

LARGE LOCA MARGINS IN CANDU REACTORS - AN OVERVIEW OF THE COG REPORT

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Abstract

This paper discusses the background and conclusions of the 2007 COG report on Large LOCA Safety Margins in CANDU Reactors, and the various initiatives that have resulted from this study since its release. The COG study challenged the notion that positive void reactivity itself is a design weakness, raised as an issue at the Convention on Nuclear Safety, to demonstrate the safety of operating CANDUs worldwide when compared to other certified LWR designs. The paper will briefly describe a new perspective on how the seemingly complex analytical results on reactor safety parameters can be compared on a level playing field, in such a manner that the non-specialist is able to understand. The paper is presented together with a companion paper that focuses on the comparison of reactivity initiated events in CANDU with some other internationally accepted LWR reactor designs.

1. Background

The issue of Large Loss of Coolant Accident (LOCA) safety margins in CANDU reactors has been the subject of a large amount of work and considerable debate for a number of years. The issue is closely linked to an inherent reactivity characteristic of CANDU reactors (viz., positive void reactivity coefficient) which leads to a power increase following a Large LOCA. The perception of the international community that a positive void reactivity coefficient is an inherent weakness has contributed to the subject of CANDU Large LOCA safety margins being raised during periodic Nuclear Safety Convention review meetings. By the same token, an inherent beneficial characteristic of CANDU design, namely its longer neutron lifetime, does not appear to have been sufficiently well described to the international community. Because all reactors have a combination of beneficial inherent characteristics and engineered design features to compensate for the limitations, it is important to review this particular area in a balanced and factual manner.

Canadian Licencees therefore requested COG to prepare an integrated document on the subject of Large LOCA safety margins. The intent of this document (Ref.1) was to assist in the establishment of a framework to direct future work in this area. The direction provided to COG was as follows:

- ✓ Produce a factual assessment of the issues in as unbiased a manner as possible.
- ✓ Approach the issue in the context of the Canadian policy direction to move towards a risk-informed framework aligned with international practices.
- ✓ Include a comparison of safety margins of the domestic CANDU fleet and other international designs to the extent practicable
- ✓ Establish a position that represents the alignment of all Canadian reactor Licences on the issues.
- ✓ To the extent practical provide a document that is both technically correct and is readable by the Industry, Regulatory and other key stakeholders who may not be reactor specialists by education.

2. Issues Examined in the COG Large LOCA Report

Over its history, the CANDU reactor has proven to be a safe producer of nuclear energy worldwide. At its beginning, highly conservative design bases and supporting analysis were provided as the basis on which to license the reactors. This included an estimate of the reactor performance under extreme accident conditions. The conclusion was that the reactors were safe to license and had adequate safety margins to account for uncertainties in knowledge. Over the years knowledge on reactor behavior has changed around the world through contributions of operating experience, advances in understanding through research and development, and the development of more powerful analytical tools.

Some of the research and development results (in particular, the coolant void reactivity) have resulted in progressively reduced estimates of safety margin, and concern with respect to the robustness of these estimates. This has led to efforts to improve the estimated margin through improved code modeling and validation, as well as to examine potential design changes to increase the real margin. In the case of the former, it was learned that the magnitude of the coolant void reactivity effect is actually larger than originally estimated. An international Independent Expert Panel subsequently concluded that the revised estimation is sufficiently accurate and that any remaining uncertainties are relatively small.

In the case of the latter, real physical changes have been made in CANDU reactors to increase safety margins. In some cases, additional shutdown rods have been installed and/or improvements have been made to rod speed acceptance criteria and initiating logic. In other reactors, fuelling regimes have been changed to improve margin. In all cases, operating limits on key parameters have been changed to improve safety margins (e.g., flux tilt, moderator poison, heat transport system and moderator isotopic purity).

Physical changes that have increased the reactor safety margins, together with the improvements in analytical methods, have combined to make the estimation of safety margins more robust and accurate. More recently, a new design of fuel, termed Low

Void Reactivity Fuel (LVRF), has been studied (and in-reactor tests are in progress) to reduce the coolant void reactivity effect.

Over the same period, understanding of piping failure phenomena has evolved considerably. Current knowledge suggests that the original specification of the design basis set and the approach to modeling of the LOCA events are unduly conservative in the light of today's understanding. For example, Germany has evolved to a 'Break Preclusion' approach. Other jurisdictions such as the USNRC are moving toward more extensive use of this type of approach through quantification of the break size versus frequency spectrum.

The issues examined in the COG Large LOCA Report (Ref.1) therefore covered the following:

- a) How do Large LOCA results for CANDU reactors compare against other Reactivity Initiated Accident (RIA) events in other reactor designs? What are the relative risks of RIA events in the various reactor designs?

As a starting point in the COG report, reference CANDU Large LOCA results were benchmarked against LWR designs to ensure that the CANDU design is consistent with international safety standards and compares favourably with these designs. A companion paper presents further detail on this study (Ref. 2).

- b) How do Large LOCA results differ between the different CANDU designs, and what is the relative importance of Large LOCA compared to other postulated accidents based on Probabilistic Safety Assessment (PSA) studies?

This issue required all Canadian Licencees to share results of their Large LOCA deterministic safety analysis, and the contribution of all postulated accident sequences to the Core Damage Frequency (CDF) using internationally accepted probabilistic safety criteria. Sample results of CDF assessments are provided in section 3.

- c) How can the seemingly complex analytical results on reactor safety parameters (for both CANDU and other internationally accepted designs) be compared on a level playing field, in such a manner that the non-specialist is able to understand?

This required the development of a novel approach for comparison of safety margins for relatively fast reactivity transients in different reactor designs. Key safety parameters and acceptance criteria were defined, and the results for the various designs were expressed in non-dimensional terms. This facilitated an easily understood graphical representation of the safety margins of each reactor design in one single plot. The results obtained are summarized in section 4.

- d) Is the current conservative approach to CANDU Large LOCA analysis justified on the basis of current world knowledge?

This required an examination of the rationale and potential for improving the robustness of the estimated safety margins through analysis/methodology changes, including the use of a Best-Estimate and Analysis of Uncertainty

(BEAU) type methodology. Discussions were also held with industry experts on the ample experimental data that indicated large break opening was far from instantaneous as had heretofore been assumed for convenience. In addition, an examination of the USNRC's expert elicitation on break size versus frequency, suggested that large breaks were of even lower frequency than had been traditionally assumed. It became evident that break opening dynamics alone would dramatically increase the estimated safety margins, and this avenue was pursued with high interest. Some sample results of these investigations are summarized in section 5.

- e) Where should resources and money be spent to improve reactor safety, and on what basis? Should the industry focus on a fuel design change to LVRF to improve Large LOCA safety margins, given that more realistic modeling might achieve similar results? Should we focus on primary side relief valve failures, secondary side failures, loss of power events, etc., which PSA results imply are far more likely, in tandem with the required periodic inspections, to decrease their likelihood?

This required an assessment of the rationale and potential for increasing the real safety margins through various design improvements, including the use of LVRF, and compared the relative gains in safety margin against those achievable with more realistic analytical modeling. The impact of LVRF was only available to the authors for the CANDU-6 design, but it was assumed that a similar magnitude change would be obtained in general for all CANDU designs. The results are summarized in section 6.

3. Core Damage Frequency Assessments

Figure 1 shows the most recently available PSA results of the overall Core Damage Frequency (CDF)¹ for the CANDU reactor fleet, assuming "at power" conditions and excluding initiating events such as fire and seismic events. The results show that the CDF is well within the internationally accepted safety goal limit of 10^{-4} per reactor-year for existing reactors (Ref.1). It is to be noted that improvements in CANDU design and operational safety over the last several years have resulted in a reduction of the CDF towards the Industry safety goal target of 10^{-5} per reactor-year. The latter value (10^{-5} per reactor-year) corresponds to the internationally accepted limit for future reactors (Ref.1).

3.1 Contribution of Large LOCA to Core Damage Frequency

Since the safety acceptance criteria are met for all design basis Large LOCAs in CANDU reactors, it would require a breakdown in cooling capability in the longer term following such accidents to potentially cause core disassembly. In the specific case of the CANDU design, both emergency cooling and moderator cooling (which are highly reliable

¹ In this report, for consistency with the terminology used for LWRs, the CDF refers to core damage that results in core disassembly. For CANDU designs, it would be more correctly referred to as the Severe Core Damage Frequency (SCDF) as discussed in Ref.1. This distinction is deliberately avoided here to avoid confusion.

independent means of long term heat removal) would have to be ineffective. Thus, given the low initiating event frequency of a Large LOCA (which ranges from 10^{-4} to 10^{-5} per reactor-year²), the contribution of Large LOCAs to the CDF would be expected to be rather small. This is indeed found to be the case in all Probabilistic Safety Assessments done to date.

Figure 2 is illustrative of the typical results obtained. The key conclusion is that the contribution of Large LOCAs with an assumed frequency of 10^{-5} per reactor-year would be less than approximately 0.1% of the overall CDF.

Note that all CANDU results shown credit shutdown by one of the two independent fast-acting shutdown systems, since simultaneous failure of both shutdown systems is considered incredible and beyond the design basis. Nevertheless, studies of a hypothetical complete loss of shutdown indicate that the consequences would be limited due to the early failure of a relatively small number of fuel channels and the strong negative reactivity change associated with those failures. The issue is further discussed in Ref. 3.

4. Safety Margin Assessments

For the purposes of comparing appropriate safety parameters of CANDU and LWR designs for accidents involving a reactivity increase, it is useful to consider the common acceptance criteria that apply in the short term versus the longer term in the accident transient.

For the short term, the most restrictive common applicable acceptance criterion is that relating to the maximum enthalpy of the fuel during the power pulse phase (i.e., up to 5 seconds). Failure to meet this acceptance criterion in either CANDU or LWR designs renders the design unacceptable. For the longer term, as long as the short-term criterion is met, acceptable cooling is demonstrated (as required for safety analysis) through analysis and comparison with other acceptance criteria as appropriate for each case (Ref.1). Therefore, the maximum or peak fuel enthalpy criterion is an appropriate choice of safety parameter for comparing the various reactor designs.

The predicted reactivity transient offers a basis for the choice of a second comparative safety parameter. The reasons for this are as follows:

- 1) The definition of reactivity is independent of reactor type.
- 2) A peak value of the transient reactivity is predicted in the short term (less than 5 seconds) for accidents involving a reactivity increase for both LWR and CANDU reactors

² The Large LOCA frequency has historically been assumed to be 10^{-4} per reactor-year. However, this has been revised to a value in the range 1 to 2×10^{-5} per reactor-year based on world experience, together with international initiatives such as described in Ref.1.

- 3) The peak value of transient reactivity can be readily compared to a threshold value known as the "prompt critical" value, which is dependent upon reactor design.

Although avoidance of prompt criticality is not an explicit acceptance criterion in either the LWR or CANDU designs, it is recognized that prompt criticality represents a threshold that could potentially be used either implicitly or explicitly to compare reactor designs in international forums. Therefore, the transient peak reactivity represents an appropriate safety parameter for comparison purposes.

For any given fast transient in an LWR or CANDU (or for that matter any reactor design) the above two key safety parameters can be expressed in non-dimensional terms (i.e., by normalizing their peak predicted values to defined acceptance criteria). When the resulting non-dimensional values are plotted together on an x-y diagram, we obtain a convenient graphical representation of the relative safety margins for different accidents in different plant designs.

Figure 3 shows an example of this graphical representation for the CANDU-6 reference Large LOCA case discussed in the companion paper (Ref. 2). In this figure, the normalized peak reactivity is plotted on the x-axis versus the normalized peak enthalpy on the y-axis. The positive safety margins to fuel melting and prompt criticality for this case are as shown in the figure. Clearly, a value falling outside the "quadrant", i.e., greater than 1 on either the x or y axes (or both) would result in a negative safety margin.

The COG report (Ref.1) presents all results for various RIA accidents in CANDU and LWR designs in this graphical manner. The LWR cases are as described in the companion paper (Ref.2). The results for all the cases examined are shown in Figure 4. In this and all subsequent figures, the peak reactivity limit shown is that adjusted for the CANDU neutron lifetime, as derived in Ref.1.

This graphical method was found particularly useful for assessing the impact of sensitivity studies for the different CANDU designs. These included sensitivity to break dynamic modeling, best-estimate assumptions, and design modifications such as the use of LVRF, as described in the following two sections.

5. Potential Improvements in Estimated Safety Margins

5.1 Best-Estimate and Analysis of Uncertainty Methodology

The Best-Estimate and Analysis of Uncertainty (BEAU) methodology that has been employed for application to CANDU safety analysis differs from the traditional approach. Whereas the latter assumes that most input modeling and plant operational parameters are simultaneously at their extreme worst-case allowed values, the BEAU methodology assumes that they are randomly distributed about their mean or best-estimate values within their uncertainty range. However, in other respects (e.g., use of an instantaneous break opening model) this methodology retains the traditional approach.

Figure 5 shows an example of the effect of using the BEAU methodology for a reference Large LOCA case. Note the significant increase in estimated safety margins obtained for peak fuel enthalpy and peak reactivity.

5.2 Break Opening Model

The traditional approach in CANDU Large LOCA thermal-hydraulic analysis has been to assume that pipe breaks develop instantaneously (within 1 ms) irrespective of the break size (discharge area). Furthermore, the maximum break discharge area possible is assumed to be twice the pipe cross-sectional area. Since the breaks are inherently assumed to run the length of the header in this simplified model, what is actually being modeled is an extremely fast fracture characteristic of through-wall cracks longer than the critical crack length. As fully described in Ref.1, this approach is not supported by current knowledge of how breaks develop in large diameter ductile piping characteristic of CANDU heat transport piping.

A more realistic, though still conservative, break opening model would be a "two-step" break development process, as follows:

1. Instantaneous (within 1 ms) opening to 10% of the pipe cross-sectional area;
2. Slower opening (within a few seconds) up to a maximum value which would depend on the magnitude of cyclic loading.

Note that the second step in this break opening process would require cyclic loading well beyond design basis loadings before an appreciably larger break size could develop. Thus, the breaks would not be expected to progress much beyond the initial opening of 10% area in the real reactor case. A maximum value of 100% area may be assumed strictly for sensitivity analysis purposes, but this is not indicative of the maximum credible break size.

Interestingly, from the risk-informed perspective proposed by the USNRC, an instantaneous 10% break opening in large diameter heat transport piping is consistent with an assumed Large LOCA frequency of 10^{-5} per reactor-year assumed in the most recent CANDU PSA studies. Larger instantaneous openings would have a lower frequency in this proposed framework, and would therefore be outside the design basis cut-off frequency of 10^{-5} per reactor-year (Ref.1).

Figure 5 shows an example of the effect of the two-step break opening model for a reference Large LOCA case. The model assumes that the break opens instantaneously (within 1 ms) to 10% of the pipe cross-sectional area, followed by a linear increase to 100% over 5 seconds. Also shown are the results for the case where the break does not develop beyond 10%. This is the expected maximum stable break size for both axial (fishmouth) and circumferential pipe breaks. Note the significant increase in estimated safety margins obtained for peak fuel enthalpy and peak reactivity.

Clearly, further improvement in the estimated safety margins could be obtained by combining the new break opening model and the BEAU methodology. Such

improvements would result in a more accurate estimate of the safety margins without any physical change to the plant.

6. Potential Improvements in Safety Margins Through Design Change

Several operational and design modifications to improve the safety margins for Large LOCAs have been studied by AECL (Ref.1), primarily for the CANDU-6 design in the context of refurbishment and new builds. These modifications are aimed at reducing the peak reactivity during the first few seconds of a Large LOCA; either through reducing the positive coolant void reactivity or increasing the rate of negative reactivity addition.

Figure 6 shows an example of the effect of various design options (details are provided in Ref.1) including the substitution of natural fuel with LVRF. It can be seen that use of LVRF confers similar safety margin improvements to the non-fuel design change options for the reference case.

7. Main Conclusions

The main conclusions of the COG Large LOCA report may be summarized as follows:

- √ The CANDU designs meet the expectations outlined in international standards through a combination of inherent reactor characteristics and defense-in-depth engineered features.
- √ The CANDU designs compare favorably to LWR designs in their ability to handle reactivity events safely with margin.
- √ Assessment of the overall impact of potential gains in safety margins for LOCA events should be based on the best possible estimation of current margin as a starting point. This would factor in both the improved knowledge of the void reactivity and the improved knowledge of piping fracture behaviour.
- √ Any design changes being considered should be subject to an agreed-upon value/impact assessment that enables sound decisions to be made to prioritize reactor safety investments as we move toward a risk-informed approach to licensing reactor facilities.

These conclusions are supported unanimously by the Canadian CANDU Licencees and the original Design Authority (AECL).

8. References

- 1) Ajit Muzumdar and Daniel Meneley, "Large LOCA Margins & Void Reactivity in CANDU Reactors", COG -07-9012, Issued August 2007.
- 2) Daniel Meneley and Ajit Muzumdar "Power Reactor Safety Comparison – A Limited Review", companion paper at Canadian Nuclear Society Annual Conference, Calgary, June 2009.
- 3) J.C. Luxat, "Reactivity Initiated Accidents and Loss of Shutdown – 20 Years Later", Proceedings of 28th Annual Conference of the Canadian Nuclear Society, Saint John, NB (Jun 2007).

9. Acknowledgements

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**FIGURE 1: Core Damage Frequency
Recent Results For Various CANDU Reactors (at Power)**

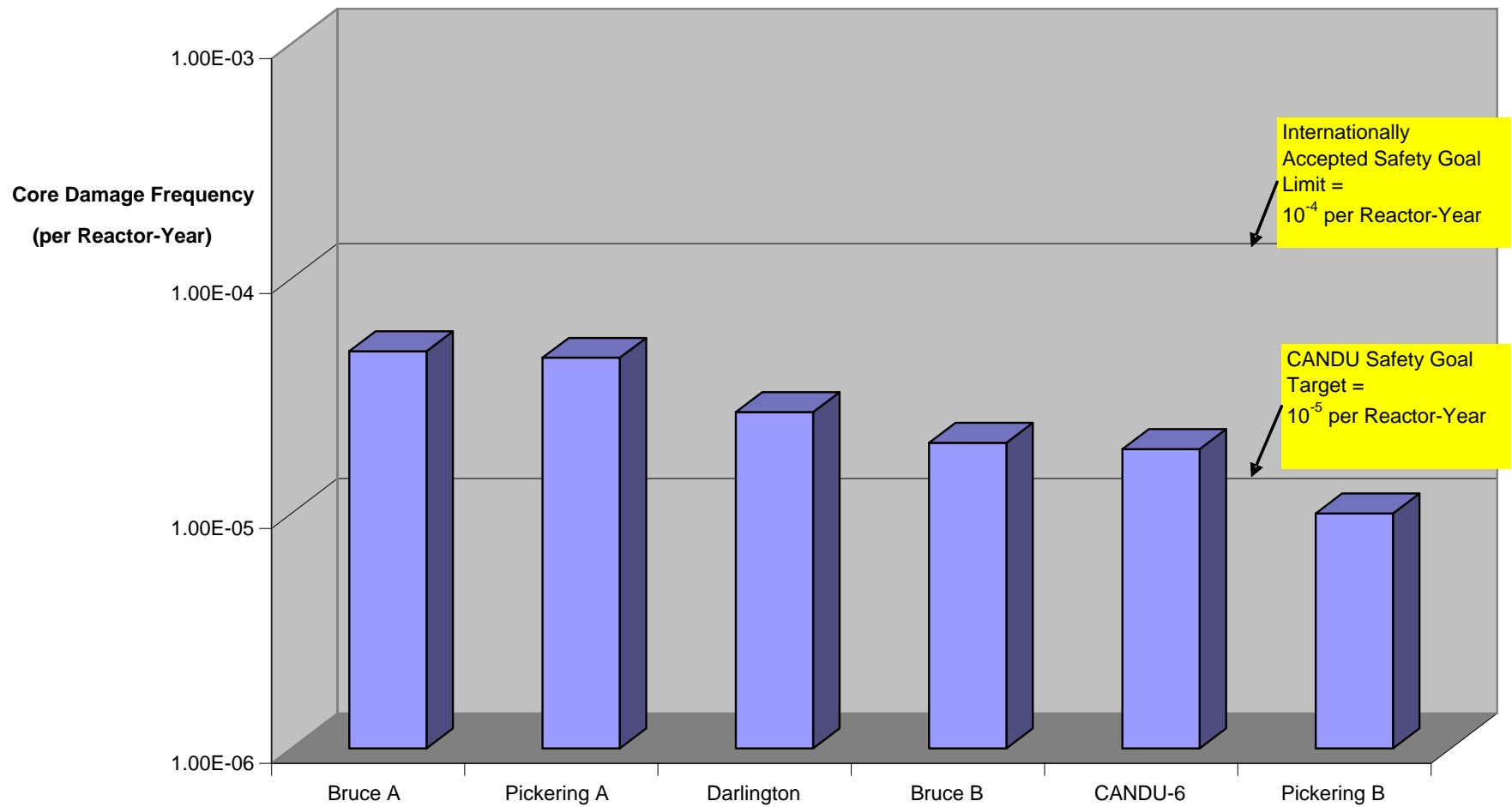
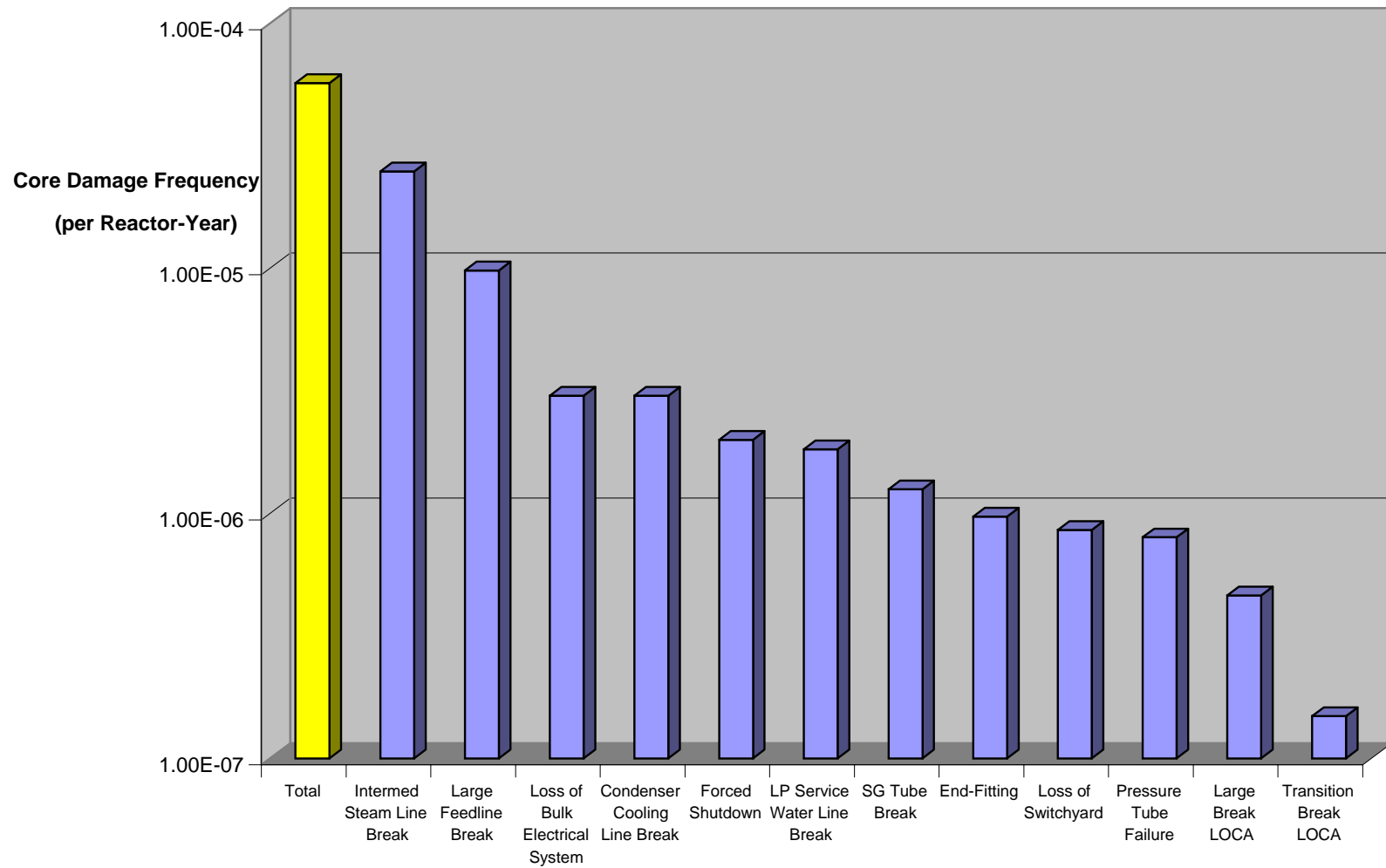


FIGURE 2: Bruce B Core Damage Frequency (at Power)



11.

**FIGURE 3 - CANDU-6 Large LOCA Reference Case
Non-Dimensional Peak Fuel Enthalpy versus Peak Reactivity**

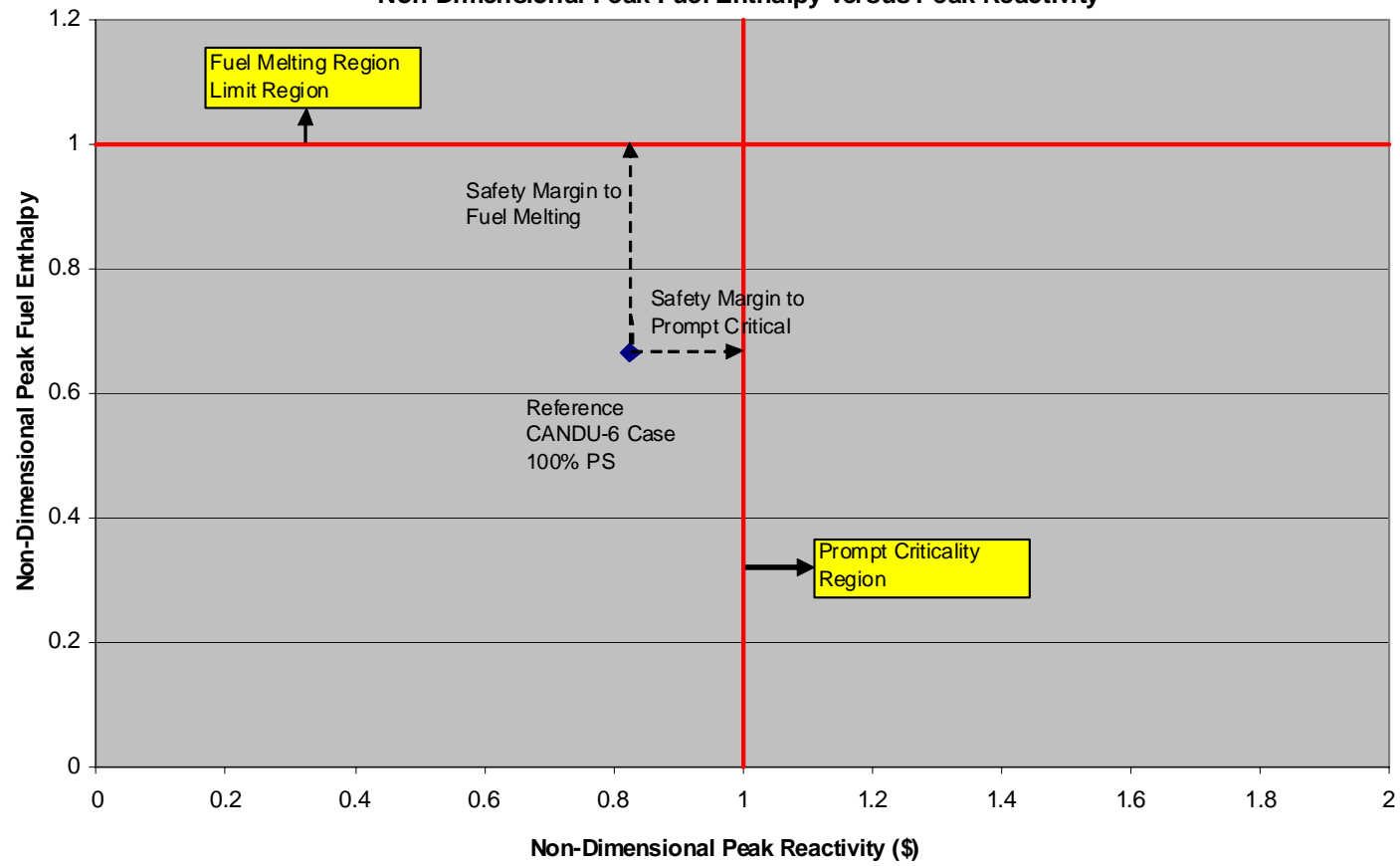


FIGURE 4 - Reactivity Limit For CANDU Versus LWR Adjusted For Effect of Neutron Lifetime

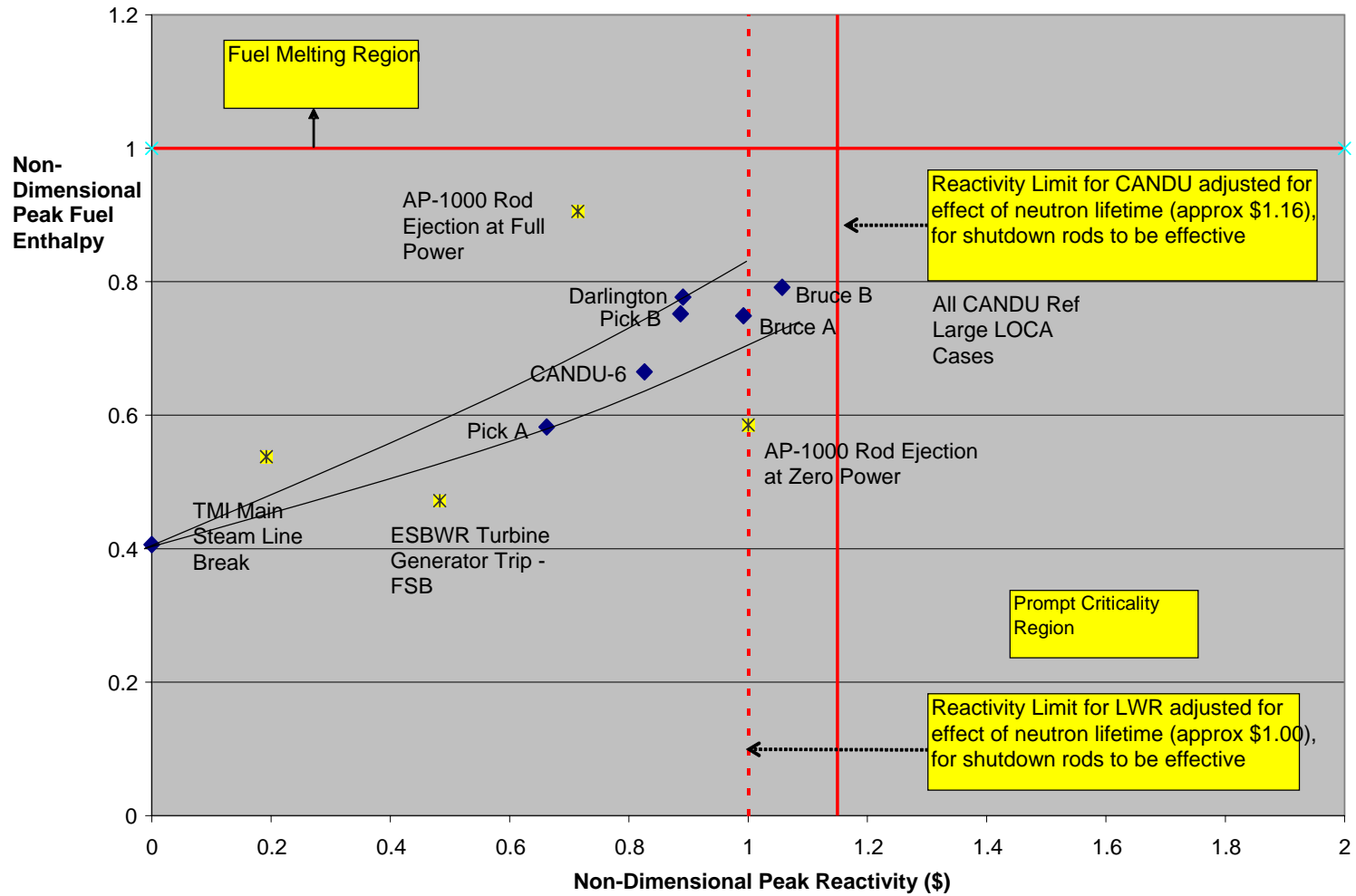
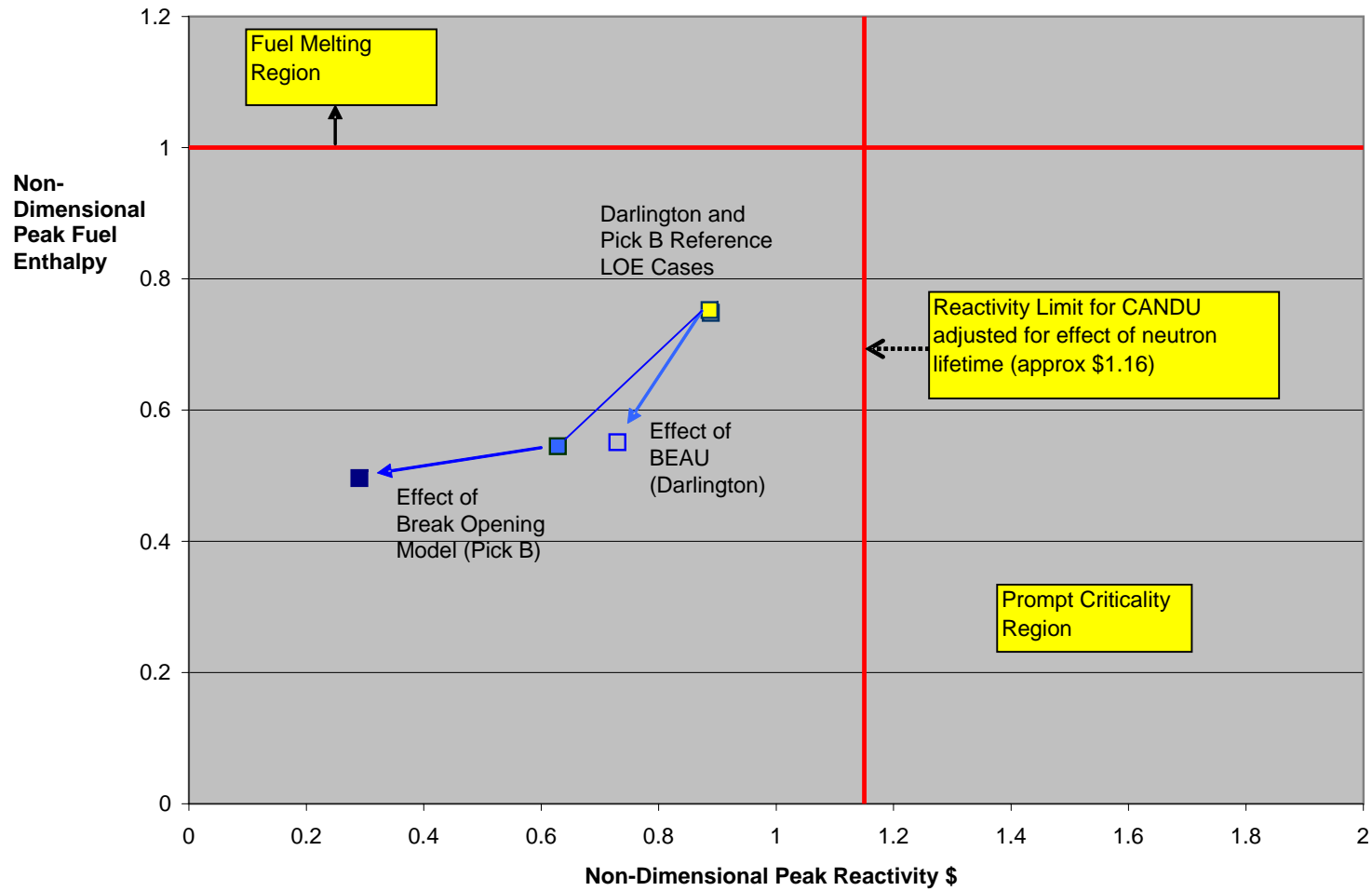


FIGURE 5: Comparison of Methodology/Modelling Improvements on Non-Dimensional Peak Fuel Enthalpy versus Peak Reactivity



**FIGURE 6: Effect of CANDU-6 Design Changes For 60% PS and 100% RIH Base Cases
Non-Dimensional Peak Fuel Enthalpy versus Peak Reactivity**

