A Composite Analytical Solution for Large Break LOCA

Joint paper by the Canadian CANDU Industry Steering Committee
on Large Break LOCA and Positive Void Reactivity

P. Purdy[1], R. Girard[2], J. Marczak[3], D. Taylor[4], R. Zemdegs[5],
T. Kapaklili[6], G. Balog[7], M. Kozluk[8], A. Oliva[9]

*(1) Bruce Power, (2) Hydro-Québec, (3) Ontario Power Generation, (4) New Brunswick Power,
(5) Atomic Energy of Canada Limited, (6) CANDU Owner's Group,
(7) AMEC NSS, (8) Independent Consultant, (9) Candesco-Part of the Kinectrics Group*

Abstract

The Canadian CANDU Industry is implementing a composite analytical solution to demonstrate, with high confidence, adequate safety margins for Large Break Loss of Coolant Accidents (LBLOCA) in existing CANDU reactors. The approach involves consolidating a number of individual approaches in a manner that alleviates reliance on any single analytical method or activity.

Using a multi-layered approach, the objective of this composite solution is to use a variety of reinforcing analytical approaches such that they complement one another to collectively form a robust solution. The composite approach involves:

i) systematic reclassification of LBLOCA to beyond design basis events based on the frequency of the limiting initiating events;
ii) more realistic modeling of break opening characteristics;
iii) application of Best Estimate and Uncertainty (BEAU) analysis methodology to provide a more realistic representation of the margins;
iv) continued application of Limit of Operating Envelope (LOE) methodology to demonstrate the adequacy of margins at the extremes of the operating envelope;
v) characterizing the coolant void reactivity, with associated uncertainties; and
vi) defining suitable acceptance criteria, accounting for the available experimental database and uncertainties.

The approach is expected to confirm the adequacy of existing design provisions and, as such, better characterize the overall safety significance of LBLOCA in CANDU reactors.

This paper describes the composite analytical approach and its development, implementation and current status.

1. Introduction

The large-break loss of coolant accident (LBLOCA) is a design basis accident (DBA) in CANDU reactors that is postulated to occur as a result of an instantaneous failure of a large diameter pipe in the heat transport system. Due to the positive coolant void reactivity characteristic of CANDU reactors, LBLOCA is characterized by a power excursion. LBLOCA is the DBA used to set the requirements for the speed of the shutdown systems and the requirements for emergency core cooling (ECC). LBLOCA involves simultaneous degradation of cooling capability and fast positive reactivity insertion, due to rapid core voiding. In the limiting events considered in the plant safety reports, the resulting power pulse is terminated by activation of one of the two independent shutdown systems within less than two seconds after accident initiation. Furthermore, unlikely combinations of events, such as LBLOCA combined with unavailability of ECC, have been considered in the design of CANDU reactors. Even though these event combinations are considered by other jurisdictions to belong to the beyond design basis accident (BDBA) category, they are currently treated as DBA in the Canadian regulatory framework.

Over the years, analysis of LBLOCA in CANDU reactors has been characterized by identification of issues that have adversely affected the predicted consequences. These have included the recognition (in the late 1980's) that operation with flux tilts can materially impact shutdown system effectiveness, identification (in the early 1990's) of the reactivity effect associated with fuel string relocation in reactors that fuel against the flow, experimental results (in the 1990's) indicating a significantly higher positive coolant void reactivity effect than originally considered in the CANDU design and in recent years, issues associated with the transition from legacy analysis tools to the more sophisticated codes in the reactor physics area.

The traditional safety analysis methodology used for LBLOCA scenarios incorporates numerous conservative assumptions with regard to the state of reactor, both before and after the accident initiation (termed *Limit of the Operating Envelope or LOE*). Current safety analyses demonstrate that the design meets the current acceptance criteria and regulatory dose limits. The LOE analysis methodology used traditionally in CANDU reactor licensing, which is contained in the current analysis basis of CANDU reactors, exaggerates LBLOCA consequences, and yields reduced margins to the safety acceptance criteria. Developments in the understanding of the physical basis of large-diameter piping failures, introduction of probabilistic fracture mechanics methodologies in assessing their failure probabilities, development of state of the art analytical methods for safety analysis, coupled with the operating experience of CANDU plants over the last three decades have not yet been systematically reviewed and incorporated in the analysis of LBLOCA accidents. With a change in approach and the incorporation of best industry practices, actual safety margins will be more readily characterized and new findings can be addressed without unnecessary constraints on plant operation to restore any loss of calculated safety margin.

Issues associated with safety margins for LBLOCA are being systematically resolved as part of the overall work to resolve CANDU safety issues [1], [2]. A risk-informed decision making process has been used in Canada as a way to risk-rank safety issues relevant to CANDU reactors and identify potential risk control measures. The issues related to LBLOCA, which are included in the group of Category 3[1] issues identified by the Canadian Nuclear Safety Commission (CNSC), are as follows:

- analysis for void reactivity;
- channel voiding during LBLOCA;
- fuel behaviour in high temperature transients;
- fuel behaviour in power pulse transients; and

In 2008, a joint Industry/CNSC working group was established to identify possible options for a resolution path to address the issues associated with LBLOCA safety margin in existing CANDU reactors. Two resolution strategies (Risk Control Measures or RCM) were evaluated by the working group:

RCM-1: the composite analytical approach (industry's primary choice).
RCM-2: the design change strategy (back-up option).

Based on the assessment, a preferred set of risk control measures (based on the composite analytical approach, RCM-1) is being systematically pursued by the Canadian Nuclear Industry to resolve the LBLOCA-related issues. Plans for the backup risk control measure based upon a fuel design change to reduce the magnitude of the positive coolant void reactivity have been established (RCM-2) should they be required, although this is considered to be highly unlikely. This paper focuses on the set of measures termed the 'Composite Analytical Approach'.

2. The Composite Analytical Approach

2.1 Framework and Objectives

The objective of the composite analytical approach is to demonstrate the following:

- The probability of having a break in a large CANDU primary heat transport system pipe is low.
- The adoption of realistic (but conservative) break opening characteristics for large diameter primary heat transport system piping is justified.
- The LBLOCA safety margins for the most probable operating states are large.

Consequently, the composite analytical approach focuses on:

- Establishing large pipe break frequencies to be used to re-classify pipe break scenarios into the DBA and BDBA categories.
- Developing and validating a more realistic break opening model for progression of a break in a large pipe (instead of the current assumption of a double-ended instantaneous guillotine break).
- Further development of a best estimate plus uncertainty (BEAU) methodology to augment the deterministic safety analysis of LBLOCA. The BEAU methodology assumes more realistic initial and boundary conditions with all uncertainties (those associated with assumptions, models, and computer codes) defined to a high level of confidence.

The approach, illustrated in Figure 1, involves consolidating a number of individual approaches in a manner that alleviates reliance on any single analytical method or activity.

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[1] Canadian Nuclear Safety Commission defines Category 3 issues as follows: "*The issue is a concern in Canada. Measures are in place to maintain safety margins, but further experiments and/or analyses are required to improve knowledge and understanding of the issue, and to confirm the adequacy of the measures.*"[2]

Using this multi-layered approach, the objective of this composite solution is to use a variety of reinforcing analytical approaches such that they complement one another to collectively form a robust solution. The composite approach involves four Technical Areas with objectives as follows:

i) characterizing the coolant void reactivity, with associated uncertainties (Technical Area 1);
ii) defining suitable acceptance criteria, accounting for the available experimental database and uncertainties (Technical Area 2);
iii) application of BEAU analysis methodology to provide a more realistic representation of the margins (Technical Area 3);
iv) continued application of LOE methodology to demonstrate the adequacy of margins at the extremes of the operating envelope (Technical Area 3);
v) systematic reclassification of LBLOCA to beyond design basis events based on the frequency of the limiting initiating events (Technical Area 4); and
vi) implementation of more realistic modeling of break opening characteristics (Technical Area 4).

As indicated in Figure 1, each Technical Area relies upon Industry R&D performed by the CANDU Owners Group (COG) in addition to analyses and assessments performed within the LBLOCA project. The industry project execution plan for the Composite Analytical Approach assigned Technical Areas #1 (Quantify Coolant Void Reactivity and Uncertainties), #2 (Define Safety Limits and Safety Margins) and #3 (Application of BEAU methodology and re-definition of LBLOCA Analysis Basis) to the Analysis Issues Resolution Working Group (AIR-WG). Technical Area 4 (Reclassification of LBLOCA and Establishment of Break Opening Characteristics) was assigned to the Failure Probability and Break Opening Characteristics Work Group (FPBOC-WG).

Each of the Technical Areas comprising the Composite Analytical Approach is described in the following sections.

2.2 Technical Area 1

Technical Area 1 is focused on the qualification of reactor physics predictions and uncertainty estimation of the key reactor core nuclear parameters, including coolant void reactivity, power coefficient of reactivity, delayed neutron fraction and neutron lifetime, with particular emphasis on the coolant void reactivity and related uncertainties. These activities are consistent with the overall objective of reducing uncertainty and increasing confidence in the assessment of the consequences and risk associated with LBLOCA events.

The objective of Technical Area 1 is to use suitable approaches to qualify the reactivity feedback coefficients and kinetics parameters for use in analyses of effectiveness of shutdown systems and consequences of the power pulse and, if needed, to evaluate the possibility and the merits of undertaking additional experiments to better quantify reactivity feedback coefficients. In particular, work is being undertaken to identify the best estimate for the value of coolant void reactivity (CVR) in a CANDU reactor, along with the bias and uncertainty in using either MCNP5 or the CANDU Industry Standard Toolset (IST) reactor physics codes. The toolset being validated by the Industry comprises the following computer codes: MCNP5, WIMS-IST 3.1, DRAGON 3.06 and RFSP 3.5, all with ENDF/B-VII nuclear data.

The proposed approach is based on qualifying a reference tool (MCNP) to be used as a validation base (a surrogate to a scaled experimental facility) to quantify the coolant void reactivity bias and uncertainty in the IST physics toolset. The process involves:

- validating MCNP against experiments performed at the ZED-2 facility;
- removing the bias in MCNP through cross section adjustments by conducting Sensitivity/Uncertainty (S/U) analysis using the TSUNAMI code[2];
- scale up and extension of the accuracy assessment to CANDU reactor conditions using TSUNAMI; and
- Evaluating the IST tool accuracy by comparing the IST tool plant model predictions to that of the validation base (MCNP)

2.3 Technical Area 2

The principal objective for Technical Area 2 is to define and formalize acceptance criteria and limits for LBLOCA scenarios based on evaluating the current state of knowledge and simulation capabilities for performance limits of fuel and pressure tube behavior under various accident conditions and, if required, performing additional experimentation and validation to close any relevant identified gaps.

Activities in Technical Area 2 are focused on the following tasks:

1. Define the overall conceptual framework for defining barriers, failure limits, margins and parameter limits.
2. Identify relevant barriers for LBLOCA which must be preserved.
3. Review existing information to define physical failure mechanisms for barriers and logical sequence of outcomes for each barrier failure.
4. Define quantitative parameter limits which prevent barrier failure for each relevant mechanism.
5. Elicit independent expert review of the results of the above tasks to provide confidence in barrier selection, failure mechanisms and selected key values.
6. Assess fuel and fuel channel code applicability to a LBLOCA and determine code accuracy statements (code biases and their variabilities (uncertainties)) that are relevant to both LOE and BEAU methodologies.
7. Recommend new R&D and/or code development as necessary and, if required, initiate redirection of current industry R&D work.

The work in Technical Area 2 relies upon the outcome of Technical Area 4 (see below), addressing piping failure probabilities and break opening characteristics. Even if Technical Area 4 cannot support a change to the traditional LBLOCA assumptions (based on analyzing the 100% instantaneous double-ended pipe break as design basis accidents), BEAU methodology will become the major tool used in implementing the CAA. However, most of the current issues on safety analysis margins, code accuracy and validity, and range of supporting experiments would remain the same, and may take a long time to resolve, partly due to the difficulty of testing at conditions which match the extreme predictions of analysis methodology when applied to the largest header breaks. This work would continue under the current COG R&D program.

Methods used in LBLOCA analysis, and the validation of the codes that support the safety analysis, will change if the work in Technical Area 4 is successful in supporting industry/regulator agreement on redefinition of the Design Basis LBLOCA based on work currently underway on maximum break size for DBA, and more realistic break opening characteristics. The consequences of a redefined DBA LBLOCA are expected to be less severe relative to current results, whether analyzed using LOE or

[2] TSUNAMI is a part of the SCALE code system, developed and maintained by ORNL[3]

BEAU. The BDBA LBLOCA would be analyzed using more realistic models and assumptions (e.g. Best Estimate) which also implies a large reduction in predicted LBLOCA consequences.

Table 1 provides a framework for how work could progress assuming that break reclassification and introduction of more realistic break opening characteristics (per Technical Area 4) is successful. It represents only a *model* as the supporting activities have yet to be completed.

Table 1 – Traditional vs. Possible Future Approaches to LBLOCA

Item	*Traditional Approach to LBLOCA*	*Possible Future Approach to LBLOCA*	
	DBA	DBA	BDBA
Break Size	Up to 2 x 100% of the flow area of the largest pipe	Up to ~10% of the flow area of the largest pipe	Up to 2 x 100% of the flow area of the largest pipe
Break Opening Time	Instantaneous (≤ 1 ms.)	More Realistic (to be determined)	More Realistic (e.g. several seconds)
Analysis methodology	LOE, recently supplemented with BEAU	LOE and/or BEAU	Best Estimate supported by sensitivity analysis to demonstrate lack of cliff edge effects

2.4 Technical Area 3

The principal objective of Technical Area 3 is to establish a new analytical basis for LBLOCA and perform pilot analyses to quantify the safety margins using state of the art analysis methodologies. Technical Area 3 integrates and makes use of the outputs from other technical areas as well as applying BEAU methodology. In particular:

- Quantification of the positive coolant void reactivity coefficient and characterization of uncertainties (from Technical Area 1).
- Quantification of parameter limits which prevent barrier failure for each mechanism relevant to LBLOCA (from Technical Area 2).
- Reclassification of LBLOCA to partition events into the DBA and BDBA categories (from Technical Area 4).
- Use of more realistic break opening characteristics in LBLOCA analysis (from Technical Area 4).

A key activity in Technical Area 3 is to support the application of BEAU methods to LBLOCA, the objective of which is to ultimately gain assurance that BEAU can be used for licensing analyses. The BEAU working group (operated by COG) is contributing to the resolution of BEAU methodology related issues in concert with the AIR-WG. The principal issues to be addressed in supporting the use of BEAU methodology in licensing analyses are:

- Code applicability, i.e. demonstrating that computer codes used by the CANDU industry possess adequate capability for the key phenomena relevant to LBLOCA.
- Code validation, i.e. undertaking assessments of code bias and uncertainty including consideration of phenomena interaction and code coupling.

- Operational compliance, i.e. establishing a framework for station compliance with the input distributions used in BEAU analysis and its application to definition of the Safe Operating Envelope.

This new analytical basis will re-baseline safety margins for CANDU reactors, re-define the applicable range of phenomena and their interaction and provide a rationale for focusing further R&D that may be required. The new basis will recognize that, because the fundamental assumptions for LBLOCA will be changed in some areas, limiting events may be re-defined and hence additional analyses beyond those already covered in the current plant Safety Analysis Bases will be required. One area that will be significantly affected will be the analysis assumptions applied to those portions of the LBLOCA break spectrum that are reclassified as BDBA events. BDBA and DBA events will need to be analysed in a manner consistent with CNSC regulatory document RD-310 [4], whose implementation is being guided by an Industry initiative through COG under the Safety Analysis Improvement Working Group (SAIWG). The additional analyses needed to complete the revised analysis basis are the focus of the LBLOCA pilot analysis that will be completed as part of Technical Area 3.

2.5 Technical Area 4

The major objective of this Technical Area is to re-establish the major assumptions related to piping failures used in safety analysis for a spectrum of LBLOCAs based on operating experience, existing defence in depth in the plant design and operational bases, international and CANDU specific experimental data and developments of the analytical tools such as probabilistic fracture mechanics for use in licensing applications.

The Failure Probability and Break Opening Characteristics Work Group (FPBOC-WG) was tasked with preparing and overseeing implementation of detailed work plans to address the four closure items and eleven resolution activities associated with Technical Area 4.

There are four major tasks in progress initiated by the FPBOC-WG:

Task 1: Failure Probabilities

Under this task a probabilistic fracture mechanics code will be developed that can be used to determine the failure probabilities for a spectrum of break sizes in CANDU PHTS piping. The computer code is to be called PRAISE-CANDU and is being developed in accordance with the requirements of CSA N286.7 99 (Quality Assurance of Analytical, Scientific and Design Computer Programs for Nuclear Power Plants) [5].

In addition to development of PRAISE-CANDU, industry partners are also considering participation in the international program called PARTRIDGE (Probabilistic Analysis as a Regulatory Tool for Risk Informed Decision Guidance) to carry out benchmarking of PRAISE-CANDU and share lessons learned through its development and use.

Task 2: Break Opening Characteristics Model

This task includes development of break opening characteristics for large-diameter PHTS piping at Canadian CANDU plants. In addition, the capability to perform finite element analysis of large-diameter PHTS piping with circumferential cracks subject to DBA (and BDBA) loading scenarios is being developed to validate that the more realistic break-opening characteristics are conservative.

Task 3: Use of External Experts

This task involves international subject matter experts to work with Canadian service providers to develop codes and analysis capabilities necessary to accomplish Tasks 1 and 2 and to review the final deliverables from these tasks.

Task 4: Surveillance Programs

This task will review existing surveillance, inspection, and leakage detection methods to ensure that key assumptions made with respect to failure probability and break-opening characteristics remain valid throughout the operating life of Canadian CANDU plants.

3. Status of Industry Initiatives

The industry project to undertake the Composite Analytical Approach was initiated in Spring 2010 as a CANDU Owners Group Joint Project. Detailed planning has been completed and a number of activities are now underway, under the management of the AIR and FPBOC working groups. The LBLOCA joint project activities are closely synchronized with industry R&D and code validation programs. In addition, close working relationship has been established with other Industry Working Groups and initiatives that relate to CAA such as BEAU-WG, SAI-WG, Independent Technical Panel on Fuel and Fuel Channel Integrity and RIISI-WG (Risk Informed In-service Inspection Working Group). The Steering Committee provides active oversight of the project and regulatory staff and management participate as observers in the committee and associated working groups. Formal reporting to the Canadian Nuclear Utilities Executive Forum (Senior Management from key industry stakeholders) is undertaken on a semi-annual basis.

As indicated in Figure 2, the closure report for the industry project to implement the Composite Analytical Approach is planned for issuance in early 2013.

4. Concluding Remarks

The CANDU industry’s strategy for demonstration of LBLOCA margins is focusing on implementation of the Composite Analytical Solution as the preferred risk control measure, while at the same time preparing for implementation of design changes as a contingency.

The composite analytical approach represents a significant commitment by the Canadian CANDU Industry to a range of initiatives that will ultimately lead to:

- a significant improvement in the underlying technical and experimental basis for LBLOCA,
- closure of the LBLOCA related Category 3 CANDU Safety Issues, and
- a robust demonstration of LBLOCA safety margins for the CANDU fleet.

5. References

1. Canadian National Report for the Convention on Nuclear Safety, Fifth Report, September 2010.
2. 2010 Annual CNSC Staff Report on the Safety Performance of Canadian Nuclear Power Plants, June 2011.
3. "SCALE: A Modular Code System for Performing Standardized Computer Analyses for Licensing Evaluation", Oak Ridge National Laboratory report, ORNL/TM-2005/39, V5.1, 2005.
4. "Safety Analysis for Nuclear Power Plants", Regulatory Document RD-310, February 2008.
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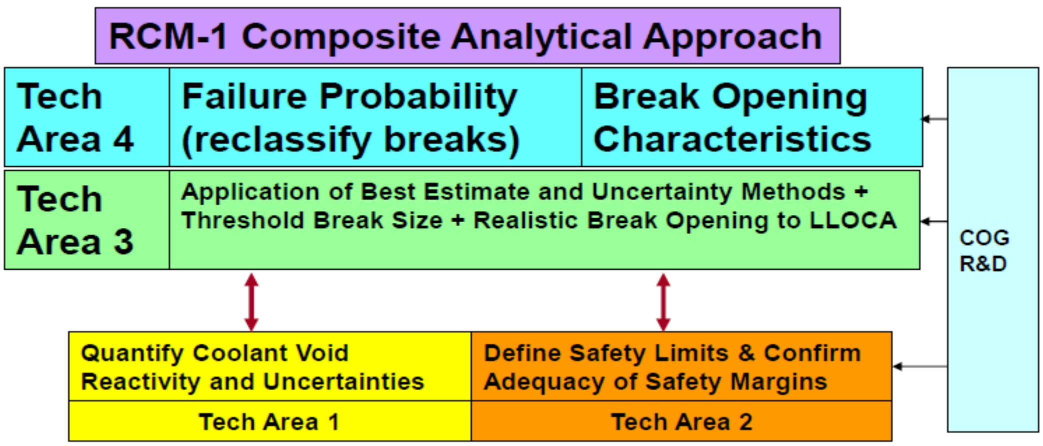

Figure 1: Composite Analytical Approach

Figure 2: Composite Analytical Approach-Overall Schedule