mechanisms considered include general Flow Accelerated Corrosion (FAC), Primary Water Stress Corrosion Cracking (PWSCC) and fatigue. PRAISE-CANDU is to be Tier II computer program in accordance with CSA N286.7-99.

6.2.2 Areas for Improvement

None

6.3 DEVELOPMENT PLAN

6.3.1 Overview and Strengths

The development plan discusses the task breakdown, key milestones, development tool and methodology, review testing, verification and validation, independence between developer and verifier, non-conformance, subcontractor components, interaction between contributors, documentation and responsibility, configuration management, version identification, change control and process for updating development plan. PRAISE-CANDU will be developed based on WinPRAISE and will take advantage of the major technical advancement and lessons learned from xLPR 1.0 to address CANDU specific issues, which are FAC plus fatigue in large-diameter piping and PWSCC in dissimilar metal welds in outlet feeders. Two levels of verifications for the software are defined, one by SIA staff, the other by AECL staff. It will not be a modification of WinPRAISE but a new tool, developed independent of WinPRAISE.

6.3.2 Areas for Improvement

Since WinPRAISE is the main material that is used for PRAISE-CANDU, the theory manual on WinPRAISE needs to be included as part of the specification documents.

6.4 THEORETICAL BACKGROUND

6.4.1 Overview and Strengths

The requirement of the theoretical background is based on Clauses 6.4 and 11.3.3 of CSA N286.7-9 and includes the following elements, theory and mathematical equations, assumptions and constraints, solution techniques and rationale, any empirical correlations and applicable existing reference. The theoretical and mathematical equations in PRAISE-CANDU should include pertinent equations and models for deterministic linear-elastic and elastic-plastic fracture mechanics and uncertainty description of parameters. The assumptions and constraints in the software are primarily in the areas of structural mechanics and elastic/elastic-plastic fracture mechanics and are associated with the structural models to be employed. In the area of structural mechanics, the loads, which are important inputs, are based on ASME Boiler and Pressure Code for Piping. In the area of elastic-fracture mechanics, the assumptions include nonlinear material behaviours such as the use of Ramberg-Osgood to describe stress strain curve, small displacements, homogeneous isotropic materials, stress intensity factor that drives fatigue and crack growth, crack stability controlled by applied value of J compared to crack growth resistance curve, or by the net section stresses, and stresses for fracture mechanics analysis come from piping stress analysis. It is also assumed that crack initiation time or cycle is controlled by user-defined function that describes the statistical distribution of initiation time (cycle) for a given stress, temperature and environment. Standard Monte Carlo simulation is used to compute probability of failure. Empirical correlations will not be used except for well documented cases such as PWSCC crack growth. Harris and Dedhia, 2007, which is WinPRAISE 07 is identified as the document that has most of the deterministic fracture mechanics models and Monte Carlo simulation algorithms.

6.4.2 Areas for Improvement

Since WinPRAISE 07, is the main material that is used for PRAISE-CANDU, it needs to be included as part of the specification documents.

6.5 REQUIREMENT SPECIFICATION

6.5.1 Overview and Strengths

The fourteen items identified and discussed as requirements specifications are the name of the computer program; functions; hardware, software and operating system requirements; user interfaces; menus; computation speed requirements; portability requirements; file size and type requirements; input and output requirements; data structure and data flow; top level data flow; level 1 data flow; analysis data flow; programming languages; imposed physical and mathematical models and numerical algorithms; error handling requirements; accuracy target; and requirements on programing practices. As its function PRAISE-CANDU deals with FAC, fatigue, PWSCC and only considers circumferential cracks in piping full-penetration girth butt welds.

The major technical specifications of PRAISE-CANDU are presented under the heading; imposed physical and mathematical models, the models and equations to be implemented in PRAISE-CANDU. The topics discussed include treatment of uncertainty, random number and statistical distributions, Monte Carlo simulation, units, crack-tip stress intensity factor, J-integral, failure criteria, leak rates, loads/stresses, normal operating loads, seismic loads, thermal transient loads, fatigue initiation, residual stresses, vibratory stresses, fatigue crack growth, PWSCC growth relations, inspection and POD, size of initiated cracks, crack coalescence, mid-life changes, crack initiation relations, time-dependent inputs, crack size stratification, seismic treatment, FAC inspection, and follow on efforts including local FAC, Axial Cracks with FAC, IGSCC.

Several models and methods described in WinPRAISE 07 are to be implemented in PRAISE-CANDU. They are automated stratified Monte Carlo simulation for problem involving a single random pre-exiting crack defect, capabilities for stress input, treatment of residual stresses without the selection based on pipe size, definition of cyclic stresses for initiation of fatigue cracks, treatment of vibratory stresses, fatigue crack growth relations, coalescence procedure, midlife changes, crack initiation relations, seismic treatment.

Models and methods to be included in PRAISE-CANDU that are not in WinPRAISE are: methods to separate epistemic (inherent randomness) and aleatoric (lack of knowledge), an optimization procedure for Monte Carlo Simulation recently developed by SIA (Wang et al, 2011) to accelerate LOCA probability calculations for problems with multiple cracks, use of detectable COA in lieu of leak rate calculations, consideration of applied loads as bending and tension instead of the conservative tension only load as is currently done in WINPRAISE, independence of parameters that define initiation fatigue and depth, a_0 and b_o; a different treatment of inspection and POD; refinement on definition of loads such as classification of loads into primary or secondary; and model of PWSCC growth relation adopted in xLPR.

Time dependent inputs to be considered in PRAISE-CANDU include thinning rate (to simulate general FAC), tensile properties (yield, flow strength, Ramberg-Osgood parameter D; to simulate ageing); toughness C_R (to simulate age-related embrittlement).

Additional features to be added to PRAISE-CANDU after completion of version 1 are local FAC, axial cracks with FAC and IGSCC. Local FAC will be treated as wall thinning, rather than uniform thinning. The thinned area will be described by depth, length and width and the failure criteria is for the local thin area, rather than a crack. The rate of growth in the three dimensions will be treated as independent or related random variables. Other random variables to be considered include the flow stress, relevant loads and initial wall thickness. Also ID and OD axial cracks in axial seam welds in straight pipe and bend/elbow will be considered. OD cracks will use crack growth relation for the different environments and will not involve FAC. The growth of axial ID crack combined with general FAC would be treated, using water crack growth relations. ID cracks can be consumed by the FAC. The size of the crack and its growth will be random variables in addition to those associated with FAC itself.

6.5.2 Areas for Improvement

There are far too many references to procedures, models and ideas from WinPRAISE 07, that form part of PRAISE-CANDU technical specifications, mentioned in the document without sufficient details to assess what they mean. For example the following: "(i*) Definition of cyclic stresses for initiation of fatigue cracks require special consideration because of the spatial variations and differences in environment between transients' types. The capability of stress input outlined in Section 3.2.23 of WinPRAISE manual shall be used. (ii) The treatment of vibratory stresses in WinPRAISE 07 shall be used (see Section 9.3 and 13.1 of the WinPRAISE 07 manual). (iii) The relations for crack initiation due to fatigue that are in WinPRAISE 07 (Section 6.1 of [12]) will be used and (iv) the relationship for PWSCC crack initiation in WinPRAISE shall be used (Section 7.1 of [12]). (iv) The treatment of residual stresses in WinPRAISE is used, however the current treatment for large-diameter pipe shall be reworked, because it does not give accurate representation of data.*" Clarity demands that these procedures be included in the report or relevant section of WinPRAISE should be included as an appendix. The absence of these details makes it impossible to assess the procedures.

Crack tip stress intensity factor is based on the circumferential surface and the through wall crack parameters in API 576, API (2007), and Takahashi (2002) respectively. All through-wall cracks are considered to have straight front, hence, when semi-elliptical surface cracks first become through-wall they are immediately transitioned to straight cracks with the same area. Assumption of circumferential crack profile although quite broad excludes other damage cases that may include axial cracks. The transition model, from semielliptical to straight cracks with same area is a conservative one. It implications on inspection, leak and rupture results should be discussed.

The definition of loads is a difficult aspect of fracture mechanics. The approach that is used should be spelt out clearly especially the procedure and conditions for combining the various loads types. The basic formula for defining peak stress is Equation (11) of NB-3653.2 of section III of the ASME Boiler and Pressure Vessel Code. Although it is mentioned that further refinement of the definition of loads, such as classifying the loads into primary or secondary shall be implemented. This has not been documented in the theory manual.

Several assumptions need justifications and clarifications including the following: (i) Through-wall variation of residual stresses shall be considered to not be influenced by general FAC thickness changes. (ii) The temperature related terms and bending moments under thermal transients shall be considered to not be influenced by general FAC thickness changes.

In Section 5.11.12, on transient load, it is stated that "*The temperature related terms shall be considered to not be influenced by general FAC thickness changes. Bending moments shall be considered to not be influenced by general FAC thickness changes*". While in Section 5.11.23, time dependent inputs, it is stated "*that the influence of thinning on piping load stresses, pressure stresses and crack opening area shall be considered*". The two statements appear to be in conflict and need to be reconciled.

Section 5.11.16 permits user specification of cracked growth rate via tabular input. As this affects the primary code purpose, only locked tables should be permitted. Section 5.13 should be titled "Precision and Accuracy Targets". The accuracy targets stated in the COG V&V report (Section 1.3)) should be repeated here.

Under Midlife change, which can include changes in water chemistry, wall thickness and/or residual loads/stresses it is stated that "it is not necessary (for conservatism) to provide provision to change crack growth characteristic as crack grow from the original material into material added during a mid-life change. It is not clear what this means.

Two different approaches for seismic treatment are provided, one that resets after seismic event (current WinPRAISE 07) and one that applies the seismic events and continues. The results from the two approaches will be different, conditions under which the two approaches should be used need clarification.

6.6 PRELIMINARY VERIFICATION AND VALIDATION

6.6.1 Overview and Strengths

The topics discussed are hardware/system test, verification of user interface and I/O requirements; and analysis of verification and validation. PRAISE-CANDU is designed and programed for the Windows XP professional and Windows 7 and the user interface is a standard Window form-based user interface. Table 7 summarises the planned verification and validation activities

Table 7: Summary of Planned Verification and Validation Exercises

	Module	V & V Activity	Tool
1	Load Module	• Check transformation of load inputs, bending moments, pressure, temperature, to stresses • Confirm proper implementation of residual stress inputs	Independent Calculation
2	Monte Carlo Sampling	• Check Monte Carlo sampling to ensure all distributions are generated properly, normal, lognormal, uniform, exponential, weibull, tabular • Check treatment of epistemic and aleotoric uncertainty	Independent Calculations MATHCAD Spreadsheet
3	SCC Crack Initiation Module	• Check SCC initiation time calculation. Generated statistic of initiated cracks and compare with input distribution	Independent Calculations MATHCAD Manual
4	Fatigue Crack Initiation Module	• Check fatigue crack initiation times. Generated statistic of initiated cracks and compare manually with input distribution	Independent Calculations MATHCAD

	Module	V & V Activity	Tool
			Manual
5	Crack Tip Stress Intensity Factor Module	• Check Crack tip stress intensity factor models • Check K-solution tables • Check Multi-dimensional interpolation	Independent calculations pc-CRACK Signal Fitness for Service
6	PWSCC Crack growth Module	• Check deterministic PWSCC crack growth calculation	Independent Calculations MATHCAD Hand Calculations pc-CRACK Signal Fitness for Service
7	Fatigue Crack growth Module	• Check deterministic fatigue crack growth calculation	Independent Calculations MATHCAD Hand Calculations pc-CRACK Signal Fitness for Service
8	Crack Coalescence Module	• Check crack coalescence of multiple crack for simplified problems.	Independent Calculations
9	Failure Criteria Module	• Check failure and crack stability treatment • Check tearing instability for part-through and through wall cracks • Check net section stress.	Not defined
10	COD	• Check COD validation	Not defined
11	Inspection	• Check corrected implementation of inspection, sizing and repair • Check post repair crack distribution with a specified size distribution	Independent Calculations
12	General FAC	• Check FAC wall thinning • Check removal of cracks by FAC • Checks using example dominated by one mechanism	Not defined
13	Integrated fatigue initiation and growth	• Check using one initiating crack convolution integral	Independent Calculations MATHCAD
14	Integrated PWSCC initiation and growth	• Check using one initiating crack and convolution integral • Check using multiple initiating crack • Check trends for within-heat and heat to	Not defined

	Module	V & V Activity	Tool
		heat, and circumferential stress gradient	
15	Trends	• Check if increased stresses increase the leak probability • The slope of the leak probability versus time decreases after each inspection • More favourable detection probability has a greater effect on the leak probability • Larger median crack size (for pre-existing cracks) lead to higher leak probability • Lower toughness lead to higher leak probability • Heat to heat and within heat scatter has effect on relative LOAC and leak probabilities • Etc.	Not defined
15	Units Verification	• Compare results obtained using SI units and customary imperial units	Not defined

6.6.2 Areas for Improvement

The tools for verification need to be identified for all cases.

7.0 A REVIEW OF COG-JP-4367-011, REVISION 0: THEORY MANUAL FOR PRAISE-CANDU 1.0

The document sets out the theoretical basis, formulas and models that are implemented in PRAISE-CANDU 1.0. It is the main document that addresses the technical content of the software. It has ten main sections: Introduction; Crack-tip stress intensity factors; J-integrals and crack opening areas; Crack initiation; Crack growth; Crack stability; Stresses; Inspection, monitoring and testing; general statistical considerations; and PRAISE-CANDU specific statistical considerations. Each of the sections is reviewed and a summary of the most important issues is given at the end of the chapter.

7.1 INTRODUCTION

7.1.1 Overview and Strengths

It covers the background on PRAISE-CANDU, the major advancement over previous series of PRAISE codes, the purpose of the report, the modules and variables in PRAISE-CANDU. PRAISE-CANDU is a tool with probabilistic models of crack initiation and crack growth that will be used to perform plant specific probabilistic fracture mechanics calculations to estimate the probability of failure for a spectrum of break sizes for CANDU Primary Heat Transport System piping. Results from such analyses will serve as the technical basis for reclassifying the instantaneous large LOCA as a beyond design basis accident. PRAISE-CANDU is an updated version of the original PRAISE code and the subsequent expanded versions that have been developed over the years. Major advancements over previous codes are mentioned including treatment of time-dependent material properties and development of the tool with full formal quality assurance procedures.

The report is prepared in accordance with CSA N286.7-99 software quality assurance standard and AECL SQA procedures. As noted in the report a fundamental requirement for the theory manual is that it provides adequate documentation of following: (i) the underlying theory and mathematical equations, (ii) assumptions and constraints, (iii) solution techniques and the rational for selecting them including adequacy requirements and other limitations, (iv) any empirical correlations, their range of application, and associated uncertainties and (v) applicable references. These requirements provide a benchmark for judging the quality of a theory manual and will be applied to PRAISE-CANDU 1.0 theory manual. The thirteen deterministic modules and the twelve random variables in PRAISE-CANDU 1.0 are mentioned in the introduction.

7.1.2 Areas for Improvements

PRAISE-CANDU is essentially PRAISE with enhanced additional features to address issues relevant to CANDU primary heat transport system piping, PHTSP. To distinguish PRAISE-CANDU from PRAISE and its subsequent modifications, and to enhance the quality of the theoretical manual, features in PRAISE-CANDU that address issues unique to CANDU PHTSP need to be presented. It is not clear from the current introduction what those features are if any.

7.2 CRACK-TIP STRESS INTENSITY FACTORS

7.2.1 Overview and Strengths

This section discusses the crack tip stress intensity factors used in PRAISE-CANDU. It is presented on pages 11-12 and pages 69-72 of the document. Stress intensity factors are the main driving force for crack growth and propagation. Formulations and solutions for part through wall stress intensity factors is derived from API 579/ASME FFS-1 (2007)[11] while results from Takshashi (2002)[12] is used for the through wall crack.

The main sources of information for the stress intensity factors are reliable. API 579/ASME FFS-1 (2007) is a high quality industry standard and Takshashi (2002) is peer reviewed material. Therefore, the generalized fourth order polynomial curve fitting solutions for local crack tip stress intensity factor at the deepest point and surface point for cracked piping, Equations 2.3 and Equation 2.4 respectively, and the Takahashi formula, Equation 2.7, for through wall cracks stress intensity factor will probably be adequate for most plant specific cases that will be handled by PRAISE-CANDU.

7.2.2 Areas for Improvements

To elicit confidence, rationales for the choice of Equations 2.3, 2.4 and 2.7 and the limits of their applicability have to be included in the document. Solution strategies that will be adopted for the rare cases where the currently implemented stress intensity factors are not adequate should be discussed. Additionally, the document has to address alternative models and solutions that were considered and discarded if any. Other specific questions that should be addressed are given below:

The K-solutions of Equation 2.3 and 2.4 are applicable for crack sizes with $\alpha \leq 0.8$. However, in PRAISE-CANDU 1.0, for crack with $\alpha > 0.8$, the crack-tip stress intensity factors are calculated using G terms evaluated at $\alpha = 0.8$. From our understanding of fracture mechanics, usually, when a crack becomes very deep and the crack front is very close to the upper surface, the stress intensity factor would increase rapidly. Therefore, in this case, the use of G values at $\alpha = 0.8$ for cracks with $\alpha > 0.8$ will have a tendency to underestimate the stress intensity factors. It is stated in the theory manual that “the behaviour as a/h exceeds 0.8 is not unreasonable” (Page 12). Evidence should be provided to support this statement as none is provided in the current manual. Also in Section 2.2 the justification for limiting the half angle to 110^{o} is missing.

The stress intensity factors obtained using the G values directly and the influence functions are presented in Figures 4 and 5 (page 60, 61). The plots showed that the results from these methods were in good agreement. However, the variables plotted in the figures are not clearly defined in the Figure titles ($K_a/B_i(a)^{1/2}$), making it difficult to understand and assess the meaning of these figures. Also since a comparison is made between G values and the “influence functions”, for clarity the term “influence function” should be explained within the document.

The formulas presented for both part-through-wall crack (Eq. (2-3) and (2-4)) and through-wall crack (Eq. (2-7)) seemed to assume that the centre of the crack was at the location of the maximum bending stress. However, in reality, this cannot always be the case. This assumption needs to be justified.

In the formula for stress intensity factors for through-wall cracks, only the tension and bending stresses were considered (Eq. (2-7)) but the polynomial stress component given in Eq. (2-1) was ignored. It appears that this stress was generated by constrained thermal expansion. What is the significance of ignoring this stress in the calculation of stress intensity factors?

7.3 J-INTEGRALS AND CRACK OPENING AREAS

7.3.1 Overview and Strengths

This section deals with the J integrals and the crack opening areas models implemented in PRAISE-CANDU. It is presented on pages 13-17 of the document. The J integrals are used in the tearing instability crack analysis and crack opening displacements to calculate the break opening area. The so called GE/EPRI method is used to calculate the J- integrals. Formulations and solutions for part through wall crack fully plastic and total J are derived from a variety of sources including Kumar et al., (1981)[13], Kanninen and Popelar, (1985)[14]; Anderson, (2005)[15] and Saxena 1998[16]. Results from Cho et al, (2011)[17]; and interpolation procedure detailed in Structural Integrity Associate (SIA), 2011a[18], and SIA, 2011b[20] are employed. The tension-bending solution in Zahoor, (1989)[19] is used for evaluating the applied J for through-wall cracks in tension and bending along with the interpolation scheme given in SIA 2011b.

The main sources of information for the methods used for the J-Integrals and Crack Opening Areas estimations are given. They are books and published reports that are widely used in the industry including Kumar et al., (1981), Kanninen and Popelar, 1985; Anderson, 2005; and Saxena 1998[16]. Scot el al., 2002 and Rudland et al, 2002 documented a range of COD prediction performance where the GE/EPRI method was suggested to be the “best” method for calculating COD. Rudland el al. 2002 provided detailed comparison of a variety of COD analysis methods with finite element calculations and concluded that the GE/EPRI method is the best choice for COD calculation. Based on these studies, the GE/EPRI method is an excellent method for PRAISE-CANDU.

7.3.2 Areas for Improvement

Several technical and documentation issues need to be addressed in this section.

Section 3.1 of the document under review, which deals with J integrals for part-through-wall cracks for both tension and bending-moment loading, has several assumptions, extrapolations, interpolation schemes, procedures for combining different J results from different sources and user defined parameters that need either expanded documentation, justification or guidance. Most of the issues in this section that need resolution are technical in nature and are discussed.

The calibration functions for semi-elliptical shape part through-wall circumferential cracks for tensile and bending moment loadings in PRAISE-CANDU are found in Table 2 and Table 3 of reference [17] respectively. It is suggested that these tables be included in the report. The tables deal with tensile and bending moment independently. They do not deal with the general case of combined bending and tensile loading that is of interest in PRAISE-CANDU. An interpolation scheme is devised in Reference [18] to obtain the calibration function for the combined loading. It is impossible to assess the interpolation scheme because the detail is not discussed in the theory manual.

Also the calibration functions in Reference [17] cover a smaller range of crack sizes than what is required for PRAISE-CANDU. To circumvent this problem, the calibration functions in Reference [17] are combined with the calibration functions in Reference [19] and the results and procedure are presented in Reference [18]. The calibration functions in Reference [17] are for semi-elliptical crack in bending moment and tensile loading, while the calibration function in Reference [19] are for crack of constant depth in tension. Essentially, the calibration functions from the two documents [17, 19] are for two different crack shapes and sizes, and two different loading scenarios. This is a major technical issue that needs clarification and justification. Details on how these functions are combined are not clear because they are not discussed in the theory manual.

Once the two results are combined, the range of crack sizes that the results can be applied is further extended to 0.95 instead of 0.8. The detailed procedure and justification for extending this range is in Reference [20], but not in the theory manual. This is also a major technical issue that needs more details and justification.

Linear multi-dimensional interpolation scheme is employed based on Equation 25.2.66 in Reference [21]. The detail scheme is not provided in the COG theory manual. The results of a multidimensional interpolation scheme can be affected by the sequence employed in the interpolation. More details and justification on the scheme should be given in the Theory manual.

Section 3.2 of the document being reviewed provides an option for the user to specify either plane stress or plane strain condition. Guidance is required for the user to make appropriate selection between using plane strain or plane stress conditions. The section also mentions Tables for h_2 in Reference [19]. It is suggested that this table be included and explained in the Theory manual.

The essential crack shape considered for through wall crack opening displacement is elliptical break opening. To account for other shapes due to mismatch of wall thickness or material properties or even damage mechanism, a user defined constant, k, is stipulated. Again guidance should be given on appropriate value for this constant.

7.4 CRACK INITIATION

7.4.1 Overview and Strengths

This section deals with the initiation models for fatigue (cycle dependent) and stress corrosion cracking (time dependent) in PRAISE-CANDU. It is presented on pages 18-22. The models are used to define the time to initiation at which a crack appears in a segment of the pipeline. The initiation time (cycles) is considered to be random but to depend on stress and service conditions. It also discusses the concept of segments, within-heat, heat-to-heat and initiation size. The fatigue crack initiation model is based on fatigue life curves developed in Argonne National Laboratory (ANL) (Chopra and Shack, 1998[24]; Chopra and Shack (2001)[25]; Chopra et al, 2001[26]; Chopra and Shack, 2007[27]. These curves were applied to fatigue initiation studies of LWR (Khaleel et al, 2000[6]; Simonen et al. (2000)[28];. The fatigue crack initiation models were developed from laboratory specimens under different controlled environmental conditions. Uncertainty in the model is introduced by two parameters, a constant C_0 and the endurance limit ε. The initiation models have parameters that account for the environment and size. Input values for a variety of piping materials for LWR applications are given and hard-wired into PRAISE-CANDU. The Monte Carlo simulation procedure implemented in PRAISE-CANDU for fatigue crack initiation is discussed in detail. Two relations, power law and Garud, for defining the initiation time in PWSCC are presented. The scatter law model is based on Amzallag et al. (2002)[30], Amzallag et al. (1999)[31]], cattant et al.(2005)[32], Daret et al 92005)[33], and the Garud model is based on Garud, (2010)[34]. The concept of segment, within-heat and heat-to-heat is introduced to translate the fatigue crack and stress cracking models, which are developed from small size laboratory specimens, to reactor components that have much larger sizes.

The main sources of information for the models are given in the report. These are mostly published NUREG reports and peer reviewed work. Detailed description is given of random parameters within the models, sources of data, and in cases were user defined parameters are mentioned, typical values, probability distributions and variances are supplied. Numerical implementation of the models is discussed in detail.

7.4.2 Areas for Improvement and Justification

From the Theory Manual it is stated in that the initiation portion of the fatigue analysis in PRAISE-CANDU is based on probabilistic fatigue life curves developed by Argonne National Laboratory which were applied to fatigue initiation studies of LWR components by Pacific Northwest National Laboratory. It is understood that the model is calibrated from laboratory specimens of different pipeline grades under different environmental condition, so it should be possible to adapt them to CANDU piping components. However, since the CANDU reactor uses heavy water as coolant, a discussion of the effect of the coolant type if any on the probabilistic fatigue life curves will be helpful.

Furthermore, two parameters in the fatigue initiation model are user specified, size and initiation time multiplier. The size is usually taken as 4 and the initiation time multiplier as 3. Guidance on how to determine the appropriate value for this parameter is required because they will influence the result of an assessment. For example in the NUREG/CR-6674 (2007) it is noted that, the size effect was taken as 4 by ANL "in order to apply the fatigue data from small test specimen to full size components" and "is intended to account for size, geometry and surface-finish differences between small fatigue test specimens and actual components." NUREG/CR-6674 also noted that the size effect In(4) term of the ANL equation may have to be modified when used to address crack initiation at multiple sites. Additionally, fatigue initiation relations are not general; they are hard-wired into PRAISE CANDU because of environmental functions. Mean value and standard deviation of C_o and variance of the endurance limit are stipulated based on results from several publications. Because the value of these stipulated parameters are fixed, it is not certain that they can be applied to CANDU piping in all cases. Therefore, guidance should, be given on the limit of applicability of the model.

In Step 3 of the Numerical Implementation of the algorithm for fatigue crack initiation (page 19), cyclic stresses are used to calculate the cycles to initiation using Equation. (4-2). However, Equation (4-2) requires strain amplitude instead. An explanation is required on how the cyclic stress is converted to strain amplitude or if there is a typo in Step 3 it should be corrected. Is the conversion based on the assumptions of uniaxial stress, plane strain conditions, plane strain conditions, linear or non-linear material behaviour?

A definition is needed for the variable I_m, in Equation 4-4, the formula for crack initiation time using the Power Law Initiation.

Crack initiation models are important drivers to predicting probability of leak and rupture in piping systems. Flaws that can lead to leak or rupture can initiate as a result of residual stresses, service loading or can grow from pre-existing flaws that are introduced during the fabrication and welding processes and associated imperfections, for example lack of fusion and porosity. Although the models presented for PWSCC initiation in PRAISE-CANDU 1.0 Theory manual, Equations (4.4, 4.5) are up to date, the issue of appropriate models for

PWSCC initiation is still debated and not yet resolved (USNRC and EPRI, 2011; NUREG-2110, 2012, Wang et al, 2011). The transient nature of the models should be noted in the report.

To convert a laboratory model to actual rector components, the pipe circumference is divided into a user-defined number of segments of about 2 inches long and the crack initiation model is then applied to each of these segments. However, it is not clear if similar divisions are also made in the axial direction. Also, it is noted in the manual that within-heat and heat-to-heat variances have a large influence on break probabilities and user defined within-heat and heat-to-heat, which is allowed in PRAISE-CANDU can be additive or multiplicative. Therefore, clarification and guidance are needed on the procedure for the axial variation of crack initiation within-heat and heat to heat variances in CANDU pipes.

7.5 CRACK GROWTH

7.5.1 Overview and Strengths

The crack growth section, presented on pages 23-26, deals with fatigue crack growth (cycle-dependent cracks), stress corrosion crack growth (time dependent cracks), coalescence and placement, and crack transitioning. After the crack initiates, its growth is controlled by the crack-tip stress intensity factor. For a crack growing with both fatigue and stress corrosion cracking, the growth due to fatigue is performed before the growth due to stress corrosion. Cracks are grown in both the depth and length directions. The fatigue crack growth rate is considered to depend on two factors, the cycle crack-tip stress intensity factor and the load ratio. Two forms of fatigue crack growth rate are implemented in PRAISE-CANDU, tabular and Equation 5-1 (from ASME Boiler and Pressure Code, 2010). Default tables for the rate of fatigue crack growth are provided for ferritic and stainless steel. The model for stress corrosion cracking employed in PRAISE-CANDU is based on relation developed for Alloy 600 and related weld materials and can be found in Section XI of ASME Boiler and Pressure Vessel Code. Multiple cracks can initiate and grow in the segments that compose a given weldment and the crack linking criteria is based on Section XI of ASME Boiler and Pressure

Code. A surface crack is considered to transition to through wall crack when the crack depth is 95% of the pipe thickness.

As in the previous section, the main sources of information, which are mostly published NUREG reports and peer reviewed work are identified in the report. The sources include the following (Chopra et al. 2001[26], ASME, 2010a[35], ASME 2010b[36], Lo et al. 1984[37], Mills 2010[38], White et al. 2003 [39], Rudland 2011[40]). The availability of two models for fatigue crack growth, analytical model and tabular model, is very good because it broadens the scope of analysis that can be performed with the tool.

7.5.2 Areas for Improvement

Assessment of fatigue damage in ferritic and stainless steel pipe will involve the use of default tables for fatigue crack growth rate coded into PRAISE-CANDU that are derived from various sources. To enhance transparency and verification of the outputs, the tables need to be a part of the Theory Manual. Additionally, the formula for the bivariate interpolation model used to interpolate the results should be included in the COG Theory manual so that it can be tested and verified.

Stress corrosion cracking is generally recognised to depend on several factors including, temperature, load, material condition, water chemistry. Several models for stress corrosion crack growth, which are likely to yield different results, are reported in the literature (White et al, (2005), Morton et al, (2005), Attanasio and Morton, (2003); Hong et al, (2002), Jenson et al., (2002); Eason, and Pathania, (2007)). Equation 5.3, the model implemented in PRAISE-CANDU, is one model out of many in the literature. Because there are so many models available in the literature, the question of which model is appropriate for CANDU piping becomes an important technical issue. This is an area that is still being actively investigated. Additionally, guideline is needed on how the value of the user specified crack growth random parameter in Equation 5.3, c_g, which is likely to drive crack growth, will be determined for specific application. Discussions on these issues will strengthen the Theory manual.

7.6 CRACK STABILITY

7.6.1 Overview and Strengths

The crack stability section is presented on pages 27-28. The two stability criteria used in PRAISE-CANDU are the net section stress and tearing instability criteria. The net section stress stability criterion is based on Li et al [41]. The stresses considered in the net section stress calculation are from global loading (pressure, deadweight, constrained thermal expansion and seismic). Only the pressure, deadweight and seismic loads, the so called load-controlled portion of stress plus a user defined portion of the displacement stress (thermal expansion) is used in the net section calculations. The net section method computes the stability of a given set of cracks with specified tension and bending loading. If the cracks are predicted to be unstable a complete pipe severance is considered to occur. In tearing instability analysis the applied value of the crack driving force, which is expressed in terms of J-integral, is computed using normal operating stress plus seismic and compared with the materials crack growth resistance. The material crack growth resistance is determined from test data.

Again, as in the previous section, the main source of the net section approach is identified. The availability of two methods is very good because it allows for alternative procedures to be evaluated.

7.6.2 Areas for Improvement

The net section stability criteria used in PRAISE-CANDU involves analytical expressions that relate the pipe geometry, crack size, material properties and applied loads to stability and plays a critical role in assessing overall pipe fracture risk. These expressions need to be verified and documented as part of the verification and validation exercise. The models need to be included in the report.

In the description of the net section stress failure, the total stress is divided into a load-controlled portion and a displacement-controlled portion. The deadweight and pressure are considered as load-controlled, whereas the stresses from thermal expansion and seismic loads are grouped into the displacement-controlled portion. Justification and explanation need to be given for excluding the displacement-controlled stresses from net section stability analysis.

PRAISE-CANDU will be used to analyse cracks in main piping as well as welds. The fracture properties of the base metal will usually be different from the weld. The strength properties that should be used in the stability analysis should be identified and discussed. Guidance should be given.

7.7 STRESSES

7.7.1 Overview and Strengths

Discussions on stresses are presented on pages 29-35. It covers several types of stresses: services, cyclic, seismic, residual and vibratory stresses. The major classes of stresses are identified as service, residual and seismic. Detailed description is given on PRAISE-CANDU'S service load input file structure. Based on the description of the input file, the main service loads are deadweight, normal operation and transients. A modified version of ASME Boiler and Pressure Vessel Code Equation (11) of NB-3650 of Section III ASME 2010c [42] is used for calculating the peak axial stress in the inside diameter of the pipe. A detailed description is also given on how transient loads and through-wall stress gradients from transients are handled in PRAISE-CANDU. Furthermore, equations are derived for stress inputs to stress intensity factor, and crack stability analysis. It is noted that cyclic stresses for fatigue crack ignition can also be input into PRAISE-CANDU and details are available in the user manual. Procedures for seismic stress inputs are mentioned and detailed description is discussed of various distributions of residual stresses, deterministically-defined, polynomial, linear circumferential variation, and linear axisymmetric. Provision is available in PRAISE-CANDU for midlife changes to models and discussion is given on vibratory stresses, which can have a big effect on fatigue crack growth because of the large number of cycles involved.

PRAISE-CANDU has sufficient provisions to handle all the load types that are encountered in nuclear piping applications. Given the large amount of uncertainty associated with residual stresses, the availability of more than one method of defining the loads will ensure that as more knowledge is gather concerning residual stress the tool can handle it.

7.7.2 Areas for Improvement

Although, a broad range of load types can be handled by the tool several issues that will improve the quality of the Theory manual are highlighted in this section.

Before delving into a discussion on the format of the input file for stresses in PRAISE-CANDU, a summary and a brief description need to be presented of the main piping loads, primary and secondary, (deadweight, normal operating or service loads, thermal expansion, transient, vibration, thermal, seismic, environmental, residual etc.) in PRAISE-CANDU. The only discussion on some of these loads is the structure of the input format. (See for example Section 3.3 of the pilot study where a discussion is given on the loads types considered in the pilot study).

The load combination strategy for stresses from the various sources such as dead weight, thermal expansion, internal pressure, transient and seismic, external vibration need to be clarified. Several terms, such as load controlled stresses (pressure etc.), and displacement controlled stresses, (thermal expansion), are introduced but not explained. These terms and others provide additional layers of concepts on stresses, making it difficult to discern the load combination approach. It appears some of these stresses are simply added together which may lead to conservatism.

Several variables in Equation (7-1), E_{ab}, T_a, T_b, α_a, α_b, are not clearly defined. They are mentioned in the List of Symbols as Young's modulus at material discontinuity and temperatures and coefficients of thermal expansion in materials *a* and *b* of dissimilar metal weld. However, there are no discussions or mention of dissimilar metal weld in the text describing the loads, for clarity, this should be added, and a diagram showing the weld configurations will definitely clarify the formula and symbols in Equation (7-1).

An inconsistency, which should be corrected or clarified, exists between the main text and Table 8 regarding the procedure for definition of resultant moments at the extremes of the transient. In the main text, it was stated that "1) The value of the resultant moment from the second line of the transient pair is taken as the maximum moment, M_{max}." However, in the example presented in Table 8, the resultant moment calculated using data in the first line is used as M_{max} instead.

Another inconsistency, which should be corrected or clarified, exists between Equation 7.5 and Figure 15. Equation (7-5) suggests that the average axial stress through the thickness only include contributions from pressure, force and moments. This is inconsistent with the temperature profile shown in Figure 15. Based on this figure, the average axial stress should also include thermal stress caused by the average temperature variation through the thickness, T. Furthermore, it is stated in the Theory Manual that "the effect of the ΔT_2 term is concentrated at the inside surface, so this term has no influence at the outside surface". However, this description is also inconsistent with Figure 15, where ΔT_2 is non-zero on both inside and outside surfaces.

A description of stress details and input is given for all loads except the cyclic stresses for fatigue crack initiation and vibratory stresses. For consistency and completeness, descriptions should be given on the stress details for cyclic stresses for fatigue crack initiation and vibratory stresses. The reader should not be referred to the User manual for a description of these stresses.

Also, in Section 7.3 on Seismic Stresses, it is stated that "The inputs are in the form shown in Table 5. There are three lines of load input, one for loads….." This is inconsistent with the format of Table 5 where each transient was represented by two lines of data and is not clear if Seismic loads are defined before, after or in-between transients. Two methods are provided to take into account the influence of the seismic stresses, one requires reset of the crack condition after the seismic event and the other allows the crack growth calculation to continue after the seismic event. These two methods will lead to different results and have practical applications which should be described in the Theory manual.

Explanation is required on the implication if any of ignoring residual stresses on crack opening area.

7.8 GENERAL FLOW ACCELERATED CORROSION

7.8.1 Overview and Strengths

A very brief discussion is presented on general flow accelerated corrosion on page 36. This type of damage mechanism, common in carbon steel pipe, is mostly a localised phenomenon that results on thinning of the pipe wall from the inside surface. The localised treatment of the damaged mechanism is beyond the current scope of PRAISE-CANDU, and FAC is modeled in PRAISE-CANDU as a thinner pipe. Thinning rate is user specified, random and time dependent. The combined effect of FAC and crack (initiation and growth) is treated in the conventional fashion of no thinning, with crack depth reduced by thinning while the circumferential extent of crack is not considered to be reduced by thinning. Although wall thinning can change the crack tip intensity factor, its effect is neglected in the current version of PRAISE-CANDU. Also, the pressure, applied moments and forces are considered to be constant and the changes in stress as the wall thins are accounted for by changing the thickness in the formula for calculating the axial stress.

Although there is not a lot of literature on the subject, the method used in PRAISE-CANDU is along the lines employed by others (Gosselin et al., 2007). It is a non-mechanistic approach that relies on wall-thinning of the pipe due to FAC.

7.8.2 Areas for Improvement

Unlike previous sections of the report, no single reference is provided on the damage mechanism. To strengthen the report and support some of the assumptions that are made, published literature on the subject need to be included in the report.

Furthermore, the impact of simplifying assumptions, such as, “the effect of changes in R/h is not accounted for, it will be small for the wall thickness changes usually encountered”, have to be supported using references or studies.

Guidelines are to be provided on how to determine the appropriate thinning rate, given that it is a user specified time dependent random variable. The analysis sequence needs to be clarified in cases of combined FAC and fatigue. Which is executed first, FAC or fatigue and what impact if any does the analysis sequence have on the result?

7.9 INSPECTION, MONITORING AND TESTING

7.9.1 Overview and Strengths

This section covers models for pre- and in-service inspection, leak detection and proof testing. It is found on pages 37-39. The inspection procedures consist of detecting, sizing and possible remedial action. The first step in inspection is the detection probability. This is represented in PRAISE-CANDU using tabular input or two functional forms, the lognormal and the logistic functions. In a given Monte Carlo trial at a given time step, there is a crack of depth a. If an inspection is performed at this time step, a unit uniform random number is sampled. The probability of not detecting is less than the sampled random number, the crack is considered to have been detected. The next step is then the sizing of the crack. The procedures for sizing, repair/replace are also discussed. A weld repair is considered to be the removal of the defect and filling the removed area with weld metal, while replacement involves making the weld as good as new. Leak rates are not computed in PRAISE-CANDU but are incorporated as inputs in terms of crack opening area

The procedure, assumptions are clearly explained.

7.9.2 Areas for Improvement

7.10 GENERAL STATISTICAL CONSIDERATIONS

7.10.1 Overview and Strengths

A discussion is presented on the general statistical considerations in PRAISE-CANDU. The information, found on page 40-42, covers basic background, Monte Carlo Simulation and sources of uncertainty. PRAISE-CANDU, uses deterministic models of crack intuition and growth to compute the probability of leak opening areas of various sizes in a piping system. Although the models are deterministic, to reflect reality, many of the inputs to the models have inherent statistical scatter and uncertainty. The scatter is characterised by considering some of the inputs to be random variables, whose distributions are based on analysis of data or engineering judgement. Five two-parameter probability distributions are available in PRAISE-CANDU, normal, lognormal, Weibull (exponential and Rayleigh as special case), symmetrical triangular, uniform. The tool also has a tabular distribution option. The random variables in PRAISE-CANDU are considered to be mostly independent. Any dependent random variables must have either normal or lognormal distributions and are treated using coefficient of linear correlation. Monte Carlo simulation technique, which employs Mersenne Twister random number generator, is used in PRAISE-CANDU to obtain the probabilistic results from underlying deterministic lifetime model. The motivation for probabilistic model is because some of the inputs cannot be accurately defined, due to inherent randomness or inadequate knowledge. These contributors to randomness are called aleatory and epistemic respectively. The uncertainty modelling framework in PRAISE_CANDU is similar to the one employed in xLPR. There is great flexibility in PRAISE-CANDU in defining input parameters as aleatory or epistemic random variables.

The presentation on the types of uncertainties and random variables, the solution method and algorithms used in PRAISE-CANDU are explained clearly and relevant references are cited. The choice of a random number generator with very long period, the Mersenne Twister, for the Monte Carlo simulation is a good one because it will ensure statistical randomness in the random variable realization. The strategy of having provision for both epistemic and aleatoric uncertainties is sound especially as another tool, xLPR, which is being developed by a regulatory agency USNRC with a vested interest in ensuring safe operations, is adopting the same approach.

7.10.2 Areas for Improvement

There are a few areas of concern that have to be justified, clarified or improved upon.

There are only 6 probability distributions that are implemented in PRAISE-CANDU. This is in keeping with the distributions used in PRAISE and most of the other PFM tools for NPP in the USA, FAVOR, PRO-LOCA, SRRA etc. These distributions, which are two parameter models and easy to calibrate, are adequate for most practical application of PFM. However, apart from the 6 distributions that are available in PRASE-CANDU, there are other probability distributions that can be used to characterise scatter in parameters. Given that the results of very small probabilities of failures can be very sensitive to the distribution choice it should be explained, what impact if any, does the unavailability of the other probability distribution have on the results, and plans to mitigate such impact by using the six distributions.

Although the theory manual may not be the right document to address parameter specific questions that can be discussed in the user manual, the following issues need to be addressed to improve the quality of the document.

- What provisions are available in PRAISE-CANDU for calibrating distributed parameters based on measured in-service or experimental data?
- What provisions will be used determine the best distributions for parameters among several alternative distributions based on measured in-service or experimental data?
- What guideline will be used to determine the minimum number of data points that is required to consider a parameter a random variable?
- What are the rationales for limiting correlation to only normal and lognormal distributions?

Given that PRAISE-CANDU has a list of input parameters that are considered random variables, and the distributions will be determined from analysis of data or engineering judgement, the quality of the document will be enhanced by designating the input random variables whose characteristics are determined from data or from judgements.

7.11 PRAISE-CANDU SPECIFIC STATISTICAL CONSIDERATIONS

7.11.1 Overview and Strengths

The section discusses PRAISE-CANDU specific statistical considerations. Four pages, 43-46, are used for the material and the topics are random variables in PRAISE-CANDU, stratified sampling, selective lifetime calculation and, heat-to-heat versus within-heat scatter. The random variables in PRAISE-CANDU are independent, except two fatigue initiation random variables, four strength random variables, and two sizing random variables. All the random variables can assume the six distributions in PRAISE-CANDU except correlated variates, epistemic description of uncertainty, and a fatigue initiation random variable which can only assume normal or lognormal descriptions. PRAISE-CANDU can be run in deterministic mode. Stratified sampling is essentially an approach that allows for samples of crack sizes to be drawn from the large-size tail of the distribution. This method is used to speed up calculation in the case of a single dominant pre-exiting crack. It cannot be used when there are multiple cracks. To facilitate the stratification, independence of the crack depths and lengths are assumed. Selecting lifetime calculation approach is used in cases of multiple cracks that can easily combine into long cracks. Scatter in fatigue and stress corrosion crack initiation is considered to be composed of heat-to-heat and within-heat contributions. The distinction between within-heat and heat-to-heat is very important when calculating probabilities of large crack opening areas.

Parameters that can be designated as correlated and uncorrelated random variables and associated distribution for correlated random variables are clearly identified in the report.

7.11.2 Areas for Improvement

A scheme for speeding up calculations of break probabilities for cases with multiple initiating cracks is developed and implemented in PRAISE-CANDU. A reference on the scheme is cited, (Wang et al. 2011[53]), but no discussion is given on the scheme in the Theory Manual. For completeness, this scheme needs to be included in the Theory manual, and verified in the V&V report.

The Theory manual states that a user specified cut-off below which life time calculation should not be performed has the potential to influence the results of analyses. Guidelines should be developed on how to choose the cut off.

The basis, practical sources and the concepts of heat-to-heat and within-heat and the associated scatter are not explained, but it is noted that the distinction between the two has a strong influence on the results. Also how the variances in within-heat and heat-to-heat will be determined for CANDU piping is not discussed. Therefore for clarity and confidence in the output more detailed explanations need to be given on these concepts, practical implication and sources. Furthermore, guidelines need to be developed on how to determine within-heat and heat-to-heat scatter.

In Section 11.2, an explanation is required on how the stratified sampling is normalized to give a total probability of unity, and justification is also required for having all cracks initiate in a short time interval.

8.0 COG-JP-4367-046, REVISION 0: PRAISE-CANDU VERSION 1.0 PILOT STUDY

The document sets out a pilot study to demonstrate the capability of PRAISE-CANDU through an application of a problem of mechanical fatigue coupled with FAC degradation of the large diameters PHTS piping in Pickering Unit 5-8. The primary goal is to show how the PRAISE-CANDU tool can be applied to address a specific problem. It has seven main sections: Introduction; Pilot Study Description; Inputs; Results; Discussion; Assumptions; Conclusions and Future Work. Each of the sections is reviewed and a summary of the most important issues is given at the end of the chapter.

8.1 INTRODUCTION

8.1.1 Overview and Strengths

The background on PRAISE-CANDU, the objective and organisation of the report are discussed in the introduction. PRAISE-CANDU, which stands for Piping Reliability Analysis Including Seismic Events for CANada Deuterium Natural Uranium reactor, can be used to estimate the failure probability for a spectrum of break sizes of PHTS piping in CANDU plants. The results will be used to define the threshold break size. The degradation mechanisms that can be studied using PRAISE-CANDU are fatigue, flow accelerated corrosion (FAC), and primary water stress corrosion cracking (PWSCC). Uncertainties in PRAISE-CANDU can be categorised into aleatory and epistemic. The objective of the pilot study is to demonstrate the capability of PRAISE-CANDU through an application of a problem of mechanical fatigue coupled with FAC degradation of the large diameters PHTS piping in Pickering Unit 5-8.

8.2 PILOT STUDY DESCRIPTION

8.2.1 Overview and Strengths

A single girth buttweld in the section of the ShutDown Cooling (SDC) piping system energized during normal operation is used for the pilot study. The identity of the selected weld is specified as PIP inspection patch SD85. Some of the characteristics of the selected welds are summarised, including the geometric dimensions of the pipe and the fatigue factor. The weld has the highest stress ratio and cumulative usage (fatigue factor). The weld is a girth buttweld that lies between a long-radius piping elbow and the north leg of the piping tee. The pilot study uses, PRAISE-CANDU 1.0 to calculate the various failure probabilities at the weld: initiation, through-wall, partial break and rupture. A partial break size is chosen for the pilot study and the objective of the study is stipulated as to verification of the threshold break size recommended for the safety analysis pilot study of Pickering units in Kozluk, 2012 [4]. This Threshold Break Size (TBS) is used to divide the spectrum of LOCA break sizes into two regions. The first region includes breaks of a size up to and including the TBS, and the second region has the breaks larger than TBS up to and including the double-ended guillotine break (DEGB) of the PHTS pipe/header.

8.3 INPUTS

8.3.1 Overview and Strengths

The values, distributions and uncertainty categories for the input parameters and models are documented in this section. The random variables are summarised in a table. The inputs discussed are the pipe size, the material properties, the loads, the fatigue crack initiation model used, the initial crack size, fatigue crack growth model, crack coalescence, crack transition, crack stability, operational leak rate limit, FAC rate and others. Although the pipe studied is at Pickering B, the material property used is taken from Darlington material characterization database because the piping specifications and welding procedures for the two stations are the same.

Three load types are applied to the piping, normal operating load, seismic load and weld residual stresses.

The normal operating loads considered in the pilot study are startup-shutdown transient, which use assigned 2 cycles per year and another transient assigned 348 cycles per year. The normal operating temperature and pressure are defined as 8.72 MPa and 293^0C respectively. The uncertainty in the loads, which is categorised as aleatoric, is 10% COV. All the normal loads are taken as primary and the Load-controlled factor is set to 1.0. The peak axial stress is calculated using Equation (11) of NB-3650 of Section III of ASME B&PV Code (ASME, 2010) with the modification of the axial term and inclusion of the axial force (Duan, 2011).

The design basis earthquake (DBE) loads are assigned 200 cycles, which is consistent with CAN3-N289.3-M81 requirements.

A weld residual stress, WRS, model based on R6 code, given by the following equation, is used.

$$\sigma_R^{OD} = \sigma_{yw}, \quad \sigma_R^{ID} = A_b \sigma_{yw}, \qquad A_b = 1 - 0.0143(h - 15)$$

Where σ_R^{OD} and σ_R^{ID} are the residual stresses at the outside and inside diameters surfaces. The uncertainty of the WRS is considered to be epistemic with a standard deviation of 30MPa. The fracture initiation model, the crack growth model, the crack transition model and the crack stability models used in the pilot study are the models in the PRAISE-CANDU Theory manual. Several assumptions are made with regard to fatigue initiation parameters and the initial crack size. The Net Section Collapse stability criterion is used for both the part-through and the through wall crack. The crack is unstable when the applied moments exceeds the bending moment corresponding to the NSC of the flawed pipe section. Operational leak rate limits are also stipulated. The FAC rate is the average bounding thinning rates of twelve lead feeders in Pickering Units 5&8. The probabilistic description for the FAC rate is stipulated.

Most sources of data are identified and some justification is given for the choice of some data.

8.3.2 Areas for Improvement

In the load section, several new terms are introduced that were not mentioned or discussed in the theory manual, including load control factor, load multiplier and primary loads. These concepts, some of which may relate to load combinations, need to be presented clearly in the theory manual so that when they are used in studies like the pilot report they are not foreign, but familiar concepts that are already part of PRAISE-CANDU lexicon.

Several improvements can be made to strengthen the section including the following.

The weld residual stress models use in the pilot study is from R6. However, three residual stress models were stipulated in the theory manual, deterministically-defined, polynomial and linear, circumferential variation, none of which was referenced to R6. The model used in the Pilot Study was not presented in the Theory manual. It appears to be a new model that is not a part of PRAISE-CANDU. It needs to be included in the theory manual. In addition, although the inside and the outside diameters' of the pipe residual stresses have different mean values, 260 MPa and 272MPa respectively, the same standard deviation of 3 0MPa, which is roughly 10%, is ascribed to both. Justification needs to be given for the choice of the standard deviation because it implies that there is more scatter in the inside diameter residual stress than on the outside, and the 10% scatter seems small given that nothing is known about the residual stresses.

Several crack initiation parameters are assumed without justification, including the size term, variances in within-heat and heat-to-heat. Some of these assumptions need to be fully investigated through extensive sensitivity study because they have the potential to alter the conclusions from the study.

Some of the models in PRAISE-CANDU, which are discussed in the theory manual, have their roots in some ASME standards and some other studies. It is suggested that when these models are cited in a study like the pilot study, reference should be made to the relevant equation in the theory manual, so that it is clear that they are part of PRAISE-CANDU.

The Fatigue crack growth model, Equation 5, is from ASME standard, yet it is stated that Equation 5 understates the crack growth rate for $0<R<25$, compared to ASME code. What does this mean?

8.4 RESULTS

8.4.1 Overview and Strengths

Results of the pilot study, which is considered to be the best estimate is presented. The basic output is cumulative probabilities of failure over time. Statistics are reported for various failure criteria: initiation, through-wall, rupture, crack depth and breaks size. The computer platform used for the analysis is stated as well as the amount of time it took to perform the analysis. A table summarising the failure probability at various percentiles is presented and some observations from the table are highlighted.

The presentation is brief and clear, and the ability to compute the percentiles for failure probability is beneficial.

8.5 DISCUSSIONS

8.5.1 Overview and Strengths

Results from the analysis are discussed. Several issues are highlighted including seismic effects, aleatory and epistemic uncertainties, and probabilities of the various break sizes and rupture frequencies. It is noted that seismic loads have no effect on probability of initiation and that the risk of rupture due to seismic effect is very small (10^{-8}). In the present study WRS is considered to be epistemic because the model is based on R6. It is noted that the effect of WRS on failure probability is small. For the pilot study problem under consideration, it is concluded, based on the result, that any work done to reduce uncertainty in WRS may not be warranted because it has very little impact on the result. It is also concluded from the probabilities of various breaks sizes, that rupture is associated with a through break size less than 3.5% flow area, (FA).

8.5.2 Areas for Improvement

The conclusion about the impact of WRS model may be true for the current study, but it needs to be fully justified because the 10% COV ascribed to the weld residual stress seems to be very small, given that nothing is known about the WRS at the joint. Any conclusion that suggests that work done to reduce WRS may not be warranted has to be fully supported through extensive sensitivity studies.

8.6 ASSUMPTIONS

8.6.1 Overview and Strengths

The assumptions are clearly stated on types of loads, normal operating loads, seismic loads, weld residual stress, multiple initiation site, COD, failure mode and net section collapse model.

8.7 CONCLUSIONS AND FUTURE WORK

8.7.1 Overview and Strengths

The pilot study is used to demonstrate the capability of PRAISE-CANDU through the application on the girth buttweld location. Various percentiles of failure probabilities can be calculated by PRAISE-CANDU. Items selected for future work include analysis of all PHTS piping system greater then NPS10, performance of sensitivity studies and consideration of periodic inspections.

8.7.2 Areas for Improvement

For completeness, extensive sensitivity studies have to be a part of the pilot study to strengthen the conclusions that are drawn. This is especially true since some of the uncertainties and models are not directly derived from the CANDU plants at Pickering.

9.0 A REVIEW OF COG-JP-4367-026: VERIFICATION AND VALIDATION REPORT FOR PRAISE-CANDU 1.0

The verification and validation analyses that were carried out for PRAISE-CANDU 1.0 are discussed in the document. Verification and validation activities are used to demonstrate that the as-built software meets its requirements, as described in the theory manual and user's guide. It includes the objectives and development of test plans, test procedures, acceptance criteria for comparing the software code results with independent calculations, and test reports. The computation algorithms implemented in the software have to reflect procedures outlined in the theory manual. During verification potential errors in the computations algorithms within the software relative to the procedures outlined in the theory manuals when found are to be properly documented so that they are traceable and corrections can be implemented in the subsequent version of the software. There are fourteen main sections in this report: Introduction; CANDU's SQA Requirements; Verification and Validation Packages; Module Validations; Deterministic Checks; Random Sampling Checks; Independent Probabilistic Validation; Other Probabilistic Checks; Trends and Sensitivity Studies; Aleatory/Epistemic Checks; Ranks of Relative Importance Random Variables; Benchmarking with Other PFM Software; Comparison with Operating Experience; and Conclusions. Each of the sections is reviewed and a summary of the most important issues is given at the end of the chapter.

9.1 INTRODUCTION

9.1.1 Overview and Strengths

The introduction discusses the background on PRAISE-CANDU, the objective of the report and the acceptance criteria. It is presented on page 17. The objective of the report is a documentation of verification and validation of PRAISE-CANDU 1.0 based on Verification and Validation plan that was developed (Duan et al. 2012)[2]. The qualitative measures presented for deterministic and probabilistic acceptance criteria are poor, reasonable/good and excellent. The deterministic acceptance criteria are defined as: poor (the difference is greater than 30%), reasonable/good (the difference is within 15%); excellent (the difference is within 5%). The probabilistic acceptance criteria are defined as: poor (the difference is greater than 2 orders of magnitude), reasonable/good (the difference is greater than 1 order of magnitude); excellent (the difference is less than 1 order of magnitude).

9.1.2 Areas for Improvements

Inclusion of the software validation and verification plan as an appendix or some summary will be helpful during review.

9.2 CANDU'S SQA REQUIREMENTS

9.2.1 Overview and Strengths

The section is presented on page 18. The requirement for a validation report is documented in Section 11.3.5 of CSA N286.7-99. It is based on the CANDU Energy Software Quality Assurance, which is in full compliance with CSA N286.7-99, and has more detailed requirements on validation reporting. It is used for the current validation exercise. The procedure for validation report outlined in CANDU (2011a)[5] include: Identification of the computer program version being validated; Identification of the validation plan corresponding to the validation report; Statement of the range of application for which the computer program is being validated; Description of the method used to validate the computer program; Identification of the data against which validation was performed. Particular attention is paid to demonstrate occurrences of target phenomena, scaling, ranges of key parameter, and assessment of measurement errors in the experimental data used in the validation; Computer program input and output; Validation results; Assessment of validation results with respect to computer program accuracy and uncertainty allowances, providing a statement of accuracy for the key output parameters where applicable; Statements regarding the acceptability of the model implemented in the computer program based on acceptance criteria appropriate to the application.

It is stated that during validation, any suggestion for improving the computer program or enhancing the validated data, including experimental data should be reported separately to the primary holder.

The section highlights the application of CSA N286.799 requirements encapsulated in CANDU Energy Software Quality Assurance and provides a framework for assessing the content of the validation and verification report.

9.2.2 Areas for Improvements

The introduction section requires that suggestion for improving the computer program be reported separately to the primary holder. This approach may make it difficult to assess the correct implementation of the suggestions. An alternatively approach is inclusion of the suggestions as an appendix in the COG V & V report. This allows for better tracking and accountability.

9.3 VERIFICATION AND VALIDATION PACKAGE

9.3.1 Overview and Strengths

Two lists are provided of the files that make up PRAISE-CANDU 1.0 and a summary of the verification and validation packages. Thirty verification and validation packages are generated to complete the project and the majority of the files were prepared by Structural Integrity Associates. The V&V packages are broken down into five types of checks, module, deterministic, probabilistic, trends, sensitivity study and validation. There are six modules checks, three deterministic checks, six probabilistic checks, ten trends checks, two sensitivity checks and three validation checks. The dates and various activities executed during the V & V exercises are briefly mentioned.

9.3.2 Areas for Improvements

None

9.4 MODULE VALIDATIONS

9.4.1 Overview and Strengths

Several PRAISE-CANDU modules, called TESTER and only available to the development team, were packaged as stand-alone code for checking purposes. The discussion is presented on pages 21-42. The modules validated are: (i) PWSCC Crack Initiation and Growth; (ii)

Fatigue Crack Initiation and Growth; (iii) Crack Placement, Coalescence and Net Section Area; and (iv) Stress Intensity Factors, J-Solutions and COD. The test plan, test implementation and test results presented for each module are summarised below.

PWSCC Crack Initiation and Growth

The aim of the test plan is to verify the accuracy of the PWSCC crack initiation and growth models in PRAISE-CANDU 1.0. The plan states "*Perform a deterministic analysis including crack initiation and observe initiation time. Compare the initiation time with hand calculations. Check both PWSCC initiation models at several temperatures and stresses, and fatigue initiation for several materials and environments*". The models verified are the Power law initiation model (Equation 4-4 theory manual); Garud relation initiation model (Equation 4.5 theory manual), the threshold stress for crack initiation (Equation 4.6 theory manual); and the PWSCC crack growth model (Equation 5.3). Equations 4.4, 4.5, 4.6 and 5.4 from the theory manual are restated in the validation and verification report document (Equations 3.1, 3.2, 3.3 and 3.4).

Several test cases are used to verify, the power law initiation model, Garud model and PWSCC crack growth model. Four test cases for the PWSCC Power law initiation, eight test for PWSCC Garud model and five test cases for the PWSCC growth model. The objective of each test case is clearly defined. For all the test cases, summaries are presented of the values of the input parameters, outputs and the results. The names of the file folders where the independent analyses are stored generally referred to as V&V packages in the documents, are given. Although the test plan stipulates that hand calculations, it is executed with Excel. Using the acceptance criteria for the deterministic analysis defined in the introduction, it is noted that excellent agreement is observed between the independent calculations using Excel and the results from PRAISE-CANDU 1.0.

The test plan and the objectives for all the test cases are clearly stated. Values of input parameters and outputs for *every* test case are written within the validation report along with V & V packages where they are stored. The section of the theory manual being verified is identified in the report. Also the equations in the theory manual that are tested are restated in the validation report, for ease of identification. The test cases span both SI and imperial units, the full scope of units in PRAISE-CANDU 1.0.

<u>Fatigue Crack Initiation and Growth</u>

The aim of the plan is stated as "*Perform a deterministic analysis including crack initiation and observe initiation time. Compare the initiation time with hand calculation. Also Perform the fatigue crack growth calculations for the R-dependent Paris equation and using da/dN-ΔK tables*." The models from the theory manual to be verified are Equation 4-1, which is numerically implemented as Equation 4.3, Equation 5.1 and 5.2. Equation 4.1 from the theory manual is restated in the validation document (Equation 3.6).

Several test cases are used to verify, the fatigue crack initiation model, R-Dependent fatigue crack growth model and da/dN-ΔK fatigue crack growth tables. They are four test cases for fatigue crack initiation, one test case for the R-dependent Paris equation and one test case for the da/dN-ΔK tables. The objectives for some fatigue crack initiation test cases and all fatigue crack growth test cases are not stated. Summaries are presented of the input, outputs and the results for some and not all the test cases. The names of the file folders, where the independent analyses are stored, generally referred to as V&V packages in the documents, are given. It is noted that excellent agreement is observed between the independent calculations using Excel and the results from PRAISE-CANDU 1.0. Although the test plans stipulates hand calculations, the models are implemented in Mathcad.

The test plan and the objective for some of the test cases are clearly stated. Values of input parameters and outputs for *some* test cases are given within the validation report along with V & V packages where they are stored. The section of the theory manual being verified is also identified for *some* test cases and *some* of the equations in the theory manual that are tested are restated in the validation report.

<u>Crack Placement, Coalescence and Net Section Stress</u>

A goal of the test plan is stated as "*Cracks are numbered sequentially around the circumference. If a crack initiates between two previously existing cracks, then the crack* *identification numbers must be re-ordered. Devise and execute an example problem that checks this crack numbering logic*." The other portion of the test plan states "*If a crack initiates with an existing crack, the crack is still placed at the center of its segment, and the sorting of crack identification number is performed. The coalescence module then eliminates the crack within a crack. Perform a deterministic analysis employing net section failure criterion with multiple cracks. Compare calculation of crack stability with independent calculation*"

Several test cases are used to check crack placement, crack coalescence and net sections, two for the crack placement, four for crack coalescence and eight for the net section. File names for the test implementation are summarised. Results for the crack placement checks are summarised. Results for the coalescence of pre-existing cracks are also summarized, where it is noted that hand calculation is used for verification. Results for the net section collapse cases are also summarised, where it is not clear whether hand calculation or Excel is used for the analysis since both are mentioned. The names of the file folders, where the analyses are stored, generally referred to as V&V packages in the documents, are given.

The test plan is stated. Values of input parameters and outputs for *some* test cases are given within the validation report along with V & V packages where they are stores. A discussion of *some* of the test results is presented. The section of the theory manual being verified is also identified for *some* test cases.

<u>*Stress Intensity Factor, J Solution and COD*</u>

Although the title Test Plan is included, the test plan is not stated. The section on the Test plan states "*Stress intensity factors were checked by generating K versus a tables with PRAISE-CANDU and comparing results with independent calculations, using pc-CRACK[10] or SignalFFS[11]. J-solutions were checked using deterministic calculations for a specified load to obtain the applied value of J as a function of crack size. A combination of tension and bending for both a surface crack and a through-wall crack were considered and results were compared with independent calculations. COD-solutions were checked using deterministic calculations for a specified load to obtain the opening displacement as a function of crack* *size. A combination of tension and bending for a through-wall crack were compared with independent calculations*.", which is a statement of what was done. The test plan itself is not given. A table summarising details of what is done is provided.

Several test cases are used to check stress intensity factors, J and COD; five for stress intensity factors, and three for J and COD. The table listing the test cases indicate that the stress intensity factor is checked using pc_CRACK and J and COD are checked using Mathcad. It is noted that comparison of PRAISE-CANDU and SignalFFS is not included because of schedule and budget constraints but will be added in a future release of PRAISE-CANDU.

Input parameters and results are presented for various cases including the stress intensity factor for surface crack tension, surface crack bending, surface crack nonlinear gradient, and through crack tension/bending; J-a for surface crack, J-a for through-wall crack; COD-a and surface crack tabular nonlinear gradient.

Values of *some* of the input parameters and outputs for *some* test cases are given within the validation report along with V & V packages where they are stores. A discussion of *some* of the test results is presented. The section of the theory manual being verified is also identified for *some* test cases.

9.4.2 Areas for Improvements

It seems a lot of work has been done. However, the documentation of the verification and validation activities in this section is uneven, with sufficient information provided in some subsections, for example PWSCC Crack Initiation and Growth subsection, while others have very scanty information making it difficult for a thorough review of the actual work done. In some cases, the main information offered is a reference to verification and validation file folder packages where inputs and results are stored. Before, offering suggestions on improvements to individual subsections, a list is summarised of items which when included in the validation and verification documentation can improve its quality.

1. As much as possible, the write-up of the verification and validation in each subsection should focus on only one model, analytical equation, logic, etc. Putting multiple models

into one subsection, in the write up, creates difficulty with assessing which item is being verified.

2. A clear written statement of the test plan should be included and in cases where more than one model is tested the test plan for each model should be clearly stated.
3. For each test case, a clear definition of the problem statement or objective, the section of the theory manual and the equations being verified, the tool/s used for testing or verification, the acceptance criteria, a description of the input parameters (for example list of parameters and units), a brief description and discussion of the results/outputs (for example list or plots etc.), need to be presented in the validation and verification report itself, in addition to information that can be used to identify file folders and tags where additional information can be obtained.
4. Since PRAISE CANDU 1.0 covers both imperial and SI unit, for completeness, the test cases involving equations should cover both units.
5. Also a brief discussion should be provided for each test case to justify the correctness or lack thereof of the test results.
6. Cases where the results are not correct should be documented within the COG V & V report for correction in future versions of the software.
7. Whenever possible, more than one independent verifier should be used to create and verify the models in Excel, Mathcad etc. to ensure that minimise programmers' errors.

PWSCC Crack Initiation and Growth

Most of the ideas for improving the quality of documentation were implemented for PWSCC Crack Initiation and Growth. The following additional items will improve the quality of the material in this subsection.

1. The test plan calls for fatigue initiation checks for several materials and environments. It will be helpful if the materials and environments investigated in the various test cases are identified, to show if the goal of the test plan has been meet or if additional tests cases are needed.
2. A brief discussion should be provided for each test case to justify the correctness of the test results. A good example of typical discussion which can be used as a model for other cases

is the discussions in section 4.1.3.5 which is helpful to understanding the initiation time of "infinite" and "zero".

3. As much as possible test cases should be developed and implemented to test the limits of the models.
4. Some typo errors, heading errors etc. exist in this section of the document and should be corrected. For instance, in Table 4-5, the description of the Table title does not match the top of the middle and right column, the title reads "Summary of Input ….. for Case 3.1-2-1 and Case 3.1-2-2 while the columns are labeled "Case 3.1-1-1 and Case 3.1-1-1", which one is correct?. Again the descriptions of the title in Table 4-11 (Summary … Case 3.1-2-4" and Case 3.1-2-5) does not march the labels in the column "Case 3.1-2-1" and Case 3.1-2-2". The title for Table 4-14 and the Case ID in column 1, which the title is meant to reflect are different" the title reads "Comparison of ….. for Case 3.1-2-1 to Case 3.1-2-3" while the column list Case 3.1-2-6 to Case 3.1-2-8.
5. It is not clear why Equation 3-4 and 3.5 on page 26 of the verification and validation report, which is also Equation 5.4 in the Theory Manual for PRAISE CANDU 1.0, an equation implemented in xLPR but not PRAISECANDU 1.0 is included in the verification and validation section of PWSCC. We suggest it should be removed from the COG V & V report because it does not appear to serve a purpose other than identify the limitation of PRAISE-CANDU 1.0.
6. The value of K is missing from Table 4-15

Fatigue Crack Initiation and Growth

The following suggestions for improving the content of this section is given in additional to the general suggestion stated earlier.

1. The first three suggestions in the PWSCC Crack Initiation and Growth section.
2. The units of some parameters in the test cases are not specified. These should be done.
3. The test cases should cover both SI and Imperial units.
4. Some variables in Table 4-23, S, D0, edot and Cycles factor, are neither used in Equation. (3-6) nor included in Table 2 of the Theory Manual. Variable, edot, is never defined in the COG V & V or Theory manual. Descriptions and use of these variables should be provided.

Crack Placement, Coalescence and Net Section Stress

The following suggestions for improving the content of this section is given in additional to the general suggestion stated earlier.

1. Suggestions 1-3 in the PWSCC Crack Initiation and Growth section.
2. In additional, the algorithm for determining the location of crack initiation was not clearly explained in the documents. On page 21 in the Theory Manual, it was stated that "*Initiating cracks are randomly placed within a segment*". However, the V&V report seems to suggest that "*crack is placed at the center of its segment*". In reality, the location of crack initiation should be controlled by the local stress distributions. Some clarifications are required on this.

Stress Intensity Factor, J Solution and COD

The following suggestions for improving the content of this section is given in additional to the general suggestion stated earlier.

1. Suggestions 1-3 in the PWSCC Crack Initiation and Growth section.
2. All the test cases in this section use Imperial units, test cases involving SI units should also be investigated.
3. Although the titles of test cases 3.4-1 and 3.4-2 suggest that they are designed for testing surface cracks in tension and bending loads, respectively, in these tests, the magnitudes of stress are directly specified as 10 ksi and 12 ksi. The difference between these test cases with respect to the load type is not clear.
4. In addition, it is not clear from the COG V & V report, which particular equations or deterministic formulas for calculating stresses, Section 7 of the Theory Manual, formulas for J-Integral and Crack Opening Areas, Section 3 of the Theory Manual, have been tested since they are not documented in the COG V & V report. Clarification is required.
5. Also within the theory manual, see for example page 17 second to the last paragraph, a linear multi-dimensional interpolation scheme is mentioned and should be tested and reported. It is not clear if that was carried out.

9.5 DETERMINISTIC CHECKS

9.5.1 Overview and Strengths

The work is presented on pages 43-58. The three modules validated in this section are: (i) Initiation and Growth with FAC; (ii) J-Integral and Tearing Instability and; (iii) Stress Intensity Factor and Crack Growth. The test plan, test implementation and test results presented for each module are summarised below.

Initiation and Growth with FAC
The test plan is stated as "*Devise initiation problems with crack growth and general wall thinning. Follow crack initiation and consuming of the crack by thinning. Compare with independent calculations (hand, pc-CRACK,* Mathcad *or SignalFFS).*" The two main checks are PWSCC initiation and growth with FAC, and fatigue initiation and growth with FAC.

Several test cases are used to check, PWSCC initiation and growth with FAC, and fatigue initiation and growth with FAC, sixteen for PWSCC initiation and growth with FAC and, twelve fatigue initiation and growth with FAC. The analyses are performed starting with the simplest problem of growth without FAC, then initiation without FAC and then FAC is added. The names of the file folders where the independent analyses are stored generally referred to as V&V packages in the documents, are given. Various figure and tables of results, trends, sensitivity studies involving time steps, and membrane or bending stresses are presented and discussed. Some of the plots are used to compare PRAISE-CANDU results with pc-CRACK. Acceptance criteria are stated for some of the results. It is concluded that the calculations show that the deterministic modules for both PWSCC and fatigue initiation are working as expected.

The test plan is clearly stated. Results are presented and discussed. File folders, known as V & V packages, where the calculation packages are stored are identified.

J-Integral Tearing Instability
The test plan is stated as "*Perform a deterministic analysis of a surface crack for a specified load and crack length to obtain the critical crack depth. Repeat for a through-wall crack. Consider a combination of tension and bending. Compare results with independent*

calculations (hand, pc-CRACK, MATHCAD or SignalFFS)." The problem is checked using Mathcad.

For surface crack check, the detailed problem description, and inputs are not given, but it is noted that they can be found in the file pcan4321.rpt and pcan4321.pcif respectively. The assumptions in the MathCAD runs are outlined and the results are presented and discussed.

The through-wall cracks test case is defined by changing the initial crack size used in the surface crack test case. Several checks are performed for this case, including instability, effect of load multiplier and crack transitioning from surface to through-wall. Acceptance criteria are stated for some of the results. It is concluded that the calculations show that the results are either reasonable or excellent.

The test plan is clearly presented. Results are presented and discussed. File folders, known as V & V packages, where the calculation packages are stored are identified.

Stress Intensity Factor and Crack Growth

The test plan is stated as "*Perform a deterministic crack growth analysis with three transient types and check that loads are being properly used in the calculation of cyclic stress intensity factors. Include a deterministic fatigue crack growth problem that also include seismic event. Perform related analysis with FAC*".

The test implementation indicates that this section is used to check the correct use of the loads for various transients for computation of cyclic stress intensity factors, analysis of fatigue crack growth or stress corrosion crack growth.

Checks are performed with MathCAD. Eight test cases are used. The names of the file folders where the independent analyses are stored are given. Some tables summarising the results are presented. It is concluded that the PRAISE-CANDU is working as expected.

The test plan is clearly stated. Results are presented and discussed. File folders, known as V & V packages, where the calculation packages are stored are identified.

9.5.2 Areas for Improvements

A good starting place is the suggestions in section 9.4.3. Unlike some of the previous sections where the input were mentioned and results not discussed, the main shortcoming of this section is that results are discussed without a clear definition of the statement of the problem, the input parameters and identity of the formula being verified. Additional improvements to individual subsections are given below.

Initiation and Growth with FAC

1. For each test case, provide a statement of the problem, the input parameters, identify the formula(s) in the theory manual that is being verified, discuss the results, and sate the conclusion on the satisfaction or lack thereof of the acceptance criteria.

J-Integral Tearing Instability

1. Suggestion 1in Initiation and Growth with FAC section
2. There are several equations on J-integral, fully plastic J, total J and also multidimensional interpolation schemes, which are discussed in other documents for example Reference [18] in the theory manual, that can be used in the testing. It is not clear from the discussion which equation is used for what. A fair assessment of the verification and validation cannot be performed.

Stress Intensity Factor and Crack Growth

1. Suggestion 1in Initiation and Growth with FAC section.
2. Far too many issues are lumped together, not enough details presented on any one in terms of input, problem description, discussion, output and conclusions. A fair assessment of the exercise cannot be carried out without improved documentation.

9.6 RANDOM SAMPLING CHECKS

9.6.1 Overview and Strengths

The presentation is on pages 59-61 of COG V & V report. The test plan states that "*checks are to be made to assure that the random Monte Carlo sampling is being performed properly. Probabilistic runs are to be defined with many random variables. All sampled values are to be printed out and compared with analytical representation of distribution, such as mean* *standard deviation and plotting of cumulative probabilities. All distribution types in PRAISE-CANDU including correlated variables are to be tested*". It is noted that these plans were implemented. A statement of test results is presented for various cases, including random variables with variability in aleatory loop only, random variables with variability in epistemic loop only, random variables with variability in both aleatory and epistemic loops and correlated random variables. Locations of V & V packages where the information can be found are identified. It is concluded that all random samples are generated as intended from black-box and white-box testing.

9.6.2 Areas for Improvements

A good starting place is the suggestions in section 7.4.3. Additional improvements to individual subsections are given below.

Although conclusions are drawn that the random sampling are generated as intended, a third party assessment of those checks cannot be made because the checks are not documented in the current COG V & V report. There are no inputs or output in the documents to back up the conclusion. There are no results showing the statistical properties (mean and standard deviation) and the probability distributions of inputs into the Monte Carlo simulation, samples generated, and their associated statistical properties and adequacy of the outputs' probability distributions using goodness of fit measures or cumulative distribution functions. Additionally for correlated random variables, the correlation coefficient before (input) and correlation coefficient (output) Monte Carlo simulation are not reported in any table, plot or figures within the verification and validation report. Therefore, it is impossible to make a third party assessment on random sampling checks from the current COG V & V report because no problem statement, plot, figures, tables of result are presented.

9.7 INDEPENDENT PROBABILISTIC VALIDATION

9.7.1 Overview and Strengths

The check in this section is contingent on all the previous validations, the deterministic models (Chapters 4, 5 of COG V & V report) and the random sampling checks (Chapter 6). The additional checks are executed for cases where probabilistic runs can be carried out independently. This section is discussed on pages 62-67 of the COG V & V report. The main items considered are: (i) Fatigue Intiation and Growth –One Initiation Site; (ii) Fatigue Initiation and Growth –One Initiation Site (Tabular da/dN); and PWSCC Initiation and Growth. The test plan, test implementation and test results are summarised below for each module.

<u>*Fatigue Initiation and Growth –One Initiation Site*</u>

The test plan states that "*problems with one initiation and growth being the only random variable can be checked with simple independent calculation. The distribution of initiation time can be described in closed form in terms of the distribution of the initiation coefficient……*". A convolution integration formulation which allows the probability of initiation time to be calculated using a tool like Mathcad is presented as part of the test plan. A test case is used to verify fatigue initiation and growth. For fatigue initiation, C_o, is the random variable. Its statistical parameters, median and shape, and probability distribution (normal) are given. Similarly for fatigue crack growth, the random variable, is the fatigue crack growth coefficient, C_f, with a lognormal distribution and specified statistical parameters. The equations in the theory manual that are being checked are identified. The names of the file folders where the independent analyses are stored generally referred to as V&V packages in the documents, are given. A figure showing the result is presented and it is concluded that excellent agreement is obtained between the test case and PRAISE-CANDU.

The test plan is clearly presented and results are discussed. File folders, known as V & V packages, where the calculation packages are stored are identified.

<u>*Fatigue Initiation and Growth –One Initiation Site (Tabular da/dN)*</u>

The test plan states that "*perform the PRAISE-CANDU runs of section 7.1 with a tabular input of da/dN corresponding to the fatigue relation used in section 7.1 Compare results with section 7.1; they should be the same.*". A summary of the modules tested is presented along with some comments in a table. A test case is used to verify the analysis. The file folder that contains the analysis is identified. Two figures are presented as part of the results.

The test plan is clearly presented and results are discussed. File folders, known as V & V packages, where the calculation packages are stored are identified.

<u>*PWSCC Initiation and Growth*</u>

The test plan states "*perform the PRAISE-CANDU run with the initiation and growth as the only random variables with one initiation site. Compare with independent calculations using the convolution procedure described in Section 7.1*". Additional details are provided in a table where it is noted that leak and rupture probabilities are to be calculated. A test case is used to verify the analysis. The equation in the theory manual under investigation is identified and restated in the COG V & V report. The file folder with the analysis is given. A figure and a table with the results are presented. It is concluded that excellent agreement is obtained between the test case and PRAISE-CANDU.

The test plan is clearly presented and results are discussed. File folders, known as V & V packages, where the calculation packages are stored are identified.

9.7.2 Strengths

9.7.3 Areas for Improvements

The areas for improvement is similar to the one offered in section 9.5.3. Additional improvements to individual subsections are given below.

<u>*Fatigue Crack and Growth –One Initiation Site*</u>

For each test case, under the test implementation, provide a statement of the problem, the input parameters, identify the formula(s) in the theory manual that is being verified, discuss the results, and sate the conclusion on the satisfaction or lack thereof of the acceptance criteria.

Looking at Figure 7.1, if the two codes, PRAISE-CANDU and Mathcad, are using the same mechanistic models, it is not obvious why the outputs diverge at low probabilities. If a thousand trials is not sufficient to achieve convergence then more samples need to be generated.

<u>*Fatigue Initiation and Growth –One Initiation Site (Tabular da/dN)*</u>

Same as above

PWSCC Initiation and Growth
Same as above

9.8 OTHER PROBABILISTIC CHECKS

9.8.1 Overview and Strengths

Other probabilistic checks are performed because in some cases independent checks cannot be made. The discussion is presented on pages 68-74. The two modules validated in this section are: (i) Inspection; and (ii) FAC. The test plan, test implementation and test results for each module are summarised below.

Inspection
The test plan states "*perform PRAISE_CANDU runs with an inspection. For each of ten (10) trails at a time of the inspection, write out the actual crack size, the indicated crack size, and the size of any post-repair crack. Do this with no uncertainty in sizing and with some uncertainty in sizing. Compare results with independent hand evaluations. Perform such checks for PWSCC initiation and growth and fatigue of pre-existing crack. Do a run with two inspections, and look at the results for each inspection.*" The test plan are summarised in a table as six test cases. The file folder with the relevant calculation is identified. Eleven files for inspection checks are summarised in a table along with their descriptions and names. Test results for one and two inspections are discussed for PWSCC Initiation-No Uncertainty in sizing, PWSCC Initiation- Uncertainty in sizing, Pre-existing Fatigue-Without Uncertainty in sizing, Pre-existing Fatigue- Uncertainty in sizing. Test result is also discussed for Pre-existing Fatigue-With FAC. For the test problems, it is mentioned that examples problems are developed, the input and output names are identified, but the problems are not described in details in the report. The objectives and results of some of the example problems are discussed. Spot checks and visual inspection are performed on some of the output from PRAISE-CANDU such as detection probability and sizing. It is concluded that all the checks demonstrate the consistency and accuracy of the logic and calculation employed.

Detailed descriptions of the test plan, objectives and results are presented. File folders are identified, known as V & V packages, where the calculation packages are stored.

<u>*FAC*</u>

The test plan states "*wall thinning by itself can cause failure when the thickness is reduced such that the critical net section stress is exceeded. Devise a problem with the wall thinning rate and flow strength being the only random variable. Compare results with independent calculations. Repeat with a mid-life change in thinning rate.*". The test plan has two test cases summarised in a table. The file folder with the relevant calculation is identified. Two files for FAC checks are summarised in a table along with their description and names. FORTRAN Monte Carlo and FORTRAN output are also mentioned in the tables. Two test cases are presented in the test results, FAC-Constant Thinning Rate and FAC-Step Change in Thinning Rate.

For FAC-Constant Thinning Rate, the two random variables considered in PRAISE-CANDU are the thinning rate and the flow strength. It is stated that a corresponding analysis was done using Monte Carlo simulation and a special purpose FORTRAN program. Equations incorporated into the special program are developed in the report. The source of the equations is identified. File names for input and outputs and the FORTRAN program are also identified. A plot is presented that shows excellent agreement between PRAISE-CANDU and the special purpose FORTRAN program.

For FAC-Step Change in Thinning Rate case, the problem for FAC-Constant Thinning Rate case, which is not clearly described in the report, is rerun with a step change in the wall thinning rate at the 5^{th} year. Again, file names are identified for the input and outputs. Plot of results are presented that shows excellent agreement with PRAISE-CANDU.

Detailed descriptions of the plan, objectives and results are presented. File folders are identified, known as V & V packages, where the calculation packages are stored.

9.8.2 Areas for Improvement

Although detailed description of the test plan and results are presented along with a reference to V & V packages, there are no detailed descriptions of the problem for each test plan along with the inputs or output in the documents to back up the conclusions. Also, to ensure accuracy of the test verification using FORTRAN, results from more than one independent developer need to be compared.

9.9 TRENDS AND SENSITIVITY STUDIES

9.9.1 Overview and Strengths

This section is presented on pages 75-104 of the COG V & V report. It focuses on specific trends expected when changes are made to the problems being analysed. Only aleatory random variables are considered. The nine items discussed are: (i) Inspection; (ii) Seismic; (iii) Multiple Transient Fatigue; (iv) Fatigue/PWSCC versus PWSCC/Fatigue; (v) Fatigue Initiation and Growth –Multiple Sites; (vi) PWSCC Initiation and Growth –Multiple Sites (vii) Residual Stresses (viii) Mid-Life Changes and (ix) Fourteen Analysis Types. The test plan, test implementation and test results for each module are summarised below.

<u>*Inspection*</u>
The test plan states "*use of better inspection should result in lower failure probability. Multiple inspections should be better than one inspection. The rate of increase of cumulative failure probability should be decrease following an inspection. Perform PRAISE-CANDU checks on these expected trends*." Eight check cases and titles are identified. The file folder for V & V packages is identified as well as a summary list of files for inspection checks. Degradation given in the list of files for inspection checks are PWSCC growth, fatigue growth, PWSCC initiation, fatigue initiation and fatigue growth. Test results are presented in the form of plots and tables for various test cases including PWSCC Growth With and Without Inspection; Fatigue Crack Growth With and Without Inspection; PWSCC Initiation and Growth –Late Inspection; PWSCC Initiation and Growth-Early Inspection; fatigue Initiation and Growth –Late Inspection, fatigue Initiation and Growth-Early Inspection; fatigue Pre-existing-Better POD; and PWSCC Pre-Existing-Multiple Inspection. It is concluded that expected trends were observed or the trend observed could be explained.

A statement of plan is given and some results are presented. File folders are identified for calculation packages.

<u>*Seismic*</u>

The test plan states "*the checks on trends with seismic events which are described in Section 8.2 of the V & V plan [2] were implemented. The table below is drawn from V&V Plan[2], and summarises the checks to be made.*" Four checks cases and titles are identified. The file folder for V & V packages is identified. The three cases discussed under test implementation are Fatigue Initiation and Growth, Pre-existing fatigue and PWSCC initiation and growth. Figures are presented to illustrate the two seismic methods, reset and set time. The list of files and end of life results are given. It is also concluded that expected effects were observed.

A statement of plan is given and some results are presented. File folders are identified for calculation packages.

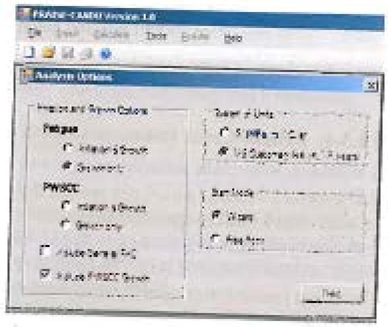
<u>*Multiple Transient Fatigue*</u>

The test plan states "*do run for fatigue growth of pre-existing crack, with multiple transient of the same amplitude. For the same total number of cycles, the results should be very close or the same as for one cycle with same amplitude and total number of cycles. Repeat with fatigue initiation.*" Five checks cases and titles are defined. Under test implementation, the file folder for V & V packages is identified and a list of five files names for multiple transient fatigue is given. The three cases discussed in test results are Fatigue Crack Growth with Multiple Transient, Fatigue Crack Initiation/Growth with Multiple Transient and Fatigue Crack Growth with Fourth Transient. The list of files where example problems are summarised is given. It is also concluded that expected behaviour was verified and graphically illustrated.

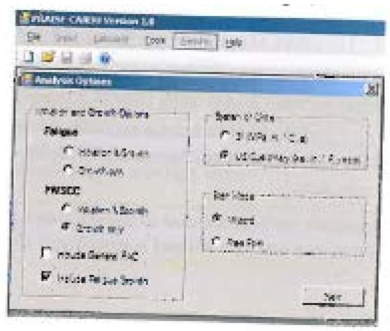
A statement of plan is given and some results are presented. File folders are identified for calculation packages.

<u>*Fatigue/PWSCC versus PWSCC/Fatigue*</u>

The test plan states "*For pre-existing crack, perform fatigue crack growth analysis including PWSCC, as indicated below*



And compare results with a PWSCC analysis including fatigue, as shown below



do both analyses with R-dependent Paris and tabular da/dN-DK. All results should be the same. Figure 9.9 is a summary." Four cases and titles, which should all give the same result, are stated in a table. Under test implementation, the file folder for V & V packages is identified. It is noted that all the input in the four analysis are the same, even though these inputs are not described in the report. It is also concluded that the results show that independent of what analysis option (fatigue with PWSCC or PWSCC with fatigue) is chosen both leak and LOCA probabilities' are exactly the same. The results for tabular and functional (R-dependent PARIS Law) definition of da/DN agree within 1%.

A statement of plan is given and some results are presented. File folders are identified for calculation packages.

<u>Fatigue Initiation and Growth –Multiple Sites</u>

The test plan states "

- *Perform fatigue initiation and growth analyses with multiple sites*
- *Compare with single site*
- *Vary heat-to-heat and within-heat variances and look at effects on leaks and large leaks*
- *Include an example with FAC. Include a problem with PWSCC as well as fatigue crack growth*

- *Vary failure criteria (net section versus tearing)*

The following table provide additional details". Five checks cases and titles are stated in a table. Under test implementation, the file folder for V & V packages is identified. A presentation on test results include, the test cases, a list of the important random variables, a list of files identifying the variance employed for H-H, W-H, SRSS, and Sum. Plots are given and discussed for, mean initiation, mean leak and mean LOCA probabilities. It is concluded that the observed effects are consistent with expectations; partitioning of a variable between heat-to-heat and within-heat has significant impact on the calculated failure probability (initiation, leak and LOCA probability).

A statement of plan is given and some results are presented. File folders are identified for calculation packages.

PWSCC Initiation and Growth –Multiple Sites

The test plan states "*Perform PWSCC initiation and growth analyses with multiple sites. Compare with single site. Vary heat-to-heat and within-heat variances and look at effects on leaks and large leaks. Include an example with FAC. Include a problem with fatigue crack as well as PWSCC growth. The following table provides additional details.*" Five checks cases and titles are defined. Under test implementation, the file folder for V & V packages is identified and list of files identifying variances employed are summarised. The two cases discussed in test results are PWSCC Initiation with multiple sites; and PWSCC Initiation with multiple sites considering FAC and fatigue growth. Plots are presented and discussed for, mean initiation, mean leak and mean LOCA probabilities. The list is given of files where example problems are summarised. It is concluded from the probability distributions that the trends observed in the failure probabilities are as expected.

A statement of plan is given and some results are presented. File folders are identified for calculation packages.

Residual Stresses

The test plan states "*Residual stresses are discussed in Section 7.4 of the Theory Manual [6]. All types of residual stresses are to be run in example problems. PWSCC and fatigue initiation and growth are to be considered. The effects of residual stresses on fatigue results* *should be minimal, and the effects on PWSCC potentially large –depending on the magnitude of the stresses. The following table provides additional details."* Eight checks cases and titles are defined. Under test implementation, the file folder for V & V packages is identified. The list of files names for residual stress checks is summarised along with the description of type of residual stress and its mean parameter. Test results are presented under five subheadings, PWSCC Initiation and Growth-Various Deterministic; PWSCC Initiation and Growth-Probabilistic Polynomial; PWSCC Initiation and Growth-Linear Axisymmetric; PWSCC Initiation and Growth-Linear Circumferential; and Fatigue Initiation and Growth-Probabilistic Polynomial. List files names for example problems are summarised. Brief discussion is presented on some of the results. It is concluded that the effect of residual stresses were performed with the expected trends being observed. For PWSCC problem, it is stated that the selection of different residual stress model has negligible effect on leak probability and significant impact on LOCA probability.

A statement of teat plan is given and some results are presented. File folders are identified for calculation packages.

<u>*Mid-Life Changes*</u>

The test plan states "*Mid-life changes can be made to mitigate unfavourable conditions (see Section 7.5 of Theory Manual). The following table provides additional details.*"

Table 9-19: Test Plan for Middle Life Change

Case ID	Check	Comment
8.8-1	use 8.7-4 as base case (PWSCC)	
8.8-2	change residual stress at 30 years	look for changes in probabilities at the time of change
8.8-3	change residual stress and wall thickness at 30 years	mid-life change effect should be higher than for 8.8-2
8.8-4	8.8-2 with wall thinning after 30 years	
8.8-4	change water chemistry at 15 years	look for changes in probabilities at time of change
8.8-5	use 8.7-8 as base case, change residual stress at about 30 years	effect of change should be minimal

Six check cases and titles are defined along with comments of the expected result. Again, under the test implementation subheading, the file folder for V & V packages is identified and the list is summarised of files names for midlife checks along with a sentence on type of check. The test are then presented results under five subheadings: PWSCC Initiation and

Growth-Residual Stress Change; PWSCC Initiation and Growth-Wall Thickness Change; PWSCC Initiation and Growth-With Wall Thinning; PWSCC Initiation and Growth-Water Chemistry; and PWSCC Initiation and Growth-Residual Stress Change. List of files names for the test cases are mentioned. Brief discussion is presented on some of the results. It is concluded that the effect of mid-life changes were performed. The expected effects were observed.

A statement of plan is given and some results are presented. File folders are identified for calculation packages.

Fourteen Analysis Types
In this section it is noted that there are fourteen types of analysis that can be performed by PRAISE-CANDU. Most of these have been checked in earlier V & V packages.. *The test plan state "the check in this section were not specified in the V & V Plan[2]. The PRAISE-CANDU 1.0 software was run on check problem covering analysis types that have not been checked in previous software V & V packages.*" The file folder for V & V packages is identified. A table is presented of checks from previous software V & V packages, and lists of additional checks, which can be categorise as either pre-exiting or initiating cracks, are provided. Five new pre-existing crack cases are identified and executed. They are: Pre-existing SCC; Pre-existing SCC and Fatigue; Pre-existing fatigue; Pre-existing FAC and Fatigue; and Pre-existing FAC with a fatigue and SCC. Four initiating cases are identified and executed. These are: Initiating SCC with Growth SCC; Initiating SCC with growth SCC and fatigue; Initiating SCC with growth SCC and FAC; Initiating SCC with growth fatigue, SCC and FAC. Detailed description of the problem statements, input parameter and result description are not presented. Two plots are shown on the effect of FAC on leak and LOCA probability. A screen capture is presented of PRAISE-CANDU menu that show alternate paths for analysis. It is concluded that the results are as expected.

A statement of plan is given and some results are presented. File folders are identified for calculation packages.

9.9.2 Areas for Improvement

The section covers a lot of material that have the potential to highlight the capability of PRAISE-CANDU. However, for a given subsection, too many example problems are lumped together under the banner of test implementation and test result, not enough details or information presented on any one in terms of input parameters description, problem description, discussion, output and conclusions. The basic problem is simply that of proper documentation of all the relevant information used and obtained from test cases so that a meaningful assessment of the verification and validation exercise can be undertaken. Unlike some of the previous sections where the inputs were mentioned and the results were not discussed, the main shortcoming of this section is that the results are discussed without a clear definition of the statement of the problem, the input parameters and identity of the formula being verified.

One other test case which might belong to this section, but which has not been discussed in the COG V & V report so far is presented below. The problem of load sequence when there are multiply loads and/or multiple damage need to be addressed.

Consider the case of a single load analysis involving more than one failure mechanism, for example the growth of stress corrosion cracking, fatigue crack and FAC. Analysis involving these damage mechanisms can be performed starting with any of the damaged mechanisms. Table 8 shows six possible damage sequences that a single load can be applied via stress intensity factors or other approach. The size of the final crack may not necessarily be the same for all the damage sequences listed in the table, it will depend on the sequence used to grow the crack.

Additionally, when there are multiple loads, for example operational loads and many transients, the size of the crack will depend on both the load combination and the sequence in which these loads are applied. It is not clear from the theory manual that load sequence is defined and from the verification and validation exercise performed that these features have been checked. Guidelines on the load sequence used in PRAISE-CANDU have to be developed to ensure accurate results or at least to ensure that the most conservative outcome is always obtained.

Table 8: Possible Damage Progression Sequence for Component with Multiple Damage Mechanisms

1	Fatigue -> Stress Corrosion Cracking ->FAC
2	Stress Corrosion Cracking -> Fatigue ->FAC
3	FAC -> Fatigue -> Stress Corrosion Cracking
4	Fatigue -> FAC -> Stress Corrosion Cracking
5	Stress Corrosion Cracking -> FAC -> Fatigue
6	FAC -> Stress Corrosion Cracking -> Fatigue

Additional improvements to individual subsections are given below.

Inspection

For each example problem, a problem description, input parameter description, similar to what is done in the COG Pilot study although not necessarily to the same scale, which are critical information needed for meaningful assessment need to be provided. The absence of this makes it difficult to assess the results in a meaningful way.

Seismic

In additional to indicating references where the test plan can be found, a description of it needs to be provided in the verification and validation document.

Multiple Transient Fatigue

Fatigue/PWSCC versus PWSCC/Fatigue

The acceptance criteria defined earlier for probabilistic results need to be consistently applied.

Although it is concluded that the results from Fatigue/PWSCC versus PWSCC/Fatigue are identical, it is not clear what is responsible for the outcome. Two possibilities exist. It could be that the two analyses performed in PRAISE-CANDU used the two different sequences but arrived at the same conclusion, or it could be that there is a check in PRAISE-CANDU that ensures that only one sequence is used regardless of how it is defined so that the outcome is always the same. Any of these two approaches will need justification and guidance (see the main discussion in 7.9.3).

Fatigue Initiation and Growth –Multiple Sites

As part of the conclusion, it is noted that partitioning of a variable between heat-to-heat and within-heat has significant impact on the calculated failure probability (initiation, leak and LOCA probability). If this is a general conclusion that is applicable to most problems then for the computed failure probabilities to be credible, there is definitely a need to develop guidelines on how to partition variables between heat-to-heat and within-heat.

PWSCC Initiation and Growth –Multiple Sites

Residual Stresses

It is stated in the test plan that "….*The effects of residual stresses on fatigue results should be minimal, and the effects on PWSCC potentially large –depending on the magnitude of the stresses.*" Is this always true and can it be justified? Does it mean that residual stress consideration can be excluded from all fatigue analysis?

It is also concluded that for PWSCC problem, "the selection of different residual stress model …. causes remarkable differences in LOCA probability". Is this a general conclusion or is it specific to this problem? This cannot be overlooked when dealing with practical problems, guidance will need to be given on residual stress models.

Mid-Life Changes

Fourteen Analysis Types

9.10 ALEATORY/EPISTEMIC CHECKS

9.10.1 Overview and Strengths

Epistemic uncertainty feature in PRAISE-CANDU is one of the distinguishing features of the tool and checks on both epistemic and aleatory features are discussed on pages 105-107. Prior checks have been on one loop or single hair. The epistemic loop allows for the generation of multiple hairs so that quartiles of probabilistic results can be obtained. The test plan, test implementation and test results are summarised.

The test plan states " *a base case problem is to be defined, drawn from the problems discussed in previous sections. All of the previous problems have been aleatory only. The first check is to change all the random variable to epistemic and run them again. The mean result should be nearly the same but the individual hair could be much different. The second check is to make some of the random variables epistemic and some aleatory. The mean result should remain the same, but the individual hairs could look different.*

Additional runs are to be made with some of the random variables having both aleatory and epistemic contribution. Checks are to be made with both contributions being considered but the standard deviation of the epistemic contributions being set to zero. The result should then be the same as for the case when the random variable was totally aleatory.

At least one run with few enough epistemic trials is to be performed to allow looking at individual hairs directly and verify correct sorting of hairs to define quartiles. The aleatory/epistemic runs are to be made for a PWSCC initiation and growth problem, fatigue initiation and growth problem, and fatigue of pre-existing crack problem"

A table is shown that summarises the base problems used (only one aleatory loop) and the input for the number of aleatory and epistemic loops and variable type. Input file names are also shown. For all cases, the 50th percentile epistemic quartile is examined. Five cases are considered: (i) 1 epistemic loop, 1000 aleatory loops (all random variables are aleatory); (ii) 100 epistemic loops, 1000 aleatory loops (all random variables are aleatory); (iii) 1000 epistemic loops, 1 aleatory loop (all random variables are epistemic); (iv) 100 epistemic loops, 1000 aleatory loops (some random variables are aleatory only and some are epistemic only); (v) 100 epistemic loops, 1000 aleatory loops (some random variables are both aleatory and epistemic);

Figures and brief discussions of some results are presented. It is concluded that the expected trends are observed for various aleatory and epistemic loops and calculations for finding epistemic quartile matches with independent checks.

9.10.2 Area for Improvement

The analyses are performed using base problems, discussed in the previous sections of this report (Section 9.9). Most of these test cases lack some basic information needed for independent assessment, such as a clear definition of problem statement, input parameters, results, discussion and conclusion, documented in the verification and validation report. Therefore suggestions for improvement in Section 9.9 are also applicable to this section of the report.

Additionally, unlike previous sections where the V & V file folders for analysis packages were identified, the file folder for this section is not identified. That needs to be done

9.11 RANK OF RELATIVE IMPORTANCE RANDOM VARIABLES

9.11.1 Overview and Strengths

The discussion is presented on pages 108-110. The test plan, test implementation and test results are summarised.

The test plan states "*Sensitivity studies on fatigue crack growth of pre-exiting crack with FAC are to be performed on two piping sizes: NPS 12 and NPS 24. Develop an ANalsis Of Variance (ANOVA) matrix. The random variables in Table 2-2 of V&V Plan[2] are ranked with their relative importance on leak probability, threshold break size and rupture probability*."

It is noted that ANOVA approach was not adopted to rank the parameters due to budget and schedule restraints. The most common approach for sensitivity study, which involves changing one parameter at a time, was adopted. Therefore, the interaction effect between variables was not assessed. Although a detailed description of the problem is not given, a table showing failure probabilities for 15 feeders is provided.

Under the subheading, PWSCC in Feeder Dissimilar Metal Weld, The V & V file location is identified. A table titled, <u>Sensitivity Study Matrix</u>, with listed parameters and values (for example WRS ID/OD, Operational leak rate limit etc.) and another table titled Failure Probability at the EOL from Sensitivity Study, with listed failure probability for base case 1,2,…..,7A,&B, are provided in the report. A figure showing the importance factor ranks is given with leak action limit identified as the number one influencing factor followed by weld residual stresses. It is noted that Reference[13] documents a detailed assessment of PWSCC in Darlington feeder Dissimilar Metal Welds (Alloy 600 to SA-106 with Alloy 82 filler materials) using PRAISE-CANDU 1.0.

Another subheading, Fatigue Carbon Steel Piping, is presented, where it is stated that due to budget and schedule restraints, the original plan was abandoned. However, it is expected that this section will be expanded in the future with the target plant being Pickering B.

9.11.2 Area for Improvement

Revise the test plan to reflect what was done. Also implement the suggestions in Section 9.4.3 such as documentation of clear statement of problem, definition of input parameters and assumptions, results presentation and discussions, summary and conclusion. Implementation of these suggestions, which is what is already done in COG-JP-4367-046 "PRAISE-CANDU Version 1.0 Pilot Study", will bring clarity to the work executed and allow for its fair assessment.

9.12 BENCHMARKING WITH OTHER PFM SOFTWARE

9.12.1 Overview and Strengths

This section deals with benchmarking and is presented on pages 111-123. It compares PRAISE-CANDU 1.0 with other PFM software tools. It is noted that there are no publicly available Tier 1 and Tier II PFM software that has been developed with full software quality assurance program. The main topics are: (i) Comparison with xLPR 1.0 and PRO-LOCA V3.0; and (ii) benchmarking with NURBIM Fatigue Base Cases. The test plan, test implementation and summary for each model are provided as discussed below.

Comparison with xLPR 1.0 and PRO-LOCA V3.0

The test plan states "*PRO-LOCA is being developed under PARTRIDGE program. Version 3.0 of the code will be benchmarked with PRAISE-CANDU for the following cases. The xLPR 1.0 base case will also be included*." A table titled, Test Plan for Benchmarking with PRO-LOCA 3.0, has 9 cases listed for benchmarking: They are: (i) PWSCC initiation and growth, with high stress (PRO-LOCA V3.0 Monte Carlo); (ii) PWSCC initiation and growth, with low stress (PRO-LOCA V3.0 Monte Carlo); (iii) PWSCC initiation and growth, with high stress (PRO-LOCA V3.0 importance sampling); (iv) PWSCC initiation and growth, with high stress (PRO-LOCA V3.0 importance sampling); (v) fatigue initiation and growth, with high stress (PRO-LOCA V3.0 Monte Carlo); (vi) fatigue initiation and growth, with low stress (PRO-LOCA V3.0 Monte Carlo); (vii) fatigue + PWSCC initiation and growth, with high stress (PRO-LOCA V3.0 importance sampling); (viii) fatigue + PWSCC initiation and growth, with high stress (PRO-LOCA V3.0 Monte Carlo); (ix) xLPR 1.0 Base case;

For the test implementation, it is noted that PRO-LOCA V3.0 had not been formally released at the time of preparing the report, therefore the planned fatigue checks have been postponed for future studies. Instead, the PWSCC example documented in the xLPR pilot study has been selected for Benchmarking. It is also stated that CANDU Energy Staff did not perform any PRO-LOCA runs rather the PRO-LOCA results were provide by Dr. Robert Kurth through PARTRIDGE. The file location for the V & V analysis is identified.

It is noted that details of the benchmarking are documented in reference Wang (2012)[16]. Nine figures are provided that compare the results from the three PFM tools. A table is supplied that summarises the model features of xLPR and PRAISE-CANDU. Some of the models are identical while some are different. It is noted that the differences in the calculated deterministic crack lengths and depths from PRAISE-CANDU and xLPR can be attributed mainly to the different crack transition models and K-solutions adopted by the two codes. However, the probabilistic analyses show excellent agreements and differ by less than one order of magnitude

Benchmarking with NURBIM Fatigue Base Cases

The test plan states "*the NURBIM [14] was focusing on the definition of best practice methodologies for performing risk analyses and establishing a set of criteria for the acceptance of risk quantities that can help Regulatory bodies in Europe to accept Risk-Informed In-Service Inspection as a valid tool for managing plant safety. The three fatigue benchmarking bases cases are to be repeated in PRAISE-CANDU*." A table titled, Test Plan for Benchmarking with NURBIM Fatigue Base Cases, has 3 cases listed for benchmarking: They are: (i) small pipe; (ii) medium pipe; and (iii) large pipe;

For the test implementation, it is noted that some cases in reference [14] were run by PRAISE-CANDU and the results compared with other 4 PFM software. No information is given on these cases. It is noted that the relevant figures in Reference [14] were digitised using the freeware GetDAT GRAPH Digitizer to facilitate comparison. The file location for the V & V analysis is identified.

In the summary section, eleven figures are provided to compare the results with the other PFM tools. The other PFM tools are named in the documents but can be discerned from the graph legend. They are WinPRAISE, ProSACC 92, PROST, PRODIGAL, WinPRAISE 2007 and SRRA. The list of variables employed in the NURBIM sensitivity study is given. The variables are crack density, crack aspect ratio, maximum load, fatigue cycles, flow stress, yield stress, fracture toughness, inspection quality and inspection frequency. It is noted that excellent agreement is obtained. All the PFM software show consistent trend for the calculated leak probability. It is also noted that the variables in all PRAISE-CANDU runs were treated as aleatory because the other four tools do not distinguish between aleatory and epistemic uncertainties. Although the rupture frequency is not reported, it is noted that interested readers can extract the results from the PRAISE-CANDU *rpt* file saved in the V & V package

9.12.2 Areas for Improvement

The cornerstone for accepting a safety related tool is its verification and validation. Verification is the process of determining that a model implementation accurately represents the developer's conceptual description of the model and the solution to the model. Verification provides evidence, or substantiation, that the conceptual model is solved correctly by the computer code in question. The fundamental strategy in verification is to identify, quantify, and reduce errors caused by the mapping of the conceptual model to a computer code. Verification does not address the issue of whether the conceptual model has any relationship to the real world. Chapters 3 to 11 of COG-JP-4367-026 "Verification and validation Report for PRAISE-CANDU" with almost 100 pages is devoted to reporting the verification exercises in PRAISE-CANDU.

Validation is the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model. It provides evidence, or substantiation, for how accurately the computational model simulates the real world for system responses of interest. Validation is meant to show that the output from the software is correct. In the context of probabilistic fracture mechanics, the only tool available for validation is benchmarking, where the results from the tool are compared either with results from other similar tools or with data from operating experience. Although benchmarking has its shortcomings, it is the only method that we know for validating a PFM tool. A good benchmark must have a clear and precise definition and description of its purpose and a very good documentation of the exercise including a detailed description of the problem, the inputs, differences between the models, inputs and outputs between the tools, assumptions that are made to reconcile the differences between the tools, inputs, descriptions of the implications of the assumptions, and detailed discussions of the results. Only, Chapters 11 and 12 of COG-JP-4367-026 "Verification and validation Report for PRAISE-CANDU" with 14 pages are used to report validation of PRAISE-CANDU.

The developers of PRAISE-CANDU recognise the importance of benchmarking the tool and have carried out several studies on it as documented in (Wang, 2012, Wang et al, 2013, Duan et al., 2013). One of the studies, Wang, 2012, is cited as a reference in the current COG V & V report. Unfortunately these documents with more details, which in our opinion should have been submitted to CNSC as part of the current submission, are not available for our assessment. Additionally, within the current report only 12 pages is devoted to validation using benchmarking with other tools. The information provided in the twelve pages are mostly graphs of results and include the test plans (case titles), test implementations (two short paragraph with information on V & V file folder locators) and summaries (several plots that compare PRAISE-CANDU results to other tools). The current section as written does not have enough details for us to pass a valid judgement on the quality of the benchmarking exercises.

Some of the details provided in the other documents will need to be included in the verification and validation report. For example in Wang et al, 2013, detailed description is given of the input parameters, the differences between the input parameters used in xLPR and PRAISE-CANDU. From Wang et al, 2013, for example, it is stated "*the temperature and pressure are considered to be random in xLPR while they are considered to be deterministic in PRAISE-CANDU*" and " *Note that the 10-based log term in* f_{H2} *was coded as natural logarithm in the Grower module source code of xLPR. This results in the growth rate being 30% lower and was taken into accounted in PRAISE-CANDU by adjusting other coefficients*". Such details and others are lacking in the current version of PRAISE-CANDU 10 V&V report and they have to be included to enhance the quality of the result and provide a basis for a fair assessment of the work.

Other improvements to the documents are as follows:

xLPR and PRAISE-CANDU are two current tools designed for PFM analysis. Some of the models implemented in PRAISE-CANDU especially the deterministic models are different from the models implemented in xLPR, including: (load combination, crack placement, PWSCC growth transition, K-solutions, J Integral, and crack stability. As noted in the report the two models can give different deterministic results, thus the need to justify the choice of models in PRAISE-CANDU.

In Section 12.2.2 for example it is noted that "*some cases in Reference [14] were run by PRAISE-CANDU*". The natural question that arises is which cases, and why are they not documented in the report? Another example is in Section 12.1.3 where it is stated "*the details* *of the benchmarking are document in Reference [16*]", which is an internal COG report. Those details should be provided in the current report.

Figure 12-10 where PRAISE - CANDU is compared with other NURBM tools show that where PRAISE - CANDU is not bounding for large pipes. As this is the target application, it requires explanation.

9.13 COMPARISON WITH OPERATING EXPERIENCE

9.13.1 Overview and Strengths

This section compares PRAISE-CANDU with operating experience. It is presented in 2 pages, on pages 124 to 125. The main topics are: (i) Canadian OPEX; and (ii) Pipe Rupture Due to FAC OPEX. The test plan, test implementation and summary for each topic is provided and are discussed below.

Canadian OPEX

The test plan states "*The calculated leak probability from the PWSCC initiation and growth models will be validated directly with the operating experience of feeder piping dissimilar metal welds in Darlington units. Some large diameter Primary Heat Transport System (PHTS) piping in Darlington units have been approved for Leak-Before-Break LBB. Two circumferential welds, one with least LBB margin and one with the largest LBB margin, will be assessed with PRAISE-CANDU and compared with deterministic LBB.* " A table titled, Test Plan for Canadian OPEX, has 3 cases listed: They are: (i) PWSCC in feeder dissimilar metal weld; (ii) fatigue weld with the least LBB margin; and (iii) fatigue weld with the largest LBB margin;

For the test implementation, the one written sentence is " *Not all cases were performed per the test plan*." The following sentences are the only things written about specific cases. For (i) listed in the previous paragraph it is stated "*See reference[13] for the detailed studies on PWSCC*" and for (ii) and (iii) it is stated "*Due to budget and schedule constraints, the above* *cases will be performed in future. This does not affect the overall quality of V&V because fatigue has been extensively covered in Section 12.2: benchmarking with NURBIM*."

The summary states "*the study in Reference [13] shows that benchmarking with OPEX is essential for calculating the failure probabilities. The parameters with the least confidence or largest uncertainty should be calibrated to the OPEX*"

Note that the text just presented above and quoted extensively constitute all the information that is given in the report under the subtitle of Canadian OPEX

Pipe Rupture to FAC OPEX

The test plan states "*This is to check FAC module in PRAISE-CANDU for pipe subject tohigh wall thinning rate*". " A table titled, Test Plan for FAC OPEX, has 1 cases listed as pipe rupture due to FAC with comment "*Mihama Unit 3 and PWR FAC rupture OPEX to be checked. The predicted time and probability of rupture are compared with OPEX*."

For the test implementation, the only information under this subsection is a statement identifying where the information for benchmarking is obtained, a summary of the key parameters in a table and the V &V storage locator for the analysis. It is noted that the information used for the benchmarking can be found in Reference [18]. A table is given that summarises the key parameters as reactor type, operating time at rupture, plant, material, outer diameter, nominal thickness, lower bound thickness within manufacturing tolerance, operating temperature at rupture, operating pressure and thinning rare.

A figure is given in the summary section. The summary states "*Figure 13-1 shows that the calculated LOCA probability. For the given lower bound initial wall thickness of 9.3 mm, PRAISE-CANDU predicts that rupture will occur between 21 EFPY and 22 EFPY. The rupture occurred at 21.2 EFPY. Excellent agreement is obtained*."

Note that the text just presented above and quoted extensively constitute all the information that is given in the report under the subtitle of Canadian OPEX

9.13.2 Areas for Improvement

This section suffers from the same problem as the section on benchmarking. A good starting point for improving the quality of the material in this section is application of the suggestions in Section 9.122. Again, the cornerstone for accepting a safety related tool is its verification and validation. Therefore effort has to be made to provide adequate documentation of the validation activity involving operating experience to facilitate the assessment of the validity of the tool.

The section on comparison with operating experience, Section 13, as currently written, needs some improvement. The information provided is not adequate for a fair judgement by a third party reviewer. Efforts must be made to provide clear and precise definition and description of the activity and a very good documentation of the exercise including a detailed description of the problem, the inputs, assumptions made concerning the inputs including its probabilistic descriptions, descriptions of the implications of the assumptions, and detailed discussions of the results.

Again the authors of the report have other publications in the public domain which may or not be relevant to the current section, Wang et al, 2011. Some of the details provided in this document, for example the issue with modelling PWSCC and the assumptions made when using PWSCC models and others, have to be included in this section of the report.

Other improvements are as follows:

A discussion of section 13.1 (page 127 of the COG-JP-4367-026) is used to highlight areas that can be improved in Section 13 of the report. In Section 13.1.1 for example a Test Plan is provided, and in Section 13.1.2 it is stated "*Not all cases were performed per the test plan*" which begs the question which ones were not performed and why are they included in the report as part of V & V. Then in Section 13.1.2.1, where an example test plan, Case 12.0-1 titled PWSCC in feeder piping dissimilar metal, is presented, the only statement written is "*See Reference [13] for the detailed studies on PWSCC.*" No discussion whatsoever on input, models, outputs, assumptions etc. is given on Case 12.0-1 titled PWSCC in feeder piping dissimilar metal in the report. This is quite sloppy and makes it impossible to assess the case study. Following this in Section 13.1.2.2 the other case studies, titled fatigue, weld with the least LBB margin and fatigue, weld with the largest LBB margin, are mention and the only text discussing this section reads "*due to budget and schedule constraints, the above cases will be performed in the future. This does not affect the quality of V&V because fatigue has been extensively covered in Section 12.2 benchmarking with NURBIM project*". Then in Section 13.1.3, titled "summary" a summary of the entire section 13.1 is given and it states only the following "*the study in Reference [13] shows that benchmarking with OPEX is essential for calculating the failure probabilities. The parameters with the least confidence or largest uncertainty should be calibrated to the OPEX*." All of the above quotes make no sense to a reviewer or any other person outside the writer of the COG V & V report because no details are provided on input, models, assumptions, discussions of results, OPEX data etc. in the report. The entire section needs a major reworking.

The next section, Section 13.2, on pipe rupture due to OPEX, has similar shortcomings as Section 13.1 and should be rewritten. It is not clear what loads, load combinations etc. are being considered because there is no problem statement. Even though a table listing key parameters is given, none of the parameter is a random variable, they all have fixed deterministic values, giving rise to the question of how do you calculate failure probabilities with only deterministic input parameters? The answer is you can't, for the output to be probabilistic there must be at least one probabilistic input.

There is a typo in the title of Table 13-3 that needs to be fixed. The Table 13-3, which has a list of key parameters and is under the subsection of FAC OPEX, has the title "Test plan for Canadian OPEX.

It is not obvious how one can claim that "*PRAISE - CANDU 1.0 meets the V&V requirements*" when only one OPEX case without failure was assessed. "*Benchmarking with OPEX is essential for calculating the failure probabilities*".

Several databases are available for validation, Pipe fracture database, IPIRG database, OPDE database and should be considered for verification and validation.

10.0 COG-11-2096: LOCA BREAK-OPENING CHARACTERISTICS FOR CANDU HTS PIPING – LITERATURE REVIEW

The document is focused on using a review of piping work, numerical and experimental, executed worldwide to argue that instantaneous rupture is an incredible mode of failure for large-diameter CANDU primary heat transport piping systems. From the review, a number of conclusions are drawn about the break-opening dynamics of large diameter CANDU primary heat transport system piping and used to propose break-opening models for large diameter CANDU pipes. It has five main sections: Introduction; Failure due to Overload; Failure Due to Cyclic Bending; Conclusions from Literature Review; and Recommended More Realistic Break-Opening Models; Each of the sections is reviewed and summarised.

10.1 INTRODUCTION

10.1.1 Overview and Strengths

Several topics are discussed, including an introduction to the original COG Technical note TN-09-2062 and its purpose, a brief discussion on large LOCA, regulatory requirements for break opening, the purpose of the current report and the methodology used.

Large LOCA is a central element in the design and licensing basis for light water and heavy water reactors. Aside from establishing the design requirements for special safety systems and for nuclear safety analysis, design requirements evolved to design against the so-called "dynamic effects" associated with postulated rupture of high energy piping. These dynamic effects include: pipe whip, jet-impingements, de-pressurization transients in the piping and attached pressure vessels, debris generation and flooding. The break sizes considered in large LOCA ranged in size and up to and including a Double-Ended Guillotine (DEGB) of the largest pipe in the primary heat transport circuit.

For the purpose of evaluation models, that is, thermalhydraulic code simulation of the postulated rupture and design for dynamic effects, the breaks have been assumed to develop instantaneously. Historically, in thermalhydraulic code simulations, an initial time step of 1 ms (one millisecond or less) has been used, and the development of the break (from zero to the full two-times the break area) was assumed to occur in that one time step. The value of 1 ms for the break-opening time is generally accepted as conservative value to establish the design requirements for special safety systems and for nuclear analysis. The consequences of rapid depressurization associated with postulated instantaneous pipe rupture of CANDU large-diameter primary heat transport piping is group into three categories: (i) voiding of the heat transport fluid, that in turn can lead to changes in reactivity of the reactor if the voiding extends into the reactor core; (ii) dynamic effects associated with fluid-dynamic loadings that act on the piping system and on the internals of pressure vessels connected to the piping; and (iii) debris generation due to shock wave and fluid jet that are a concern for blockage of the screens on the emergency core injection sumps. The scale of these effects depend on the size of the postulated breaks, the location of the postulated breaks and the length of time assumed for the break to develop (break opening time).

The regulatory requirements in the United States for break opening are discussed. The instantaneous DEGB of the largest main coolant piping has been considered as a basis for the design, reliability and operating requirements for the Emergency Core Cooling System (ECCS). Part 50.46 of 10CFR are the acceptance criteria for ECCS for light-water reactors and it requires the ECCS to be able to mitigate the postulated LOCA. The requirements for instantaneous break opening is specified in the Appendix K to Part 50 for ECCS Evaluations Models, where it is noted that paragraph (I)(C) on Blowdown Phenomena states "*1. Break Characteristic and Flow. a In analyses of hypothetical loss-of-coolant accidents, a spectrum of possible pipe breaks shall be considered. This spectrum shall include instantaneous double-ended breaks ranging in cross-sectional area up to and including that of the largest pipe in the primary coolant system. The analysis shall also include the effects of longitudinal splits in the largest pipes, with the split area equal to the cross sectional area of the pipe*." Appendix A to Part 50 (10CFR) which establishes the minimum requirements for General Design Criteria (GDC) for water-cooled nuclear power plants is also noted and GDC 4, which is the design criterion for overall environmental and dynamic effects associated with postulated pipe ruptures, is also quoted in the report. The Standard Review Plan (SRP) Section 3.6.3 that provides non-mandatory leak-before-break evaluation procedure that are considered acceptable and adequate analysis that may be used to eliminate the dynamic effects of the pipe ruptures postulated in SRP 3.6.2 from design basis, that is satisfies the requirements of GDC 4 is briefly mentioned. The COG report also notes that a US-NRC staff approved leak-before-break analysis permits licensees to remove protective hardware such as: pipe-whip restraints and jet-impingement barriers, redesign pipe connected components, their supports and their internals.

Darlington NGS was the first CANDU plant for which the requirements for addressing postulated pipe ruptures were explicitly identified in the construction license for the plant. Clause 25 of the construction license for Darlington NGS is quoted as "*Except as otherwise approved by the Board, all piping and headers which form part of the primary heat transport system shall be restrained to the extent necessary to ensure that their failure could not cause consequential damage which would render invalid the analyses in the Safety report or other submissions to the Board*." A leak-before-break methodology similar to that used for SPR Section 3.6.3 in the US was adopted and applied to relax the requirements for restraints of the large-diameter-primary transport system in Darlington. The LBB in Darlington was implemented to justify the elimination of pipe whip restraints, not for the reclassification of large LOCA to beyond design basis accidents. Pipe whip restraints can cause obstructions that may affect access to components for inspection and maintenance. The deterministic LBB requirement that has been accepted in the US and for Darlington was accepted to allow design of a plant without excessive use of pipe whip restraints. For analysis of a large LOCA, the plants are still required to demonstrate that safety systems can respond to a 1 ms break of the largest pipe in the PHTS to prevent fuel damage.

The American National Standard for protection against the effects of postulated pipe ruptures presents methods for complying with DGDC 4 that is less restrictive than US-NRC requirements. This standard has not been accepted in any leak-before-break related licensing actions for NPP by the US-NRC. The ANS jet model is under further review by US-NRC staff and acceptance of submission using the ANS jet model is on a case-by-case basis. The break-opening time recommended by the ANS standard is 1 ms break-opening time for axial breaks that have a flow area equal to the flow area of the pipe and permits the use of larger break-opening times when justified. The break opening time criteria in SRP 3.6.2 used in dynamic analysis models for evaluating the dynamic effects associated with postulated pipe ruptures is stated as "*III.2.C(ii) A rise time not exceeding one milliseconds should be used for the initial pulse, unless a combined crack propagation time and break-opening time greater than one millisecond can be substantiated by experimental data or analytical theory based on dynamic structural response*."

A very brief summary is presented on several pipe fracture tests and experiments that were conducted during the past 45 years. The early work, sponsored by the oil industry, involved burst-pressure testing of relatively thin-walled straight seam-weld pipes fabricated from low toughness carbon steel. This was followed by testing from the nuclear industry that involved seamless thick-wall pipes with higher toughness containing axial flaws subjected to internal pressure loading. Subsequent studies involved circumferential flaws and more complex loading. It is stated in the COG report that evidence from these studies indicate that instantaneous double-ended guillotine break could not happen in large-diameter nuclear grade piping under normal operation or accidental loading conditions unless a very large flaw was present in the pipe. The results of the pipe rupture tests was used in the US to establish the technical basis for leak-before-break methods to resolve some of the outstanding licensing issues associated with the design methodologies for the dynamic effects associated with the postulated rupture of primary coolant piping. The test results were also used to establish the break-preclusion methodology in Germany and France. The break preclusion assessment has been used in France for newer reactor designs to limit the size of the piping for which a LOCA must be treated as a design basis accident, but the analysis is based upon strict design guidelines and a deterministic assessment of fracture behavior of piping using conservative assumptions.

An extensive review is presented on the history of threshold break sizes in the US. Starting with the adoption of risk informed changes to the technical requirements of 10 CFR 50. One element of this effort was to evolve regulation and redefine large LOCA from design basis to beyond design basis accident when utilizing a risk-informed approach. In spite of this redefinition, significant risk-significant scenarios would remain within the design basis and their consideration would be enhanced by a new focus on their risk-importance. However, during the 2000 October refuelling outage at the V.C. Summer PWR plant, a 60 mm-long through-wall axial crack was found in dissimilar metal weld to one of the hot-leg nozzles of the main reactor vessel. The LBB relaxation for pipe-whip restraints had been used for the large-diameter primary coolant piping at this plant. The root cause of the crack was Primary Water Stress Corrosion Cracking, an active degradation. The occurrence of active degradation other than fatigue violated a condition of the leak-before-break which only permitted its use for systems that are not susceptible to service induced degradation. Subsequently, more safety significant circumferential PWSCC have been found in other dissimilar metal nozzle welds in PWRs. The COG report notes that the discovery of active degradation in the primary coolant piping in PWRs has disrupted the issuing of the US-NRC regulatory guide on deterministic LBB evaluation procedures, which would have provided guidance to licenses and applicants on implementing the requirements of GDC-4. This issue has highlighted that an alternative approach to deal with the GDC-4 requirements is through demonstrating an e<u>x</u>treme Low probability of Rupture (xLPR) that is consistent with risk-informed changes proposed to the technical requirements of 10 CFR 50 is needed.

In 2002, the US-NRC staff began preparing a draft of a proposed rule that contains alternative ECCS evaluation requirements, which would be codified in a new regulation to 10 CFR 50.46a that could be used by licenses in lieu of the requirements in the current 10 CFR 50.46. The new draft proposed regulations divide LOCA break sizes into two regions determined by the Threshold Break Size. The first region includes small breaks of a size up to and including the TBS. The second region includes break larger than the TBS up to and including the DEGB of the largest reactor coolant system pipe. The appropriate TBS proposed by US-NRC is the cross-sectional area of the largest pipe attached to the reactor coolant system. Thus TBS will vary from plant to plant depending on the specific piping system design. The largest pipe diameter is 200 mm to 350 mm for Primary Water Reactors and 500 mm for Boiling Water Reactors. A history of the draft rule is discussed and the current status indicates that decisions have not been finalised due to Japan’s Fukushima Daiichi disaster. In the final rule when adopted, each break region, small and larger, will be subject to ECCS requirements and analysis assumptions, commensurate with their relative likelihood of break. This rule will be subject to periodic review and monitor by the US-NRC staff.

The purpose of the COG report is to recommend a more realistic break opening model to replace the conventional instantaneous double-ended guillotine break for large LOCA safety analysis. The approach adopted by the COG is to review pipe fracture test and draw relevant conclusions. A list of specific pipe integrity programs costing more than $110 million that are reviewed is provided, including the US-AEC Ductile Rupture Program (1967-1971); the US-NRC Degraded piping Program (1981-1989); The US-NRC Short Cracks Program (1993-1994); The International Piping Integrity Group Programs (1986-1997); the Battelle Integrity of Nuclear piping Program (1997-2003) and the German Phenomenological Vessel Failure and Pipe Burst Test Programs (1977-1994). The COG report states that any process to exclude instantaneous ruptures has to be mechanistic, where potential mode of failures are determined and explicitly considered. The failure modes identified for nuclear piping systems in Canadian power plants based on operational history are fatigue and overloads. Both are addressed in the report. Conclusions drawn are not appropriate for failure due to FAC. The COG report has six sections and three appendices.

10.1.2 Areas for Improvement

The approach adopted by the COG to argue for more realistic break opening model for axial and circumferential flaws in large-diameter CANDU PHT piping rely solely on the literature review of non-CANDU work done by others. Although this is a good approach, it is not sufficient for making changes to break opening times in large CANDU PHTS because the material, experimental and testing conditions do not always have a direct one-to-one relationship with large-diameter CANDU PHT piping and typical CANDU plants in Canada. To ensure safety, arguments for changes in the break opening model need also to be justified and substantiated through detailed studies and review of work on typical CANDU plants as well. Conclusions based solely on non-CANDU literature review are not considered adequate/appropriate.

10.2 FAILURE DUE TO OVERLOAD

10.2.1 Overview and Strengths

Extensive discussion is provided on failure due to overload. The section covers several topics, including failure pressure of straight pipes, critical crack length, bending failure of pressurised pipes, failure pressure of piping elbows, bending failure of pressurised piping elbows and failure pressure of piping tee. Majority of testing of piping, and piping components was performed to study the behaviour of the components containing a simulated flaw under overload conditions. In general, the tests were performed using quasi-static loading rates with a monotonically increasing loads dynamic and/or cyclic loading. From the test of piping components containing large surface flaws, it is observed that the failure process due to overload occurs in two steps: the first step is ligament rupture, which involves the development of leaking through-wall crack; and the second step involves the progression of the through-wall crack after ligament fracture of the surface flaw into one of three parts, no crack propagation, crack arrest or crack instability.

Several research documents are identified and reviewed that focused on understanding the failure pressure and crack propagation behaviour of straight section pipes containing axial flaws and loaded with internal pressure. It is concluded that from the review that the failure pressure of straight sections of ductile pipe containing an axial force is independent of applied mechanical loads, that is, axial force and/or bending moments. Critical crack lengths, break opening time and break size are discussed and several conclusions are drawn. The critical crack lengths discussions use results from various tests that were performed on other piping that are not CANDU. To apply the results to CANDU pipes two issues, the toughness of the respective piping materials and the differences in the pipe sizes, are covered. It is concluded that for straight sections of large diameter CANDU PHTS piping (operating on the upper shelf of the material), the critical crack length for an axial flaw is greater than 1.2 times the mean diameter of the pipe. The issue of break opening time and break size are discussed using results from German Vessel Program, where it is noted that it takes from 2 1/2 ms to 5 ms for an axial break area that is 10% of the flow area of the pipe to develop. However, it is concluded that the development of an axial break of a size of 10% of the flow area of the pipe in a pressurised straight pipe can be a rapid process taking about 5 ms. Results from the German Vessel Failure program is used to establish the relationship between the flow area (size) and the resulting break. This result is extended to CANDU PHTS pipes with a pre-exiting axial flaw and it is concluded that for straight sections of large-diameter PHTS piping (operating on the upper shelf of the material) containing an axial flaw with length less than one times the mean diameter of the pipe, any axial propagation of a resulting through-wall flaw will be stable and the resulting break area will be less than 7% of the flow area of the pipe.

Discussions on the bending failure of pressurised straight pipes are also presented. The issues of crack initiation and stability are considered. Several conclusions are noted for the test results, including crack initiations for low and high toughness materials. The crack initiation for low toughness materials tends to occur before maximum load is reach while it occurs near maximum loads for high toughness materials. The four steps in the development of circumferential crack are (i) a small amount of stable surface crack growth in the through thickness direction, (ii) pop-thru of the pre-exiting surface flaw into a through-wall circumferential crack (ligament rupture tended to be rapid), (iii) continued rapid growth around the pipe circumference to the ends of the pre-existing surface flaw and (iv) subsequent through-wall crack growth in the circumferential direction was dependent on the type of overload. It is concluded that the dynamic response of the piping system controls the opening area of circumferential through-wall crack under dynamic loading.

The critical crack length, the break opening time and the break size under bending failure of pressurized straight pipes are discussed. Several studies are used to back up the three conclusions in this section including the German Vessel Study and the US-NRC Degraded piping Program. The conclusions are: (i) ligament rupture in a large circumferential surface flaw is a rapid process taking about 7 ms. The break size corresponding to the ligament rupture will be less than 3.5 % of the flow area of the pipe; (ii) the time required for a circumferential break area that is greater than 3.5 % of the flow area is dictated by the interaction of the failed piping section with the rest of the piping system. It will take more than 2.5 s for a DEGB to develop; and (iii) the initial break size resulting from the ligament rupture of circumferential flaws is less than 3.5% of the flow area of the pipe.

The failure pressure piping elbows, and piping tees are discussed, where it is concluded that (i) the failure pressure characteristic of a long-radius elbow with an axial flaw will be similar to those of the same size straight section of pipe with the same size axial flaw; (ii) that for piping elbows in CANDU PHTS piping system, the crack opening areas for axial flaws is controlled primarily by the internal pressure; and (iii) the failure pressure for flaw-free piping tees (operating on the upper shelf of the material) in the large-diameter PHTS circuit will be equivalent to the normal failure pressure for the flaw-free sections of straight pipes.

The presentation is logical and most of the conclusions are clear.

10.2.2 Areas for Improvement

It is not clear why the term operating on the upper shelf is a constant refrain used in some of the conclusions. The logical question is what happens if the pipe does not operate on the upper shelf of the material because of mistakes say for example human error.

Justification is needed for conclusion (2) where it its stated that the critical crack length for the flaw is 1.2 for all pipe sizes when the figure shown on page 2-4 indicates that the critical crack range could range from 1.01 to 1.30 depending upon the diameter and wall thickness.

Justification is also required on conclusion (3) where it is stated that "*the development of an axial break size of a size 10% of the flow area of the pipe in a pressurised straight pipe can be a rapid process taking about 5 ms*" when the German study used as the basis for the conclusion, concluded that it takes from 2 1/2 ms to 5 ms.

Although most of the conclusions sound reasonable, general and are drawn from large experiments database from worldwide experience, some of them especially the ones that are CANDU specific will have to be substantiated with detailed CANDU pipe analyses. Also material strength, toughness differences between CANDU piping and the other databases cited need to be fully accounted for when broad conclusions are drawn.

10.3 FAILURE DUE TO CYCLING BENDING

10.3.1 Overview and Strengths

Most of the cyclic testings' of piping and piping components have been executed under cyclic bending. Typically fatigue is divided into low or high cycle fatigue. High cycle fatigue is associated with normal stress levels well below the yield strength for the material; it does not involve any cyclic plasticity. Low cycle fatigue, which is characterised by failure in less than 50,000 cycles, is more complicated as material yielding occurs for each cycle. The cyclic stresses are applied as either load controlled or displacement controlled. For load controlled, the ratio of the maximum stress to minimum stress in a cycle (the so called R ratio) together with the stress amplitude is used to characterise the loading. For displacement control, the loading is characterised by the strain increment per cycle. Cyclic bending for straight pipes, piping elbows and piping tees are discussed.

Using the results from Phase III of the German Vessel Failure programs as the basis, two conclusions are drawn for bending fatigue of straight pipes: (i) bending fatigue of straight pipes will result in circumferential through-wall cracks that have a length that is equal to six times the thickness of the pipe; and (ii) in a flaw-free components, 90% of the fatigue life is requires to develop a surface flaw that is 10% of the wall thickness in depth. Based on a review of several references it is also concluded that cyclic bending failure of pressurized flaw-free piping elbows (operating on the upper shelf of the material) is through the development of stable through-wall cracks. The location and orientation of the fatigue failures is dependent primarily on the diameter-to-thickness ratio and the enclosed angle of the elbow. For piping tee it is concluded that the most critical loading on a piping tee are the piping section loads transmitted to the fitting via the branch-pipe. The modes of fatigue failure in a flaw-free piping tee due to bending are similar to the fatigue failure observed in flaw-free elbows.

10.4 CONCLUSIONS FROM LITERATURE REVIEW

10.4.1 Overview and Strengths

The conclusion of the literature review is that from all the testing programs that were reviewed instantaneous rupture of nuclear grade piping system in which there are no degradation mechanism active is an extremely low probability mode of failure. Some of the points from the previous sections are reiterated.

10.5 RECOMMENDED MORE REALISTIC BREAK-OPENING MODELS

10.5.1 Overview and Strengths

This section begins by noting that there is no established international precedence or practice for the use of deterministic break-opening models in the so-called evaluation methods for large LOCA. However, it notes that there is established international practice and precedence for using deterministic break-opening models of engineered systems designed to mitigate the dynamic effects arising from postulated rupture of high-energy piping systems. It cites both the ANS-58-2 and US-NRC's SPR 3.6.2 as examples of method used to design against the effect of postulated pipe rupture with the intention of satisfying the requirements of GDC 4. It is also noted that in the United States, Leak-before-break principles and more realistic break-opening times have been proposed to resolve GSI-191 Assessment of Debris Accumulation on PWR Sump Performance, where shock wave is the issue under consideration. Studies for the potential for a shock wave conclude that a shock wave will not be present for large-diameter opening piping when the break-opening time is greater than approximately 10ms.

Several break-opening models are recommended, which are considered more realistic based on the review of the pipe fracture testing. The recommended models are considered to be appropriate only for cases with fatigue and overloads as potential modes of failure. They are not appropriate for failures due to flow-accelerated corrosion.

The recommended break-opening model for axial breaks in large CANDU PHTS piping is that the initial break develops to a size of 7% of the flow area of the pipe in 5ms. Since the length of the assumed flaw is less than the critical crack length, the initial break is stable, that is, does not increase in size.

The recommended break-opening model for circumferential breaks in large-diameter CANDU PHTS piping is that the initial break develops to a size of 3.5% of the flaw area of the pipe in 5 ms. This initial break is followed by an increase in the size of the break to 200% of the flow area of the pipe in an unspecified long-length of time that would depend on the dynamics of the piping system but would be in excess of 2.5 s.

In order to support the break-opening times for double-guillotine break in excess of 2.5 s, it is recommended that finite element simulations be performed of the piping system with a postulated through-wall circumferential crack that has a circumferential extent that corresponds to six times the wall thickness for design-basis (and greater) earthquake loading.

10.5.2 Areas for Improvement

Since these are essentially a request for change in philosophy, detailed CANDU specific analyses and experiments are needed to substantiate and justify such a large change in break-opening time philosophy. This is particular true because there is no established international precedence or practice for what is being requested.

11.0 COG-JP-4367-041-R0: FPBOC-WG INTEGRATED CLOSE-OUT REPORT

11.1 INTRODUCTION

11.1.1 Overview and Strengths

The section begins with a discussion on the Composite Analytic Approach (CAA) developed by the Canadian CANDU industry. The Composite Analytic Approach is intended to demonstrate, with high confidence, adequate safety margins for large-break loss-of-coolant accident events in existing CANDU rectors. The CAA approach is one of the two potential risk control measures investigated to resolve the issue related to positive coolant void reactivity feedback and large-break loss-of-coolant accident safety margins have been endorsed by the Canadian Nuclear Utility Executive Forum (CNUEF) and executives of the Canadian Nuclear Safety Commission (SNSC). The objective of CAA is stated. It is to use a variety of reinforcing analytical elements such that they complement one another to collectively form a robust solution that alleviates reliance on any single method or activity. Three principal objective of CAA are stated: (i) the probability of having a break in a large-diameter CANDU primary heat transport system is low and the probability of having a large break is extremely low, to the extent that it is appropriate to reclassify LBLOCA as a Beyond Design Basis Accident (BDBA) event. (ii) the adoption of realistic (yet robust) break-opening characteristic for large-diameter primary heat transport system piping is justified; and (iii) the large-break loss-of-coolant accident safety margins obtained through break size reclassification and the application of physically based assumptions and realistic analysis method are large.

The purpose of the report is to document the work that was overseen by the Failure Probability and Break-Opening Characteristics Working Group (FPBOC-WG) and to describe how that work supports the industry proposed Composite Analytic Approach. The report is intended as an integrated close-out that summarises all the work performed under the oversight of the FPBOC-WG.

Background is provided on two joint Industry/CNSC working groups (LBLOCA and RIDM), which were sponsored by the executive of CNSC and CNUEF, that were established to address issues of high regulatory significance within the Canadian Nuclear Industry. The first working group dealt with finding options to deal with the issue of positive Coolant Void Reactivity (CVR) and Large-Break Loss-of-Coolant Accident (LBLOCA) in exiting CANDU plants within a risk-informed framework and the second working group dealt with the application of Risk Informed Decision making (RIDM) principles to a set of CANDU safety issues identified by CNSC as having high risk significance.

The LBLOCA working group dealt with the issues related to CVR and LOLOCA safety margins in five major technical areas. (i) Positive void reactivity coefficient; (ii) code and acceptance criteria; (iii) large LOCA analyses and basis; (iv) reclassification of LBLOCA; and (v) low void reactivity fuel (LVRF). Several candidate risk control measures (RCM) and strategies to address LBLOCA safety margins were developed. Two with the potential for success, Composite Analytic Approach and implementation of fuel design changes, were identified. These two RCM candidates were reviewed by the RIDM Woking group and concluded that both were comparable in addressing LBLOCA safety related issues.

An Industry steering committee was established by CNUEF and tasked with implementing the five elements of the Composite Analytic Approach including two tasks, which are the responsibility of the Failure Probability and Break-Opening Characteristic Working Group (FPBOC-WG), reclassification of the LBLOCA analysis basis through application of break size reclassification and realistic break opening model.

Several technical terminology used in the report are defined, including break size, critical crack length, extreme load, extreme/extremely low probability, failure probability, girth buttweld, instantaneous rupture, large-diameter primary hear transport system piping, nominal pipe size, reclassification, redefinition, robust, threshold break size and transition break size. The organization of the report into eight sections and one appendix is also summarised.

11.1.2 Areas for Improvement

None.

11.2 TECHNICAL AREA 4

11.2.1 Overview and Strengths

Technical Area 4 (TA4) deals with Reclassification of Large-Break Loss-of-Coolant Accident. It is the responsibility of the Failure probability and Break Opening Characteristic Working Group (FPBOC-WG) to implement this technical area. Several main items are covered under the discussion of Technical area 4 including, the problem statement, TA4 workshop, and FPBOC-WG.

The original problem statement for TA4 was to develop a suitable approach and program to support break size reclassification of LBLOCA events based on: (i) the use of expert elicitation process to quantify the probability of large-diameter pipe failure as a function of pipe diameter; (ii) the use of fracture mechanics to understand the time-dependent behaviour of large-diameter pipe failure; (iii) the incorporation of pipe failure mechanics and break opening time into the safety analysis for LBLOCA events; and (iv) the introduction of requirements for a risk-informed periodic inspection program.

A workshop focused on TA4 was organised to identify and document key aspects of the Canadian Nuclear Industry and CNSC specialists' view on TA4. The area covered include: key technical issues; existing regulatory expectation and industry standards and guides; benchmarking against relevant international practices; key areas of disagreement between the CNSC and Industry Specialist; and key challenges and alternatives for processes for developing an acceptable resolution path. Several areas of general agreement between the Industry and CSNC are listed, including the failure characteristic of primary heat transport system piping; the possibility of assessing the relationship between break frequency and pipe size based on operating experience, expert elicitation and probability fracture mechanics; the possibility of developing time dependent break-opening model; the (equivalent) break size corresponding to 10^{-5} failure per reactor year; risk informed in-service inspection as a viable means to reduce risk in the context of LBLOCA as a low frequency event; and LBB as a credible methodology for assessing the integrity of large-diameter PHTS that do not have active degradation. The closure issues covered are probability of failure, break opening dynamics, additional surveillance and treatment of large LOCA in licensing. Eleven potential resolution activities were developed and cross reference to the four resolution issues. Items that should be given consideration along with candidate resolution activities were identified.

The FPBOC-WG working group was responsible for preparing and overseeing the implementation of detailed work plans to address the four closure items and the eleven resolution activities associated with TA4 that are necessary to support two of the four candidate resolution activities. The mandate, objective and the work plan of the FPBOC-WG are stated. The five tasks identified by the FPBOC-WG are; (i) CANDU probabilistic fracture mechanics code; (ii) Break opening characteristic model; (iii) Use of external experts; (iv) additional surveillance program; and (v) break exclusion. Each task was subdivided into a number of subtasks. An overview of the FPBOC-WG meetings is presented along with changes to the work plan. One of the changes was the need to develop a qualified, state-of-the-art probabilistic fracture mechanics code that addresses CANDU PHTS degradation mechanism and to restrict expert review of PRAISE-CANDU to the Theory Manual. Several external experts and the roles were identified and documented, with Structural Integrity Associate being identified as the expert that was to provide technical input and oversight for the technical specification of PRAISE-CANDU and also the developer of beta, alpha and version 1.0 releases of the tool.

11.2.2 Areas for Improvement

None.

11.3 BREAK-OPENING CHARACTERISTICS

11.3.1 Overview and Strengths

This section summarises the Task 2 of FPBOC-WG work plan, which included undertaking a review of existing experimental information and establishing more realistic break opening models for large-diameter PHTS piping at Canadian CANDU plants. The task was complicated by lack of failures of large-diameter piping in any CANDU plants, a good thing. Although there have been failures of small-diameter PHTS piping, which are not directly related to large diameter PHTS piping because of the different design, fabrication and inspection requirements as well as operational conditions.

A primer is given on why the probability of catastrophic rupture of CANDU large-diameter PHTS piping and header is extremely low. Among the many reason offered are the design features of large-diameter PHTS pipes and headers, the active degradation mechanisms and lessons from international experimental pipe fractures database. The major components of the PHTS in a typical CANDU plant are identified as, horizontal reactor fuel channels, vertical recirculating steam generators, motor driven primary heat transport pumps, reactor inlet headers, reactor outlet headers, feeders, and associated interconnected piping.

A general description is given of large-diameter PHTS piping. It refers to the ASME Boiler and Pressure Vessel Code Class 1 piping larger than NPS 6 and the reactor headers. This includes the piping that is located inside the reactor vault/building (containment) and connects: the steam generators, the primary heat transport pumps, the pressurizer, the bled condenser and the reactor outlet and inlet headers, together with the balance line and those portions of the emergency coolant injection and maintenance/shutdown cooling piping located between the PHTS and the first D_2O isolation valve n the auxiliary system. The code of constructions for the PHTS is in accordance with CSA N285 series of standards and PHTS of CANDU plants are classified as ASME B&PV Section III, Class 1 system. The pipe/header dimensions and material of constructions are also presented. In general, large-diameter PHTS pipe are Schedule 100 and have a mean diameter-to-thickness ratio of about 15. The materials (pipe, fittings, and welding consumables) used for the construction of the PHTS of Canadian CANDU plant was procured to ASME material specification SA-106 Grade B, “Specification for Seamless Carbon Steel Pipe for High-Temperature Service”, SA-105, “Specification for Carbon Steel Forgings for piping Applications”. The materials are classified as carbon steels and exhibit good tensile properties and fracture toughness at CANDU operating temperatures. The four welding procedures used in fabricating the large-diameter portion of the PHTS piping in Canadian CANDU plants are discussed. In addition, the inspection requirements and the operating conditions are summarised. Traditional sources of leakage and the six leakage detection methods are discussed.

References that present a review of degradation mechanisms in PHTS piping in Canadian CANDU plants are identified. These reviews which covered the period up to 1995 identified the only active degradation mechanism to be fatigue and flow-acceleration corrosion. A description of recent industry review of PHTS degradation mechanism is presented. The mechanism covered are flow accelerated corrosion and fatigue. It is concluded that there is no evidence of active degradation mechanism that pose an immediate risk to the integrity of large diameter PHTS piping in Canadian CANDU plants. Potential degradation mechanisms that could be active in large-diameter PHTS piping of Canadian CANDU plants are identified as fatigue in all piping, FAC in the boiler inlet piping, and thermal fatigue in the pressurizer interconnect line. It is recognised that FAC is active in CANDU large-diameter PHTS piping and the most susceptible components are the elbows in the boiler inlet lines (between the reactor outlet headers and the steam generators). It is concluded that the industry experience with FAC thinning is that it is slow, predictable, can be effectively managed through a degradation management program and it does not pose an immediate risk to the integrity of CANDU large-diameter PHTS piping. Also continue monitoring of FAC in the susceptible regions is needed to refine the FAC thinning rates and to provide ongoing justification for excluding FAC failure in these lines.

A schematic diagram is given to illustrate the four-step model for crack evolution in the section of a pipe. A discussion is given of the four step process from initiation to through-wall crack growth to consumption of thin ligament and the growth of through-wall crack.

A summary is given of lessons from the international experimental pipe fracture database. These lessons, which cover the necessary condition for failure, break opening characteristics, axial breaks and circumferential break, are summarised. The proposed break opening model already summarised in Chapter 10 of the current report is reiterated.

A discussion on the response of cracked piping subject to extreme loading events is presented. It is noted that the FPBOC-WG determined that it was not practical to perform additional pipe fracture experiments form a technical, cost and schedule perspective. The working group however recognised that modern analytical tools could be used to simulate break opening propagation in specific CANDU PHTS piping/headers. The group has a goal to develop and document an efficient methodology that could be used to perform finite element simulation of cracked CANDU PHTS piping systems under extreme dynamic loading events. The work plan identified training in Abaqus-based finite element simulation of piping systems with circumferential surface and through-wall cracks under seismic loading conditions. Engineering Mechanics Corporation of Columbus was chosen to give the training, provide technical oversight for the validation exercise and to perform the independent verification of the pilot finite element simulations. The pilot simulations were performed validated and verified. The conclusion of the expert review was that the analyses performed and documented in the pilot study were thorough and competently performed. The independent validation analysis confirmed that the postulated through-wall crack was stable under extreme seismic loading consistent with an earthquake with peak motion parameters with a return period of ten times the design basis earthquake for the plant.

11.3.2 Areas for Improvement

None.

11.4 FAILURE PROBABILITY

11.4.1 Overview

Task 2 of the FPBOC-WG Work Plan, which called for the development of a validated, state-of-the-art Probabilistic Fracture Mechanics computer code that would predict the failure probabilities, with uncertainty, for a range of break sizes of CANDU large-diameter PHTS piping, is summarised in this section. The section has an introduction and a discussion of PRAISE-CANDU in terms of the requirements, quality assurance, computer language, Input/Output, documentation, verification and validation, use of external experts and implementation. Discussion is also given on threshold break sizes and pilot analysis. Most of the topics discussed in this section are already covered in details in Chapters 4 to 9 of the current report and will not be repeated here.

11.5 SURVEILLANCE PROGRAMS

11.5.1 Overview and Strengths

The results of the review of existing surveillance program, inspection and leakage detection methods for which ongoing surveillance will be required to ensure that key assumptions made with respect to break-opening characteristic and failure probability for use in the reclassification of LBLOCA remain valid throughout the operating life of a CANDU plant are described in this section. It is noted that it was agreed that the existing periodic inspection program is sufficient and that there was little benefit in doing a critical review of existing programs. The key conclusions on additional surveillance programs are presented and are summarised in Table 9.

Table 9: Summary of Conclusions on Additional Surveillance Program

Damage Mode	Conclusion
Fatigue	Fatigue is an active degradation mechanism in large-diameter PHTS piping. The potential for fatigue in circumferential welds is adequately addressed by the current periodic inspection plans.
FAC	FAC is an active degradation mechanism in large-diameter PHTS piping, however the conditions in the large-diameter PHTS piping are relatively benign and any wall thinning is expected to progress slowly. The potential deficiency identified with FAC is that the review was unable to confirm that monitoring FAC in the large-diameter PHTS piping at Canadian CANDU plant is being adequately addressed in the existing station periodic and/or in-service inspection program.
Fabrication Flaws	The likelihood of a flaw of sufficient size to cause a LBLOCA failure, remaining undetected through the rigorous examination requirements associated with inaugural periodic inspection is extremely remote.
Service Induced Flaws	The periodic inspection plans select welds subject to the most severe service loading conditions and as such they should be the first ones to exhibit fatigue cracking. Therefore, the likelihood of a fatigue crack developing in-service and remaining undetected by periodic inspection is low.
Instantaneous Rupture	Instantaneous rupture of large-diameter PHTS piping is not likely.
Axial Seam Welds	The review was unable to confirm whether sections of the axial seam welds in the Bruce reactor headers were being volumetrically inspected as part of

Damage Mode	Conclusion
	the existing periodic inspection plans for the Bruce plants

In summary it is concluded that there are a number of barriers in place to support the contention that the existence of a large (undetected) crack in the large-diameter PHTS piping and reactor header is an extremely low probability condition. The barriers include: the extensive inaugural inspections conducted on large-diameter PHTS piping and headers in Canadian CANDU plants; the existing periodic inspection programs conducted under CSA/N285.4 provides a barrier that fatigue induced cracking is not active; should a through-wall crack develop the existing redundant methods for detecting operational leakage from the PHTS are sufficiently sensitive.

11.6 DISCUSSION

11.6.1 Overview and Strengths

A number of issues associated with the development of the recommended threshold break size and break-opening model for use in reclassification of LBLOCA at Canadian CANDU plants, including developments in the USA, subject matter experts' review, review of assumptions, review of TA4 closure issues and applications are discussed in this section.

It is noted that the approach for reclassification of LBLOCA for CANDU plants is consistent with the approach that was develop for definition of LBLOCA for LWR in the United States. The detailed discussion of the US approach is included as an appendix. Several subject matter experts and corporations used for the review and the development of the break-opening models, and the probabilistic fracture mechanics tool, along with the tasks that they performed, are mentioned by name.

A review of the assumptions made to simplify, develop and adapt models is given. The assumptions are discussed under the broad headlines of generic, break opening characteristic and threshold break size. Among the generic assumptions is no evidence of active degradation mechanism that pose immediate risk to integrity of large-diameter PHTS CANDU pipes and existing leakage monitoring methods and operating procedures provide an effective barrier against stable leaking developing into a rupture.

11.6.2 Areas for Improvement

None.

12.0 REVIEW OF CNSC STAFF COMMENTS AND DEVELOPERS' RESPONSES ON PRAISE-CANDU

12.1 INTRODUCTION

Several CNSC staff comments on the development of PRAISE-CANDU codes and the developer's responses are reviewed in this section. These comments were forwarded to the FPBOC-WG prior to the formal submission of the COG reports to the CNSC and do not represent a complete list of detailed CNSC staff comments on those COG reports. The questions and the responses are grouped into two categories, active and closed. There are eight and eighteen active and closed questions respectively. The layout is the same for all the questions. The first section provides the basic parameters of the question in terms the identifier, the date, the title, the owner, the originator, the delegate and the status. The main body has four sections, which are the context, the question, the disposition, the response/resolution and the status. A summary of our review is presented in Table 10 and Table 11.

12.2 REVIEW OF SOME CNSC ACTIVE QUESTIONS

Table 10: Summary of Some CNSC Question Disposition -Active

No	Issue	Review
1.	Inspection Interval for Main PHT Piping System *Identifier*: **FPBOC-2011-06**	The question from the CNSC staff concerns further justification on how to identify pipe wall thinning and the locations of interest, given that the inspection interval and location for the main PHT piping system is not sufficient to properly capture potential degradation mechanisms, such as, wall thinning and cracking. The disposition from the COG states that the current PIP program includes wall thickness checks. Example studies are presented that applies CHECKWORKS methodology to large-diameter PHT piping of Canadian CANDU. The response and resolution is that no further action is required and the issue will have to be resolved during the closeout report and that the potential for localised FAC in PHTS piping will be addressed in licensing specific applications. **Our View**

No	Issue	Review
		The question, disposition and the response/resolution are reasonable given that safety related decisions should be based on adequate knowledge that is derived either from observations or studies.
2.	Selection of 1.2D as the Critical Crack Length *Identifier*: **FPBOC-2012-18**	The question from the CNSC staff is centred on justification for selecting 1.2D as the critical crack length for axial flaws because based on the literature review presented by the COG the range of possible values is from 1.01D to 1.3D. The disposition from the COG is that an independent reviewer has proposed additional test, that there is conservatism associated with the Folias critical crack length model. Additionally, it is noted that the value of the normalised critical length, which ranges from 1.15D to 1.3D for PHTS pipes larger that NPS 10, are -4% to 8% of the chosen nominal value. Therefore, the variation is sufficiently small and can be disregarded considering the conservatism in the Folias factor. The follow up response from the CNSC is that it will be useful to provide calculations to support the proposition that the critical crack length variation can be disregarded. A follow-up action to provide the requested calculation is accepted by the COG. **Our View** The question from the CNSC staff is reasonable. The industry disposition need further justification, the answer offered for the choice of 1.2D as the critical crack length is not adequate.
3.	Selection of 5 ms for an axial break size of 10% flow area. *Identifier*: **FPBOC-2012-19**	The issue raised by the CNSC staff concerns the choice 5 ms by the COG for an axial break size of 10% flow area to develop, when times ranging from 2.5 ms to 5 ms were observed in the German testing that is used as the basis for the selection. There is also a concern about the lack of discussion on the potential effects of differences in material strength for the piping used in the German program compared to CANDU piping. Additionally, it is noted that the USNRC has not approved break-opening times longer than 1 ms due to unresolved issue on the effect of a shock wave. The disposition from the COG includes discussion on the two materials, actual and worst-case, included in the German program. It is mentioned that the Charpy impact energy of the material from the Darlington LBB database has value that is smaller than the German worst case material. It is concluded that the German program includes materials with toughness

No	Issue	Review
		comparable to CANDU PHTS piping. Several reference documents that offer further rational for selecting 5 ms are cited. A discussion is also given by the author on what the NRC staff intend to do with regard to closure of GSI-191. The response from the CNSC staff notes that the disposition did not address the material strength differences between CANDU PHTS piping and the German test program piping. It is also recommended that the effect of shock wave on break-opening time be evaluated. **Our View** Again the question from the CNSC staff is a reasonable one because, COG is drawing conclusion that ultimately has impact on safety and regulations. We agree with the CNSC staff that the response from COG did not address the material strength differences between the German pipes and CANDU PHTS piping. The recommendation that the effect of shock wave on break-opening time be evaluated is fair.
4.	Applicability of stainless steel weld test results from US to A106 Grade B stainless steel and the validity of Conclusion 6 in [2] and also Conclusion 8 *Identifier*: **FPBOC-2012-20**	The issue raised by the CNSC staff is about the validity of Conclusion 6 and 8 in [2]. These conclusions are based on the similarity of the toughness of the stainless steel from US programme to A106 Grade B stainless steel. The CNSC staff noted that the material property that will govern failure is material strength and not material toughness since the materials are sufficiently tough to prevent brittle fracture. The disposition from the COG is that this specific USA test was included based on recommendation from one of COG's independent reviewer. The main rational for including the test is that it had additional instrumentation to measure the time of propagation of the through-wall crack. The response from the CNSC staff is that the COG did not address the material strength differences between CANDU PHTS piping and the stainless steel piping used in the US test program. The CNSC staffs supported their position by citing the requirements from ASME Section XI and concluded that the use of stainless steel results could only be applicable to the low alloy steel in very limited cases. **Our View** The issue raised by the CNSC staff is quite good and we agree that the response from the COG did not address the material strength differences between the US test pipes and CANDU

No	Issue	Review
		PHTS piping.
5	Request for work executed to demonstrate the applicability of Conclusion 9 to piping with different *D/t* ratio. *Identifier*: **FPBOC-2012-21**	This question from the CNSC staff is on Conclusion 9, which is based on observation from feeder bend test. The CNSC staff wanted to know what work was carried out by the COG to demonstrate that the test rests are applicable to piping with significant different *D/t* ratio. The disposition from the COG is that the tests are used as a technical basis for the application of Folias flaw model to long-radius piping elbows. The similarity between the average diameter to thickness ratio for feeder bends tested and PHTS is noted. The response from the CNSC staff is that the conclusion would be strengthened if the methodology for the assessment of feeders was demonstrated to be applicable to large diameter piping. **Our View** Both the question from CNSC staff and the response from COG are reasonable. The requirement to strengthen the conclusion by demonstrating the applicability of the methodology to large PHTS is okay.
6	Discussion on how potential FAC failure will be accounted for. *Identifier*: **FPBOC-2012-24**	Given that all possible potential mechanisms need to be accounted for and COG stated that its conclusions do not apply to FAC degradation, the CNSC staff wanted to know how potential FAC related failure will be accounted for. The COG agreed with the CNSC staff that all possible potential mechanism needs to be accounted for and noted that the industry experience with FAC thinning is that it is slow, predictable and does not pose immediate risk to the integrity of large-diameter CANDU PHTS piping. The response from the CNSC staff is that no further action is required at this time. Licence activities for potential FAC will be addressed in licence specific applications related to large LOCA reclassification. Licensee will need to demonstrate that an effective FAC degradation management program is in place to support request for large LOCA reclassification. **Our View** The question and follow-up action from the CNSC staff and the response from the COG are good.
7.	Applicability of	The question from the CNSC staff is how the quoted FAC rate

No	Issue	Review
	quoted FAC rate to highly localised FAC *Identifier*: **FPBOC-2012-25**	in the COG-11-2096 report is applicable to highly localised FAC. The disposition from the COG is that the assumed thinning rate is considered to be conservative for general FAC in the large-diameter portions of the PHTS piping/header. It is also noted that the industry has performed FAC assessments for large-diameter PHTS piping. The response from the CNSC staff is that the potential for localised FAC in PHTS piping and associated wall thinning rate will be addressed in licensee specific application related to large LOCA reclassification. **Our View** The question and follow-up action from the CNSC staff and the response from COG are reasonable. As noted in our review of the COG documents on PRAISE-CANDU, there is a need to demonstrate that for FAC, the general thinning model is at least as conservative as the more appropriate localised model.
8.	Comparison of fracture toughness and residual stresses of header seam weld and seamless PHTS piping. *Identifier*: **FPBOC-2012-26**	The CNSC staff wanted to know how the header seam welds compare to seamless PHTS piping in terms of fracture toughness and residual stress. The COG responded by giving a lengthy discussion on the fabrication process, material type and composition of header seam welds and PHTS girth welds. And concluded that the residual stress in the header seam weld will be similar to the residual stress in the large-diameter PHTS girth buttwelds, and the toughness of the header seam welds should be comparable to or better that the large-diameter PHTS pipe girth buttweld. The CNSC responded that no further action is required at this time and that material property data/test will have to be defended in licensee specific application related to large LOCA reclassification. **Our View** The question and follow-up action from the CNSC staff and the response from COG are reasonable.

12.3 REVIEW OF SOME CNSC CLOSED QUESTIONS

Table 11: Summary of Some CNSC Question Disposition -Closed

No	Issue	Review
1.	Workshop to obtain knowledge of the cracked element used as through-wall circumferential crack in Darlington PHTS main piping FE model *Identifier*: **FPBOC-2011-01**	The CNSC staff requested a workshop to obtain knowledge of the cracked element used as through-wall circumferential crack in Darlington PHTS piping FE model to simulate postulated cracks at elbow weld regions and T-Junction. The COG arranged with Emc^2 to allow for two CNSC staff to participate in the training. **Our View** The question, disposition and the response/resolution are reasonable.
2.	Detailed criteria to determine a Threshold Break Size *Identifier*: **FPBOC-2011-02**	The CNSC staff requested from COG a more detailed criteria to determine a Threshold Break Size (TBS) and the relationship between TBS and a critical crack size. The COG agreed and noted that there were three documents prepared on the topic which will be sent to CNSC when they become available. The final versions of all three documents were sent to CNSC. One other document, titled Maximum Load Capacity of Circumferential Flawed Pipes and accompanying Excel workbook were also given to CNSC. **Our View** The question, disposition, response/resolution and follow-up actions are very reasonable.
3.	Request for more clear definition of beyond design basis loading due to the sensitivity of the margins of the structural integrity of the Darlington PHT piping system. *Identifier*: **FPBOC-2011-03**	The CNSC staff requested from COG a more clear definition of beyond design basis lading in terms of types of loading because the margin of the structural integrity of the Darlington PHT system would be sensitive to the level of loading. The COG responded by citing and quoting extensively from a draft report which was being prepared and will be sent to CNSC. The CNSC staff was satisfied with the response. **Our View**

No	Issue	Review
		Both the question and the response from the CNSC staff and COG are reasonable.
4.	Request for further technical justification on time to reach first leakage and pipe rupture *Identifier*: **FPBOC-2011-04**	The CNSC staff demanded further technical justification on time to reach the first leakage and pipe rupture assumed in the proposed break-opening model because the time is doubled when compared with the time used in circumferential crack breaks. The COG responded by referring to the response given in FPBOC-2011-02 which deals with detailed criteria to determine a Threshold Break Size. The CNSC staff considered the matter closed and the resolution is similar to FPBOC-2011-02. **Our View** Both the question and the response from the CNSC staff and COG are fair.
5	Request for further study to develop forcing function for J-R curve *Identifier*: **FPBOC-2011-05**	The CNSC staff requested further study to develop the forcing function which takes into account crack behaviour under combined loading condition. This is because the J-R curve is usually developed under single loading condition while actual crack in piping system will be subject to combined loadings during seismic events. The COG responded by noting that it is not feasible to perform assessment for arbitrary located cracks under arbitrary loading. The simplifying assumption used assumed that the crack is center at the location of maximum bending stress. The document that explained the methodology is cited. The CNSC staff responded by noting that information will be provided on the cracked element modelling process so that the assumptions and methods employed can be reviewed. A report was sent to the CNSC observer. It documents the FEA simulations of the Darlington pump discharge piping with postulated through-wall circumferential crack under design basis and beyond design basis seismic loading. The matter was considered closed. **Our View** Both the question from CNSC staff and the response from COG are reasonable.
6	Request for more realistic header to	The CNSC staff asked for more realistic header to feeder interface to capture any weakness in the region under seismic

No	Issue	Review
	feeder nozzle interface. *Identifier*: **FPBOC-2011-07**	loading. The concerned region is between header holes and also feeder nozzle interface. The COG noted that the request is beyond the scope of work being done by AMES/NSS and that the focus of the piping simulation is in support of reclassification of large LOCA, with emphasis on the response and development of postulated through-wall circumferential cracks under accident loading conditions. The response and resolution is that the closeout report will describe the translation of the NASTRAN GENELS that were used to model the feeder. It was also agreed that there would be a low likelihood of sudden header rupture due to failure on the interface feeder nozzle and headers. The issue was closed **Our View** It is important that clarity be given on an issue that has the potential to compromise safety. In this regard, we consider the discussion on the topic helpful.
7.	Request for elaboration on plan for validation through comparison to service data. *Identifier*: **FPBOC-2012-01**	The CNSC staff asked for more detailed explanation on the plan for validation through comparison with service data because there is potential for statistical uncertainty. The COG responded by noting that there are not aware of any pipe rupture due to mechanical fatigue mechanism or FAC for CANDU Class 1 PHTS piping and that there is no service data to benchmark against. The response from the CNSC staff is that no further action is required but the issue will be addressed during formal CNSC review of COG V & V report. CNSC staff anticipated that there will be several issues related to quantification of uncertainties that may not be resolved in the short term and may depend on international activities related to PFM codes. **Our View** The question and follow-up action from the CNSC staff are reasonable. A more adequate explanation on uncertainty in the context of Validation should have been offered by the COG. Based on our review of the COG V & V report this issue is has not been adequately addressed by the COG more validation problems with operational experience data needs to be executed.
8.	Request for quantification of	The CNSC staff requested that uncertainties involved in many places, such as crack initiation rates, reliability of inspection in

No	Issue	Review
	uncertainties so that the acceptance of the software can be assess. *Identifier*: **FPBOC-2012-02**	detecting part-through wall cracks, be quantified. This will help in assessing the acceptance of the software. The COG responded by stating that they will use example to illustrate how to treat the sources of uncertainties and the uncertainties of the calculated leaks or rupture probabilities. The CNSC staff noted that no further action is required and the issue will have to be resolved during the formal CNSC review of the COG V & V report. CNSC staff anticipated that there will be several issues related to quantification of uncertainties that may not be resolved in the short term and may depend on international activities related to PFM codes. **Our View** The question and follow-up action from the CNSC staff and the response from COG are reasonable. The introduction of epistemic uncertainty by the COG in the PRAISE-CANDU tool will enable the modelling of parameters with inadequate knowledge. The COG needs to present more example in the COG V & V report that show how epistemic uncertainties can be applied to unknown parameters such as crack initiation rates and reliability of inspection in detecting part-through wall cracks.
9.	Request for clarification on the objective of benchmarking with other software *Identifier*: **FPBOC-2012-03**	The CNSC staff asked for clarification on the objective of benchmarking with other software in the plan from the validation perspective. They also noted that comparison with other non-QA'ed software would not be considered a part of validation. The COG responded by stating that to the best of their knowledge, there is no fully QA'ed commercial PFM software and that it is okay to use non-QA'ed software for performing the QA as long as it was independently developed. The CNSC staff noted that no further action is required and the issue will have to be resolved during the formal CNSC review of the COG V & V report. CNSC staff anticipated that there will be several issues related to quantification of uncertainties that may not be resolved in the short term and may depend on international activities related to PFM codes. **Our View** The CNSC staff request for clarification on the objective of benchmarking for validation perspective is reasonable. Given

No	Issue	Review
		that there are no other PFM codes that are fully QA'ed, the COG idea to use non-QA'ed software as part of validation as long as they were independently develop should be considered okay.
10.	Request for stating the input parameters for each validation case in the V & V report before executing the work *Identifier*: **FPBOC-2012-04**	To ensure that there is not bias in the outcome of the validation exercise, The CNSC staff requested that the input parameters for each validation case be stated in the COG V & V report before executing the work. The COG responded by stating that this request is possible for a well-defined problem and may not be that easy for others. To ensure transparency, the COG will make the inputs and outputs of V & V cases available to CNSC staff for review and check. The CNSC staff noted that no further action is required and the issue will have to be resolved during the formal CNSC review of the COG V & V report. **Our View** The CNSC staff request on the input parameters definition before execution of the software is reasonable. The COG idea that this can be done for well-defined problem and not for others is also okay. The promise to ensure transparency by ensuring that the input and output parameter used is available to CNSC is also a fair. The COG could also have satisfied CNSC request for the so called well-defined problems.
11.	Request for technical guidance on how to assume the type of uncertainties. *Identifier*: **FPBOC-2012-05**	The CNSC staff asked for further technical justification and guidance on how to assume the type of uncertainties because this will impart the results. The COG responded by stating that no guidance on uncertainties will be provided in the COG V & V report but guidelines will be supplied in the User manual The CNSC staff noted that no further action is required and the issue will have to be resolved during the formal CNSC review of the PRAISE-CANDU Users' manual. Additional guidance may be obtained through the Canadian participation in the PARTRIDGE program **Our View** The question and subsequent response are very reasonable.
12.	Request information on how accident (seismic) loading will	The CNSC staff wanted to know how the proposed methodology for crack pipe simulation will establish the accident (seismic) loading for Pickering A and Bruce A plant

No	Issue	Review
	be established. *Identifier*: **FPBOC-2012-06**	since the seismic margin for assessment methodology has been used for this plant. The COG responded by offering several approaches, including reviewing similarity in the design, development of seismic time history and using seismic time history from other plants. The CNSC staff noted that no further action is required and the issue will have to be addressed in the closeout report. It is also noted that some of the methods suggested are indirect and further technical justification will be required when the indirect methods are used. **Our View** The question and subsequent responses are very reasonable.
13.	Request information on limit of applicability of proposed cracked pipe element. *Identifier*: **FPBOC-2012-13**	For the proposed cyclic loading simulation, the CNSC staff inquired on the limit of applicability of the cracked pipe element methodology in relation to design and loading applied to a CANDU PHTS. The COG responded by stating their intention, which is that the cracked-pipe simulation will be performed for CANDU PHTS piping systems to which reclassification is to be applied. The length of the through-wall circumferential crack will be at least six times the wall thickness, loading will be the time history for the Design Basis Earthquake and sensitivity study will be included that amplifies the DBE time history by a factor of at least five times. The CNSC staff noted further detailed technical explanation is required to address limitations of the cracked pipe element when modelling a postulated crack by this element. The report, COG-JP-4367-031, which documents FEA simulation of the Darlington Pump Discharge Piping with a postulated through-wall circumferential crack under design basis, was sent to CNSC by the COG. **Our View** The question is reasonable. The COG needs to state the limits of applicability of proposed cracked pipe element. So far this has not been adequately addressed.
14.	Request clarification on apparent inconsistency on the	The CNSC staff asked for clarification concerning the break opening area criteria proposed by COG, which involved either a 10” pipe diameter or a percentage of the flaw area.

No	Issue	Review
	criteria on break-open area. *Identifier*: **FPBOC-2012-14**	The COG responded by stating that the equivalent diameter is not a criteria, it was introduced to put the size of the TBS into perspective. It was clearly addressed the 10" pipe should be used as a reference pipe size in order to determine the TBS and that the TBS for NPS 10" pipe or smaller shall be 100% DEGB while the TBS for larger than NPS 10" should be 5% DEGB for a circumferential crack. The CNSC staff was satisfied with the clarification **Our View** The question is essential and reasonable to sure that both the regulator and the industry are in agreement.
15.	Request further detailed explanation on methodology used to evaluate leak rates *Identifier*: **FPBOC-2012-17**	Further detailed explanation was requested by the CNSC staff on the methodology, assumptions and computer code used for leak rates because some limitations on the use of SQUIRT is expected for certain sizes of through wall cracks. The COG responded by noting that PRAISE-CANDU has decoupled thermal hydraulic leak rate calculations from the PFM simulations. The user will input detectable break size to PRAISE-CANDU. Two documents, which were e-mailed to CNSC, were cited that describe the methodology adopted for establishing detectable beak size for input to PRAISE-CANDU. The CNSC staff was satisfied with the clarification and noted that acceptance criteria of detectable leak sizes will be addressed in licence submission related to large LOCA reclassification on a case-by-case basis. **Our View** The question and subsequent responses are very reasonable.
16.	Request further detailed explanation on methodology used to evaluate leak rates *Identifier*: **FPBOC-2012-17**	Further detailed explanation was requested by the CNSC staff on methodology, assumptions and computer code used for leak rates because some limitations on the use of SQUIRT is expected for certain sizes of through wall crack. The COG responded noting that PRAISE-CANDU has decoupled thermal hydraulic leak rate calculations form the PFM simulations and that the user will input detectable break size to PRAISE-CANDU. Two documents, which were e-mailed to CNSC, were cited that describe the methodology adopted for establishing detectable beak size for input to PRAISE-CANDU.

No	Issue	Review
		The CNSC staff was satisfied with the clarification and noted that acceptance criteria of detectable leak sizes will be addressed in licence submission related to large LOCA reclassification on a case-by-case basis. **Our View** The question and subsequent responses are very reasonable.
17.	Request for references *Identifier*: **FPBOC-2012-23**	The CNSC Staff requested references 19 and 20. The COG responded by sending the references to CNSC. **Our View** Request and response are very reasonable.

13.0 SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

13.1 INTRODUCTION

The objective of the work is to provide an independent third-party evaluation of the PRAISE-CANDU Probabilistic Fracture Mechanics (PFM) code development process carried out for the Composite Analytical Approach to address Large Break Loss of Coolant Accident safety margins. The scope of work involves technical evaluation of the CANDU Owner's Group (COG) reports prepared during the development of PRAISE-CANDU: to provide an independent evaluation of the suitability of the PFM code degradation models; to address the adequacy of PRAISE-CANDU validation and verification (V&V) and benchmarking activities; to highlight the limitations of the probabilistic simulation and uncertainty analyses techniques used in PRAISE-CANDU and offer recommendations for improvements; and to review the extent to which PFM codes are accepted in regulatory decision making in the United States, Europe and Japan.

13.2 APPLICATION OF PFM IN OTHER COUNTRIES

An exhaustive review on the application of probabilistic fracture mechanic (PFM) to nuclear power plants, NPP, components and systems indicates that it is used as a part of risk informed decision making (RIDM), along with expert opinions, engineering judgement and experience, to assess the structural integrity of two components, the reactor pressure vessels RPV and the piping systems. The most active country in the area of PFM, at both the regulatory and operational levels, is the USA, with a large involvement of the USNRC and the US nuclear industry. A few other active countries are Sweden, Canada, Japan, UK, South Korea, Czech Republic and Spain. Several probabilistic fracture mechanics tools are identified and summarised. In response to a questionnaire developed and administered to regulators from several countries, two countries, USA and Sweden, listed fourteen decisions made or going to be made based partly on PFM. Of the fourteen decisions, two were regulatory and twelve were licensing. The two regulations in the US are CFR 50.61, titled "Fracture Toughness Requirements for Protection Against Pressurized Thermal Shock Events", and CFR 50.61a, titled "Alternate Fracture Toughness Requirements for Protection Against Pressurized Thermal

Shock Events", were made using PFM as part of RIDM with input from expert opinion (acceptance criteria), engineering analyses and operational experience (PRA event sequence and thermal hydraulic analyses etc.). In the area of pipeline reliability the USNRC along with industry partners is also developing a new tool that may be used to satisfy existing regulation as a part of RIDM.

13.3 SUMMARY AND CONCLUSIONS

The six COG reports reviewed are: (i) COG-JP-4367-005, Revision 2, Specification for PRAISE-CANDU 1.0; (ii) COG-JP-4367-011, Revision 0, Theory Manual for PRAISE-CANDU 1.0; (iii) COG-JP-4367-046, Revision 0, PRAISE-CANDU Version 1.0 Pilot Study; and (iv) COG-JP-4367-026, Verification and Validation Report for PRAISE-CANDU 1.0. (v) COG-JP-4367-041-R0, FPBOC-WG Integrated Close-out Report; (vi) COG-11-2096, LOCA Break-Opening Characteristics for CANDU HTS Piping – Literature Review.

The goals of the review include: (i) determination the applicability of degradation assessment models used in PRAISE-CANDU and the potential gaps in the models; (ii) the adequacy of the theory presented in PRAISE-CANDU to describe the basis for the selection of input parameters to ensure that consistent results would be generated by different users; (iii) the suitability of PRAISE-CANDU input parameters by answering whether the input parameters accurately describe the loading, environmental conditions which could lead to crack initiation and subsequent pipe breaks; and (iv) The suitability of the methodology used to address uncertainties in input and output. The six documents were reviewed individually and the pertinent issues emphasised in each document were studied to determine the adequacy of PRAISE-CANDU Tool. For ease of presentation, traceability and tracking each document was reviewed using its sectional outline. For a given section, an overview of the section, the strengths and suggestions for improving the report are summarised. The main outcome are summarised below.

The structural and the probabilistic models in PRAISE-CANDU are quite general, up to date, and based on our review, should be adequate for assessing the structural integrity of most

CANDU piping when the issues summarised in the next subsections are successfully addressed.

13.3.1 Software Plan

From the review we conclude that the basic software plan is sound, as the standard used, CSA N286.7-99, when properly followed would lead to a great product. In addition, as part of the software plan, independence between the developer and the verifier was identified as necessary, and the software developer selected is familiar with both the nuclear industry and PFM. Also, there is provision for tracking, documentation, verification and validation defined as part of the plan. It is recommended that a higher level of transparency need to be in place for tracking and documenting errors during the software development.

13.3.2 Deterministic Models

The COG documents that are reviewed have deterministic models for the crack tip stress intensity factor, the J-integral and crack opening areas, crack initiation and growth, crack stability, stresses and general flow acceleration. These models, which are mostly current and versatile, are used to represent the pipeline structure, material strengths, loading, damage initiation and progression in CANDU piping. Damage modes that can be studied are fatigue and stress corrosion crack initiations and growth and FAC. Nuclear piping loads that can be modeled is broad, and include both normal and transient service loads, deadweight, environmental loads, seismic, vibratory and weld residual stresses. In keeping with CSA-N286.7-99 requirements, most of the model assumptions, sources, methods, and limitations are identified and explained.

With regard to the deterministic models, the most pertinent issues that need addressing are summarised here, including documentation, justifications and explanations. First, frequent reference made to information or models in WINPRAISE 07 without fleshing out the details in the COG report need to be corrected. Second, discussions on bias or error in the models have to be provided. Deterministic models have bias that could impact the accuracy of the results. There is no mention in any of the COG reports on the treatment of bias determined from validation. Third, the number of user defined inputs puts intense emphasis on a Theory

Manual and a User Manual providing a high level of guidance to the user. Assumptions and default values need to be clearly defined and explained.

On the deterministic load front, the categorization has to be consistent across the various COG documents. Several load related vocabularies, including primary loads, secondary, displacement controlled stress etc., need more detail discussion, clarification and definition. For multiple loads, detailed presentation on the load combination and the load sequence used for damage initiation and growth should be provided. Clarity needs to be supplied on the distinctions between secondary and primary loads and the implementation of the two loads type. Other load related issues that need addressing are: the meaning of the variables for dissimilar metals welds, E_{ab}, T_a, T_b, α_a, α_b, presents in the main equation for translating loads; guidance on selecting appropriate set of stress indices (Ci, Ki); discussion on the accuracy of the residual stresses treatment for large diameter pipes; and detailed presentation on the sources of vibratory stresses in CANDU piping.

Other deterministic modelling issues that need to be attended to are: justification for using values of crack tip stress intensity factor beyond the limit of their intended application, that is using $\alpha = 0.8$ for $\alpha > 0.8$; justification of the assumptions made in adapting several existing independent tensile and bending part-wall cracks solutions for combined tensile and bending situations; detailed description of models (equations) for the linear multidimensional interpolation scheme used in the J-solutions; guidance on defining the appropriate value of k for non-elliptical crack opening area; and the suitability of the Romberg-Osgood model when employed for dissimilar metal welds. Guidance needs to be provided on the limit of application of the fatigue crack initiation models because some of the model parameters, which are from Argonne National Laboratory, are hard-wired, stipulated, fixed and cannot be changed. Detailed explanations and guidance should be offered on the concepts of heat-to-heat and within heat because the COG reports states that variances of these parameters have a large influence on break probabilities and user defined values of these parameters can be additive or multiplicative.

The two forms of fatigue crack growth rate in PRAISE-CANDU are Equation 5-1 (from ASME Boiler and Pressure Code, 2010) and tables, which involves some default hard-wired tables for fatigue crack growth rate for ferritic and stainless steel derived from various sources. For testing, transparency and verification, the equation for the bivariate interpolation scheme and the hard-wired tabular numbers need to the incorporated in the COG report. The current COG report on stability criteria does not delineate between part-through and through-wall cracks. Two separate discussions should be offered on the topic because the stability criteria for the two are not the same. The mathematical formulas (equations) associated with the net-section and tearing instability criteria have to be documented as part of the COG report. Justification and explanation need to be given on the use of only the load-controlled stresses for net section stability analysis. Since PRAISE-CANDU will be used to analyse crack in the piping system as well as welds, where the fracture properties of the base metal will usually be different from the weld, guidance need to be presented on the material properties to be used in the stability analysis in these cases. Reference materials should be provided to support the modelling strategy for FAC. Furthermore, the impacts of several simplifying assumptions in FAC modelling have to be supported using references or studies. Guidelines should be provided on how to determine the appropriate FAC thinning rate. Although FAC is a localised phenomenon, it is modelled as uniform thinning. To ensure confidence in the FAC modelling approach, the degree of conservatism in the current model compared to the more appropriate localised model should be investigated and reported.

13.3.3 Probabilistic Models

The two main probabilistic features of PRAISE-CANDU are provision for probabilistic description of the input parameters as random variables and Monte Carlo simulation capability. The probabilistic models are discussed under two broad titles, general statistical consideration and PRAISE-CANDU statistical consideration. PRAISE-CANDU uses deterministic models of damage initiation namely crack initiation and growth, and FAC to compute the probability of leak opening areas of various sizes in a piping system. Scatter is characterised by considering some of the inputs to be random variables, whose distributions are based on analysis of data or engineering judgement. These contributors to randomness, which are either aleatory or epistemic, offer potential benefits when used in PFM. In general, probabilistic fracture mechanics rely on deterministic fracture mechanics models and is meant to enhance and add value to deterministic results. Most deterministic structural integrity decision frameworks assume that parameters are known constants, and use factors of safety, designed to capture uncertainties, to make decisions. Factors of safety, which are essentially arbitrary numbers suggested by experts, have the potential to be conservative because it lumps all uncertainties, known and unknown, into one big number. Using Monte Carlo simulation for example, the probabilistic framework seeks to exploit information on known uncertainties, statistics and probability distribution of input parameters, for decision making. Multi Monte Carlo Simulations runs are essentially multiple deterministic analyses with combinations of many possible input parameters, allowing for investigation of possible deterministic results from all possible values of deterministic input parameters.

When PRAISE-CANDU is fully certified, its epistemic uncertainty capability will provide a rational and systematic basis for incorporating incomplete or inadequate knowledge. The statistic of the failure probabilities (mean, standard deviation, median, and quartile) derived from the epistemic runs will provide the ability to introduce a graded scale of conservatism into the decision making process. For example leak related safety decisions could be based on the median failure probability of leak, while rupture related decisions are based on 99% quartile statistic of probability of rupture, a graded scale that is only possible with a tool that has epistemic modelling capability. This is a very neat feature of PRAISE-CANDU and should be encouraged. It is also the reason why the US-NRC and EPRI are pursuing this approach in the development of the xLPR tool.

The probabilistic models in PRAISE-CANDU are current and versatile. The most important issues that need to be addressed are summarised, including documentation, justifications and explanations of assumptions in the models. First is it is not clear, from a review of the COG reports, how model uncertainties are handled in PRAISE-CANDU. These uncertainties arise from the use of simplified models to speed up computation, and could result in deterministic predictions that are slightly different from the more elaborate models or experimental tests or operational results. Second, the rational for limiting the number of probability distributions to two-six parameters distribution, should be provided. Although there are many probability distributions that can be used, only six two-parameter probability distributions, which should be adequate for most practical application of PFM, are used in PRAISE-CANDU. Given that the results of very small probabilities of failures can be very sensitive to the distribution choice it should be explained, what impact if any, the unavailability of other probability distributions may have on the results, and plans to mitigate it.

Other probabilistic model issues that need to be addressed are (i) the provisions for calibrating distributed parameters based on measured in-service or experimental data; (ii) the provisions for determining the most suitable distributions for parameters among several alternative distributions based on measured in-service or experimental data; (iii) guideline for determining the minimum number of data points that is required to consider a parameter a random variable and (iv) the rationales for limiting correlation to only normal and lognormal distributions. In addition detailed discussion needs to be provided on the scheme for speeding up calculations on break probabilities for cases with multiple initiating cracks. The model for this scheme and its implementation needs to be provided. Also, it is stated that a user specified cut-off below which life time calculation should not be performed, and the distinction between heat-to-heat and within-heat scatters, have strong influence on analysis results. More detailed explanations and guidelines need to be given on these concepts, practical implications and sources.

13.3.4 Verification and Validation

Verification and validation activities are used to demonstrate that the as-built software meets its requirements, as described in the theory manual and user's guide. They are the main tools used to prove that the computer program results are reasonable. Verification is used to check if we are solving the equations right in the computer code. It is essentially an error check. Validation checks if we are using the right equations and if the model is an accurate representation of the real system. The standards used for the verification and validation exercise, CSA N286.7-99 and CANDU Energy Standard Quality Assurance, are of high quality and if they are correctly implemented can result in a great product.

The Specification report, states what will be done. Sixteen tasks that cover a broad scope are stipulated in the report for execution. Most of the tasks were carried and documented to some extent in the Verification and Validation report. Documentations and/or executions on a few tasks are missing, including the following: (i) Load Module Verification that involves transformation of bending moments, pressures and temperatures to provide stresses by independent calculations and the residual stress input; (ii) Crack-Tip Stress Intensity Factor Module Validation for K-solution in terms of tabulated values and the multi-dimensional interpolation within such tables by independent calculations; (iii) Failure Criteria Module validation that includes check on the tearing instability for part-through and through-wall cracks will be made, as well as check on net section stress; and (iv) Unit Verification where comparison is made between the results obtained using SI units and customary Imperials units. The independence of the developers and the verifiers should be addressed. Based on information from the COG V & V report it is difficult to judge the independence between the two. This was an idea that was advanced in the COG Specification report to ensure the quality of the product.

A review of the Verification and Validation report show that the adequacy and completeness of the verification exercise especially the documentation is in question and needs to be addressed. The definition of the acceptance criteria is reasonable. The basic approach adopted for documenting the verification activities consists of four steps: (i) Definition of a Test plan; (ii) Documentation of the Test implementation; (iii) Test Results; and (iv) Summary. This basic approach is sound but the detailed implementations and documentations in most cases have issues that need to be addressed. The test plan states the plan to be carried out to verify a model implemented in PRAISE-CANDU from the theory manual. For clarity, verification and validation assessment should deal with one model at a time; identify the output and the means/tool to be used. Some of the test plans follow this approach. However, many test plans lack a clear statement of the plan; define too many models in one plan; and/or lack of identification of means/tools used for verification, making it difficult to assess the implementation of the test plan. Problems with individual test plans are highlighted in the detailed review of the documents, Chapter 5 and 9 of the current report. The test implementation and test results portion of the verification exercise are designed to flesh out the execution of the test plan. At a minimum the documentation of the test implementation and results within the COG V & V report need to have a problem statement, method used, the input parameters, assumptions, the results and a brief discussion of the result. The level of details should be such that an independent verification can be carried out to arrive at the same or different outcome before consulting the results in the archives. In addition a good record keeping where the above details, along with the test plan and summary are archived during the verification exercise is essential. Most of the test implementations in PRAISE-CANDU appear to have been archived well. However, the level of details on the test implementations in the verifications and validation report is at best uneven, with most being very sparse or non-existent. This is a major problem that needs to be corrected.

The validation in PRAISE-CANDU is centered on using benchmarking exercises to compare PRAISE-CANDU results to other similar PFM tools and operating experience. A good benchmark must have a clear and precise definition and description of its purpose and a very good documentation of the exercise, including detailed description of the problem, the inputs, differences between the models, inputs and outputs between the tools, assumptions that are made to reconcile the differences between the tools, a description of the implications of the assumptions, and detailed discussions of the results A review of the benchmark activities presented in the COG V & V report shows that documentation is very sparse and needs major reworking, there is not enough information for a meaningful assessment. Furthermore, xLPR and PRAISE-CANDU are two current tools for PFM analysis but some of the basic deterministic models in the two tools are different and produce different results, thus the need to justify the choice of models in PRAISE-CANDU. Several Benchmark case studies, executed using PRAISE-CANDU, documented in other reports, need to be included in the COG V & V report. PRAISE - CANDU results when compared with other NURBM tools is not bounding for large pipes. As this is the target application, it requires explanation.

The section of the validation that compares PRAISE-CANDU with operating experience has shortcomings that need to be corrected. Along with detailed documentation of reported work, the test plans on Canadian OPEX that were deemed essential but not carried out due to budget and scheduled constraint should be executed. More detailed reporting need to be presented on the validation study that involves Pipe Rupture to FAC OPEX. Details should includes problem statement, loads, load combinations etc. that were considered. It is not obvious how one can claim that "PRAISE - CANDU 1.0 meets the V&V requirements" when only one OPEX case without failure was assessed. "Benchmarking with OPEX is essential for calculating the failure probabilities." The scope of the validation exercises needs to be expanded to include other databases, such as Pipe fracture database, IPIRG database and OPDE database.

13.3.5 Pilot Study

The pilot study used to demonstrate the capability of PRAISE-CANDU involves an application of a problem of mechanical fatigue coupled with FAC degradation of the large diameters PHTS piping in Pickering Unit 5-8. The goal is to show how the PRAISE-CANDU tool can be applied to address a specific problem, and ultimately as an aid to the operators and the regulators in making decisions, that is, to showcase the capabilities of PRAISE-CANDU as a tool for decision making. The current pilot study, which has one example problem, is a good one but incomplete because it does not covers all the bases, including sensitivities analyses. Additionally, the models used in the Pilot Study need to come from PRAISE-CANDU Theory manual and not outside sources. New models that are not available in the Theory Manual should not be introduced in the pilot study, as it is currently done, because it gives the impression that the PRAISE-CANDU models are either not suitable or incomplete.

13.3.6 Proposed Break Opening Characteristic Models

Using extensive literature review of international studies, the COG recommends break opening models for axial and circumferential flaws in large-diameter CANDU PHTS piping. For axial breaks, it is recommended that the initial break develops to a size of 7% of the flow area of the pipe in 5 ms. For circumferential breaks, it is recommended that the initial break develops to a size of 3.5% of the flow area of the pipe in 5 ms, followed by an increase in the size of the break to 200% of the flow area of the pipe in an unspecified long-length of time that would depend on the dynamics of the piping system but that would be in excess of 2.5 s.

The proposed models deviate from international practice and are based mostly on literature review of studies that do not involve large CANDU PHTS piping directly. They do not have precedence and will involve significant changes in break-opening time philosophy for large

CANDU PHTS piping. To ensure safety, detailed studies of typical CANDU plants are needed to substantiate and justify the proposed models.

13.3.7 CNSC Questions and Responses

A review of industry responses to CNSC staff comments and questions concerning PRAISE-CANDU development activities, which were raised prior to the preparation of the final PRAISE-CANDU documentation, indicated that the follow-up and conclusions were reasonable.

13.4 RECOMMENDATIONS

13.4.1 COG Reports

Several recommendations have already been presented to improve the COG report. A summary of some recommendations is presented here.

1. A higher level of transparency need to be in place for tracking and documenting errors during the software development.
2. The theory manual should be revised to address the items discussed in Section 13.3.2 and 13.3.3.
3. The Validation and Verification report needs major reworking to address the uneven and sparse documentation and all the issues discussed in Section 13.3.4.
4. More complete Pilot study that covers all the damaged models in PRAISE-CANDU, and more than one example, should be undertaken.
5. Because there are many instances where the user is expected to stipulate parameters, a guidance document for the end-users needs to be developed.
6. Detailed studies of typical CANDU plants are needed to substantiate and justify the proposed break-opening models for large diameter CANDU piping because they involve significant changes in break-opening time philosophy for large CANDU PHTS without precedence and deviate from international practice. Using literature review of studies that do not involve large CANDU PHTS piping directly is not a sufficient justification.

13.4.2 CNSC Activities on PFM

Effort should be initiated by CNSC to undertake independent probabilistic fracture mechanics investigations, starting with some of the models in PRAISE-CANDU and others, so that the CNSC can be better prepared if/when they have to make licencing and regulatory decisions on the subject.

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16.0 GLOSSARY

ACRS	Advisory Committee on Reactor Safeguards
AECL	Atomic Energy Canada Limited
ASME	American Society of Mechanical Engineers
BDBA	Beyond Design Basis Accident
CAA	Composite Analytical Approach
CALREL	CALibration of RELiability
CANDU	CANada Deuterium Uranium
CCDP	Conditional Core Damage Probability
CLERP	Conditional Large Early Release Probability
CNSC	Canadian Nuclear Safety Commission
COF	Consequence of Failure
COG	CANDU Owners Group
COMPASS	Computer Methods for Probability Analysis pf Structures and Systems
COV	Coefficient of Variation
DBA	Design Basis Accident
DM	Dissimilar Metal
ECCS	Emergency Core Cooling System
EDF	Electricité de France
EPRI	Electric Power Research Institute
FAC	Flow Accelerated Corrosion
FAVOR	Fracture Analysis of Vessels – Oak Ridge
FORM	First Order Reliability Method
GDC	General Design Criterion
IGSCC	Inter-Granular Stress Corrosion Cracking
ISI	In-Service Inspection
JAERI	Japan Atomic Energy Agency
JRC	Joint Research Center (European Commission)
JSME	Japan Society of Mechanical Engineers
LBB	Leak Before Break
LBLOCA	Large Break Loss of Coolant Accident
LLNL	Lawrence Livermore National Laboratory
LOCA	Loss of Coolant Accident
LWR	Light Water Reactors
MCS	Monte Carlo Simulation
MERIT	Maximizing Enhancements in Risk-Informed Technology
NEA	Nuclear Energy Agency
NDE	Non Destructive Evaluation
NDT	Non Destructive Testing
NEI	Nuclear Energy Institute
NISA	Nuclear Industrial Safety Agency
NPP	Nuclear Power Plant
NRC	Nuclear Regulatory Commission (US)
NRR	Nuclear Reactor Regulation

NTIS	National Technical Information Service
PARTRIDGE	Probabilistic Analysis as a Regulatory Tool for Risk-Informed Decision Guidance
PASCAL	Probabilistic Analysis of Structural Components in Aging LWR
PEPPER	Probabilistic Evaluation Program for Pipe aiming Economical and Reliable design
P_f	Probability of Failure
PFM	Probabilistic Fracture Mechanics
PHTS	Primary Heat Transport System
PIFRAP	PIpe FRActure Probaailities
PINEP	Probabilistic INtegrity Evaluation for nuclear Piping
PNNL	Pacific North National Laboratory
POD	Probability of Detection
POF	Probability of Failure
PRAISE	Piping Reliability Analysis Including Seismic Events
PROPSE	PRObabistic Program for Safety Evaluation
ProSINTAP	PRObabilistic Structural INTegrity Assessment Procedure
PROST	PRObabistic STructure Analysis
PSA	Probabilistic Safety Analysis
PTS	Pressurized Thermal Shocks
PWR	Pressurized Water Reactor
PWSCC	Primary Water Stress Corrosion Cracking
RCPB	Reactor Coolant Pressure Boundary
RIDM	Risk Informed Decision Making
RPV	Reactor Pressure Vessel
SCC	Stress Corrosion Cracking
SIA	Structural Integrity Associates
SINTAP	Structural INTegrity Assessment Procedure
SORM	Second Order Reliability Method
SRM	Structural Reliability Methods
SRP	Standard Review Plan
SRRA	Structural Reliability & Risk-Assessment
STRUREL	STRUctural RELiability
TBS	Transition Break Size
TSA	Traditional Safety Analysis
UK	United Kingdom
US	United States
USA	United States of America
USNRC	United States Nuclear Safety Commission
UTS	Ultrasonic Test & Evaluation for Maintenance Standards
VISA	Vessel Integrity Simulation Analysis
WOG	Westinghouse Working Group
WRS	Weld Residual Stress
xLPR	eXtremely Low Probability of Rupture

17.0 APPENDIX A: QUESTIONNAIRE SENT TO REGULATORS IN VARIOUS COUNTRIES

The Canadian Nuclear Safety Commission, CNSC, has contracted Martec Limited a member of the Lloyd's Register Group, to undertake a Third party Review of a Probabilistic Fracture Mechanics Code, PFM. As part of the study, it is required to obtain information on the extent to which PFM has been used in regulatory and licensing activities in other countries. This questionnaire is designed to solicit information from individuals in various countries.

The objective of this questionnaire is to address the following:

> Establish the extent to which probabilistic fracture mechanics is used in formulating regulations and implementing licensing activities in the operations of Nuclear Power Plant in various countries.

Information is being sought from various countries in North America, Europe and Japan.

Information collected will be presented in aggregated form and will be destroyed at the conclusion of the project, after the final report is finalized and accepted by CNSC.

Table 12: Sample Questionnaire sent to Regulators in Various Countries

	Question	**Answer**
1	Name of Regulatory Agency	Name: ________ Name of Contact: ________ Telephone/E-mail: _ ________ Contact's Field of Expertise: ☐Safety ☐Regulation ☐Engineering ☐Other:

	Question	Answer
		______________________________
2	(a) How long have you been working in the nuclear industry? (b) How long have you been working in agency?	(a) ______________________________ (b) ______________________________
3	Does your agency use probabilistic fracture mechanics in regulatory and licensing decisions?	☐ No. If no, please provide reasons, if known ______________________________ ______________________________ ☐ Yes. If yes, please answer Questions 4 to 5
4	Please provide a list of regulations/ licensing decisions that are based **solely** on PFM	1 2 3 4
5	Please provide a list of regulations/ licensing decisions that are based **partly** on PFM	1 2 3 4
6	Please provide names and contact information of any other person in your organization or other similar organizations in other countries that may have relevant information to	1 2

	Question	Answer
	contribute.	3 4

18.0 APPENDIX B: SUMMARY NUREG 1829: ESTIMATING LOSS-OF-COOLANT ACCIDENT (LOCA) FREQUENCIES THROUGH THE ELICITATION PROCESS

In the US, the requirements for the emergency core cooling system (ECCS) to ensure that the system can successfully mitigate postulated loss-of-coolant-accidents (LOCAs) are contained in 10 CFR 50.46, Appendix K to Part 50, and GDC 35. Consideration of an instantaneous break with a flow rate equivalent to a double-ended guillotine break (DEGB) of the largest primary piping system, which is widely recognized as an extremely unlikely, is used to provide the limiting condition in the required 10 CFR Part 50, Appendix K analysis.

The US-NRC is establishing a risk-informed revision of the design-basis break size requirements for operating commercial nuclear power plants. A central consideration in selecting a risk-informed design basis break size is an understanding of the LOCA frequency as a function of break size. LOCA frequency estimates were calculated in NUREG 1829 using an expert elicitation process to consolidate operating experience and insights from PFM studies with knowledge of plant design, operation, and material performance. Two approaches traditionally used to assess LOCA frequencies and their relationship to pipe size, namely estimates based on statistical analysis of operating experience and probabilistic fracture mechanics (PFM) analysis of specific postulated failure mechanisms were not considered suited to evaluate LOCA event frequencies due to the rareness of these events and the modeling complexity.

The principal objective of the study was to develop separate boiling water reactor (BWR) and pressurized water reactor (PWR) piping and non-piping passive system LOCA frequency estimates as a function of effective break size at three distinct time periods: current-day (25 years fleet average), end-of-plant license (40 years fleet average), and end-of-plant-license-renewal (60 years fleet average). These estimates are based on the responses from an expert panel. The aim of the study was to obtain estimates that represent a type of group consensus. and to reflect both the uncertainty in each panelist's estimates as well as the diversity among the individual estimates.

A flow chart of the elicitation process employed in the study is shown in Figure 2 and a detailed description of the steps can be found in NUREG-1829, 2008.

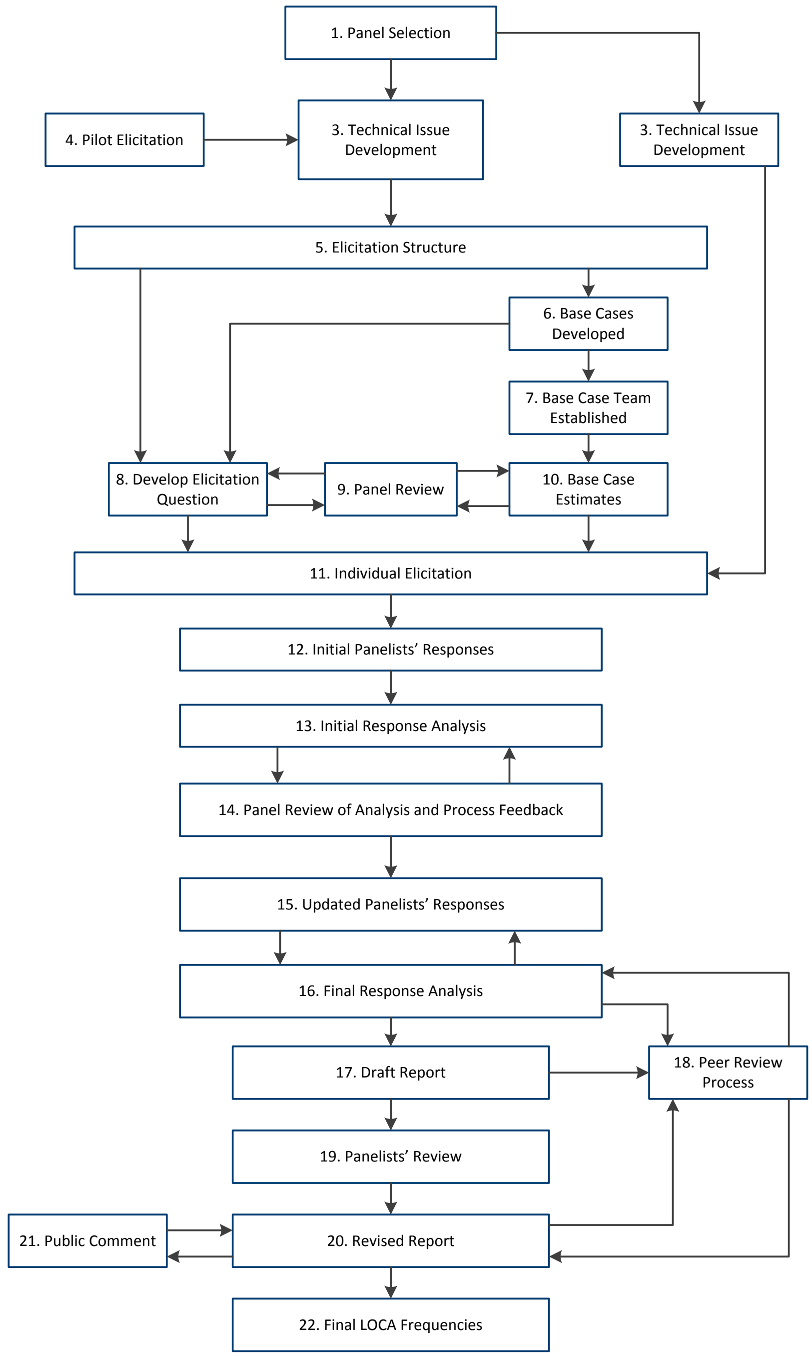

Figure 2 Flow Chart of the Overall Elicitation Process in NUREG 1829 for LOCA

The elicitation focused on developing generic, or average, estimates and the uncertainty bounds on LOCA frequencies that initiate by unisolable primary system side failures that can be exacerbated by material degradation with age. Active system failures (e.g., stuck open valve, pump seals, interfacing system LOCAs) and consequential primary pressure boundary failures due to either secondary side failures or failures of other plant structures (e.g., crane drops) were not considered. LOCA frequency estimates consistent with historical small break (SB), medium break (MB), and large break (LB) flow rate definitions were developed. Three larger LOCA categories were defined within the classical LB LOCA regime to examine trends with increasing break size, up to and including, a DEGB of the largest piping system in the plant.

The elicitation considered normal plant operational cycles and loading histories. The loads include representative constant stresses (e.g. pressure, thermal, residual) and expected transient stresses (e.g. thermal striping, heat-up/cool-down, pressure transients). All modes of operation based on the loading or operational experience associated with each piping system or non-piping component were considered. Rare event loading from seismic, severe water hammer, and other sources was also not excluded.

Panelists identified several advantages and disadvantages with determining the base case LOCA frequencies through operating experience assessment or PFM analyses. There was a general consensus that operating experience provides the best basis for evaluating current-day, small-break LOCA estimates. Many panelists used the operating-experience base cases to anchor their elicitation responses.

Several technical insights were identified by participants, including the following: (i) the number of precursor events (e.g., cracks and leaks) is generally a good barometer of the LOCA susceptibility for the associated degradation mechanism (ii) welds are likely failure locations because they can have relatively high residual stress, are preferentially-attacked by many degradation mechanisms, and are most likely to have pre-existing fabrication defects (iii) complete break of a smaller pipe, or non-piping component, is generally more likely than an equivalent size opening in a larger pipe, or component, because of the increased severity of fabrication or service cracking (iv) thermal fatigue, stress corrosion cracking (SCC), flow accelerated corrosion (FAC), and mechanical fatigue as the degradation mechanisms that most significantly contribute to LOCA frequencies in BWR plants (v) the most important BWR degradation mechanism is intergranular SCC (IGSCC)

Individual quantitative responses from panel members were uncertain and there was relatively large differences among the panelists' responses because of the underlying scientific uncertainty. The analysis of these responses was structured to account for the uncertainty in the individual estimates and the diversity among the panelists. The quantitative responses were analysed separately for each panel member to develop individual BWR and PWR total LOCA frequency estimates. A unified analysis format was developed to ensure consistency in processing the panelists' inputs. The panelists' mid-value, upper bound and lower bound responses were assumed to represent the median, 95th, and 5th percentiles, respectively, of their subjective uncertainty distributions for each elicitation response. The analysis structure was based on the assumption that all the responses correspond to percentiles of lognormal distributions. These distributions were then combined using a lognormal framework. The final outputs for each panelist are estimates for the means, medians and 5th and 95th percentiles of the total BWR and PWR LOCA frequencies. The panelists' estimates were then aggregated to obtain group LOCA frequency estimates, along with measures of panel diversity.

Several assumptions were made when calculating the individual and group estimates for the means, medians, 5th and 95th percentiles of the LOCA. In the report, these six assumptions and choices define what are termed the summary estimates. The report indicates that the resultant individual and group summary estimates are consistent with the elicitation objectives and structure and are reasonably representative of the panelists' quantitative judgments, which are not dominated by extreme results, either on the high or low end. The geometric means of the individual estimates approximate the medians of these estimates. The median is often used to represent group opinion in elicitations, especially when the individual estimates differ by several orders of magnitude, as they do in this study.

The LOCA frequency summary estimates for the current-day (25 years) and end-of-plant-license (40 years) periods are provided in the report for both BWR and PWR plant types. Sensitivity analyses were also conducted to examine the robustness of the quantitative results to the analysis procedure used to develop the summary estimates. These sensitivity analyses investigated the effect of distribution shape, as well as the effects of correlation structure, panellist overconfidence, panel diversity measure, and aggregation method on the estimated parameters. The largest sensitivity was found to be associated with the method used to aggregate the individual panellist estimates to obtain group estimates. The effect of using alternative aggregation methods to calculate the group estimates was also studied.