SAFETY ANALYSIS METHODOLOGY WITH ASSESSMENT OF THE IMPACT OF THE PREDICTION ERRORS OF RELEVANT PARAMETERS

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Abstract

The best estimate plus uncertainty approach (BEAU) requires the use of extensive resources and therefore it is usually applied for cases in which the available safety margin obtained with a conservative methodology can be questioned.

Outside the BEAU methodology, there is not a clear approach on how to deal with the issue of considering the uncertainties resulting from prediction errors in the safety analyses performed for licensing submissions. However, the regulatory document RD-310 mentions that *the analysis method shall account for uncertainties in the analysis data and models.*

A possible approach is presented, that is simple and reasonable, representing just the author's views, to take into account the impact of prediction errors and other uncertainties when performing safety analysis in line with regulatory requirements. The approach proposes taking into account the prediction error of relevant parameters.

Relevant parameters would be those plant parameters that are surveyed and are used to initiate the action of a mitigating system or those that are representative of the most challenging phenomena for the integrity of a fission barrier.

Examples of the application of the methodology are presented involving a comparison between the results with the new approach and a best estimate calculation during the blowdown phase for two small breaks in a generic CANDU 6 station. The calculations are performed with the CATHENA computer code.

1. Introduction

Currently, the most common approach to perform safety analyses is to utilize, instead of a conservative code, a 'best estimate' computer code with conservative assumptions.

A safety analysis methodology that is gaining acceptance in the nuclear industry and regulators around the world is what is called the Best Estimate Plus/And Uncertainty (BEPU) or (BEAU). In this approach uncertainties are propagated either in the code inputs or are taken into account somehow in the code outputs [1].

However, the BEAU approach requires the use of extensive resources and therefore it is usually applied for cases in which the available safety margin obtained with a conservative methodology can be questioned.

Outside the BEAU methodology, there is not a clear guideline on how to deal with the issue of considering uncertainties, coming from prediction errors, in the safety analyses performed for licensing submissions. However, the regulatory document RD-310 [2], among other requirements, mentions that *the analysis method shall account for uncertainties in the analysis data and models.*

The work presented here intends to provide a possible approach, representing the author's view, which is believed to be simple and logical, to take into account the impact of prediction errors and other uncertainties when performing safety analysis in line with regulatory requirements.

2. Prediction Errors and Code Accuracy

The following definition of prediction error is provided:

A discrepancy between a computed value and the true, specified, or theoretically correct value including that resulting from human actions.

The prediction error is quantitatively characterized by the code accuracy and should be defined for each parameter of interest during the code validation tasks.

Code accuracy: *The bias and standard deviation of a computer code that are derived from the comparison of code predictions with experimental data.*

CODE ACCURACY: BIAS + VARIABILITY OF THE BIAS

where:

$$\text{BIAS} = \overline{X} = \sum_{1}^{N} \varepsilon_i / N = \sum_{1}^{N} (P_i - D_i) / N \qquad (1.2\text{-}1)$$

$\varepsilon_i = (P_i - D_i)$ is the difference between the code prediction P_i and the measured data D_i. The bias, or systematic error, is the average of the difference between the predicted and the measured values[1]. In the above expression the average is taken over N comparisons between the code prediction and the experimental data.

The variability of the BIAS[2] (or standard deviation) is defined as:

$$\sigma = \sqrt{\sum_{1}^{N} (\varepsilon_i - \overline{X})^2 / (N-1)} \qquad (1.2\text{-}2)$$

[1] A more rigorous definition would be to use the "true" value instead of the measured values, but the true values are unknown.

[2] By using the measured value instead of the "true" value (see previous footnote) expression (1.2-2) is, in fact, the standard deviation of the residuals. The resulting expressions (1.2-1) and (1.2-2) have embedded the uncertainty in the measurements. However, these altered definitions should not have a significant impact on the thoughts presented here.

Both the bias, in case it is non conservative, and the standard deviation should always be considered when performing safety analysis that takes into account modeling or plant parameters uncertainties. The uncertainties should be considered in a way that renders the results to be more pessimistic.

2.1 Proposed Approach to Include Allowances for the Uncertainties Resulting from a Computer Code Prediction Errors

One of the main purposes of any safety analysis is to demonstrate that the action of the mitigating systems can avoid a serious challenge to the barriers that prevent the release of fission products to the environment.

Based on the above it should be logical to consider uncertainties in the prediction of the parameters that can affect the actuation of a mitigating system or the phenomena that can have a significant impact in the integrity of a fission barrier. We call them relevant parameters.

Thus, relevant parameters would be those that are either monitored at the plant and are used to start the action of a mitigating system and/or can have a significant impact in the phenomena that challenge the integrity of a barrier preveting the release of fission products.

For instance, during the early stages of a postulated event the prediction of the margin between the occurrence of the trip and the occurrence of fuel dry out entails the prediction of a certain value for a given process parameter that trips the reactor and the prediction of heat transfer to the coolant and sheath dry-out. The latter are relevant parameters for the prediction of dry-out

Therefore uncertainty allowances should be applied such that the reactor trip is delayed and the occurrence of dry out is advanced in time. To achieve the first, a value that takes into account the code accuracy to predict the parameter credited to trip the reactor should be considered with the objective of delaying the action of the mitigating system.

The dry out prediction can be affected by more than one modeling parameter and therefore it will require some engineering judgment. The prediction of dry-out can be affected by uncertainties in the coolant flow, channel voiding, heat transfer to the coolant, etc. An example on how to proceed is provided later.

Therefore the relevant parameters in this case would be the one that is credited to trip the reactor and the ones that can anticipate the prediction of sheath dry-out.

The same approach should be applied to other stages of a postulated event in which uncertainty allowances are required to assess other mitigating systems or where other physical barriers could be challenged.

For instance after reactor trip, during a loss of coolant accident, ECC injection is required to avoid fuel failure. Hence, uncertainty allowances should be included to delay the initiation of the ECC and for the parameters that are important for the prediction of the phenomenon that imposes the most serious challenge to the integrity of the fuel channels.

The consideration of uncertainty allowances for the relevant parameters for each stage of the accident is logical and is a relatively simple process. It would also provide the required degree of confidence in the predicted safety margins.

The suggested approach is called methodology with Assessment of the impact of the Prediction Errors of Relevant Parameters or, for short, APERP methodology.

2.1.1 Uncertainty Allowances for the Actuation of Mitigating Systems

If the validation task indicates that the code predicts a parameter that is used in the plant to trigger the action of a mitigating system with a given accuracy, then the analysis set point to predict the action of a mitigating system based on a value of that parameter should be:

ANALYSIS SET POINT = NOMINAL SET POINT ± (IU + CA) (2.1.1-1)

IU = Instrumentation uncertainty = BIAS + 1.645*STANDARD DEVIATION (2.1.1-2)
CA = Code Accuracy = BIAS + 1.645*STANDARD DEVIATION[3] (2.1.1-3)

The uncertainty in the instrumentation should be available from the plant Instrument and Control documentation. The bias in the instrument uncertainty is reduced by calibration of the measuring instrument and the bias in the simulation uncertainty should be reduced by optimizing the models embedded in the code. Both are expected to be small. In the above expression the bracket should be preceded by the sign that delays the actuation of the mitigating system.

2.1.2 Uncertainty Allowances for Assessing a Fission Barrier

When assessing the integrity of barriers to the release of fission products, the best estimate value of the parameters that are most critical for the integrity of the particular barrier should be modified by a factor that takes into account the code accuracy for those parameters.

Modeling Parameter Analysis Value = (Model Parameter BE Value)*code accuracy (2.1.2-1)

The bias should be considered only if it makes the results more conservative. Again, the bias is expected to be small and the standard deviation should be multiplied by 1.645. The code accuracy should be obtained from the validation task that was performed to assess the ability to predict that particular phenomenon with the computational tool. Usually for those parameters the code accuracy is expected to be determined from validation of separate effect tests.

3. Examples of Application of the APERP Methodology

This section presents examples on how the views expressed in the previous sections can be put into practice. No licensing implication is meant for the analysis results presented here.
The calculations involved small break simulations in a generic CANDU reactor. The calculations are performed with the CATHENA computer code [3] to [5]. The CATHENA plant model used

[3] The assumption is made that the simulation error follows a normal distribution. The reason to multiply the standard deviation times 1.645 is to have a 95% confidence interval.

in these simulations represents the beginning of the plant life. The calculations consist of different simulations of two breaks of different sizes, 2.5 and 5.0%, in reactor inlet header 2, which is one of the two inlet headers opposite to the pressurizer.

For each break size, two types of simulations are performed. One simulation is performed with the best estimate (BE) methodology and the other following the APERP methodology. The results obtained with the proposed approach are compared with those obtained with the BE simulations.

To demonstrate that the methodology is conservative the results should show that by introducing uncertainties the time of the trip is delayed and the time of the dry-out is anticipated in reference to a BE calculation.

The chosen values of the modeling uncertainties are arbitrary because the accuracy of the CATHENA code for the prediction of those parameters and phenomena is not available. This limitation is not considered important as the purpose of the work documented here is to provide an example on how to deal with the issue of including uncertainties in the calculations. At the same time, the arbitrary values of the prediction errors do not permit to extract any licensing conclusion from these calculations.

For consistency with what is mentioned in section 2.1, in each case what is examined is the time of the trip and the time of dry-out. The time of dry-out is taken as the time when the ratio between the wall temperature at critical heat flux conditions and the wall temperature of the fuel elements (T_{CHF}/T_{WALL} ratio) becomes 1.

In the examples presented here, and for simplicity, the T_{CHF} and T_{WALL} values are those that correspond to one of the fuel channel groups in which a core pass is represented in the plant model. A more rigorous approach would require obtaining those values from a single channel calculation.

For these particular simulations "relevant" parameters are considered to be the pressure in the primary heat transport system (PHTS), the pressurizer level, the critical heat flux (CHF) value and the nucleate boiling heat transfer to the coolant.

For the sake of simplicity we have chosen to use some engineering judgment to define the relevant parameters. However, a more rigorous approach can be followed by creating a Phenomena Key Parameter Identification and Ranking Table (PKPIRT) process [6]. This will ensure that the most critical parameters and phenomena for each stage of the accident are included. However, to keep the simplicity of the approach no more than two modeling parameters and the plant parameter used to start the action of the mitigating system is recommended to consider for each stage.

The prediction and measurement errors of the pressurizer liquid level and the outlet header pressure are taken into account by modifying the nominal set points at which the reactor would trip.

For the pressurizer liquid level the assumed total uncertainty is 1.45m. This results in an analysis set-point for the low pressurizer level trip signal of 5.81m, as the nominal set-point for the trip is 7.26m. For the low HT pressure trip the assumed uncertainty is 600kPa. The nominal set-point for the low pressure trip is 8.8MPa(a), and this results in an analysis set-point of 8.2MPa(a).

For the CHF and the nucleate boiling heat transfer calculations the assumed uncertainty is 10%. This represents the CATHENA prediction error of these phenomena. These are introduced in the code by using a correction factor of 0.90 in the correlations that are used for the calculations of these phenomena. All the values are arbitrary. It is assumed that the uncertainty values include the bias and the random uncertainty (see Sections 2.1.1 and 2.1.2).

4. Results

For the initial conditions before the beginning of the transient calculations the nominal thermal full power (FP) assumed value is 2056MW. To this value is added a 3% measurement uncertainty which results in a total power from the fuel to the coolant of 2118MW. The initial conditions are obtained by running a steady state calculation. The same initial conditions are used for the two break cases and the calculations with the BE and the APERP methodologies. The results are listed in Table 1. The initial temperature in inlet header 2 has deliberately incorporated a 3°C measurement uncertainty as the inlet header temperature for the beginning of plant life is about 263°C.

4.1 Transient Calculations Results

The transient calculations were performed by assuming the break instant opening after 2s of the end of the steady state. The calculations proceeded without reducing the power once the trip signal was announced. This was done in order to determine the time of dry-out. The comparison of the transient calculations with both methodologies, for each break, size is provided in Table 2.

For the 2.5% RIHB case, the comparison between the BE and the APERP results indicate that the uncertainty allowances in the relevant plant parameters delay the trip signal by roughly 27 and 17s in, respectively, the low PHTS pressure and low pressurizer level trip. The uncertainty allowances in the modelling parameters advance the time of dry-out by 7s.

For the 5% RIHB case, the comparison between the BE and the APERP results indicate that the uncertainty allowances in the relevant plant parameters delay the trip signal by roughly 10s in both cases. The uncertainty allowances in the modelling parameters advance the time of dry-out by 13s.

Figure 1 and Figure 2 show respectively the OH1 pressure and pressurizer liquid level transients for the 2.5% RIH break and the respective analysis set-points values used in the calculations. Figure 3 and Figure 4 present the same results for the 5% RIH break.

The results presented in the figures show that the OH1 pressure and the pressurizer liquid level transient are not affected by the modelling uncertainties. Thus, the differences in the trip times listed in Table 2 are a consequence of the different analysis set-points used in the calculations.

Figure 5 presents the T_{CHF}/T_{WALL} ratio for the 2.5% RIHB and Figure 6 presents the same results for the 5% RIHB with both methodologies. Dry-out occurs when the T_{CHF}/T_{WALL} ratio crosses the horizontal line.

These results indicate that with the approach followed one could obtain a conservative calculation in which uncertainties had been taken into account. This would make the methodology consistent with RD-310 requirements.

5. Conclusions

This paper presented a possible approach that is simple and reasonable to take into account the impact of prediction errors and other uncertainties when performing conservative safety analysis for design basis accidents. The methodology is named Safety Analysis Methodology with Assessment of the impact of the Prediction Errors of Relevant Parameters or, for short, APERP methodology.

A couple of examples were presented to show the application of the proposed approach. The examples involved a comparison between the results with the new approach and a best estimate calculation during the blowdown phase for two small break loss of coolant accident simulations in a generic CANDU 6 station. The calculations were performed with the CATHENA computer code.

For these examples both, the code accuracy of the relevant parameters and the measurement uncertainties (errors) of relevant plant parameters, were arbitrarily assumed. Therefore, no licensing implications should be extracted from the results.

These results indicate that with the approach followed one could obtain a conservative calculation in which uncertainties had been taken into account. This would make the methodology consistent with RD-310 requirements.

Table 1 – Relevant Plant Parameters Initial Values

IH2 Temperature (°C)	OH1 Pressure (MPa(a))	Pressurizer liquid level (m)
266	9.99	11.1

Table 2 - CATHENA Simulation Results

CASE	Time of Low Pressure Trip (s)	Time of Low Level Pressurizer Trip (s)	Time of Dry-Out (s)
2.5% RIHB			
B.E.	45.43	49.18	146.4
APERP	72.97	66.31	139.4
5% RIHB			
B.E.	18.53	33.02	57.0
APERP	28.4	43.23	44.0

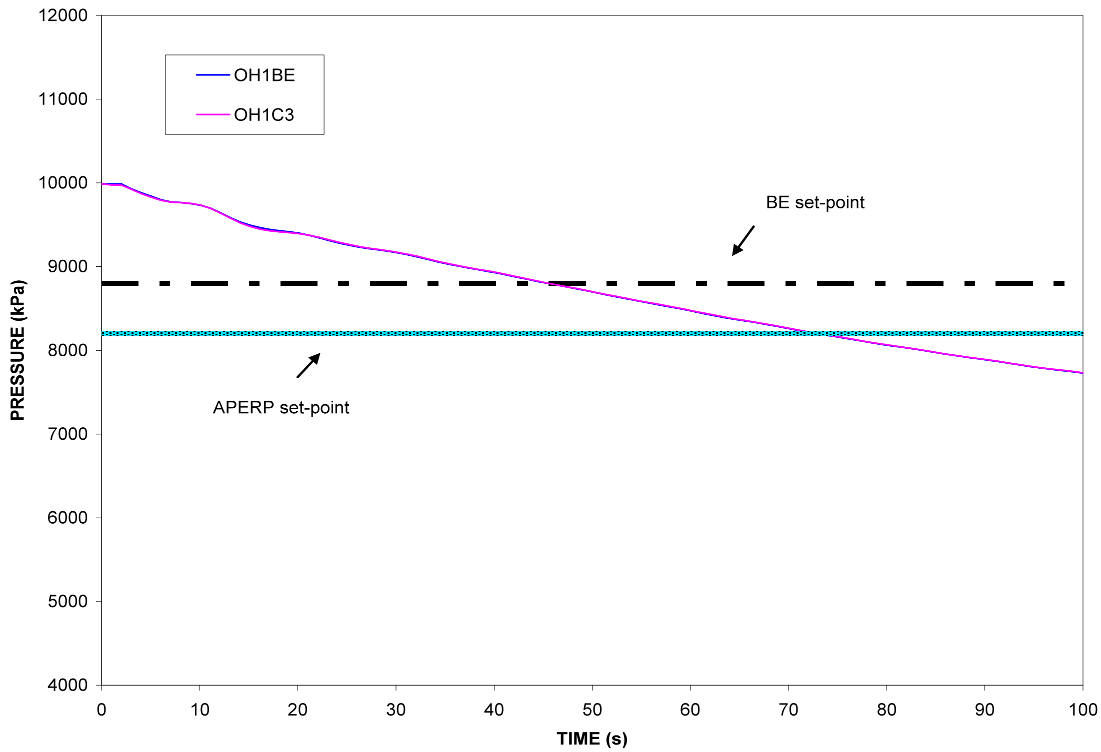

Figure 1 - 2.5% RIHB - OH1 pressure transient

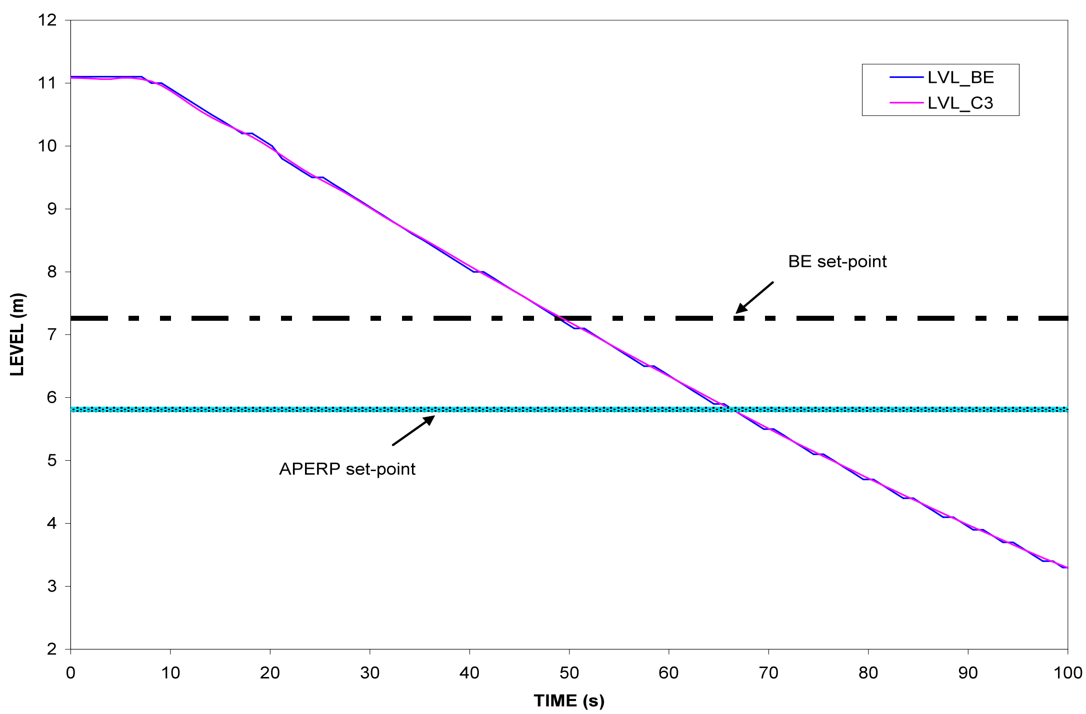

Figure 2 - 2.5% RIHB - Pressurizer liquid level transient

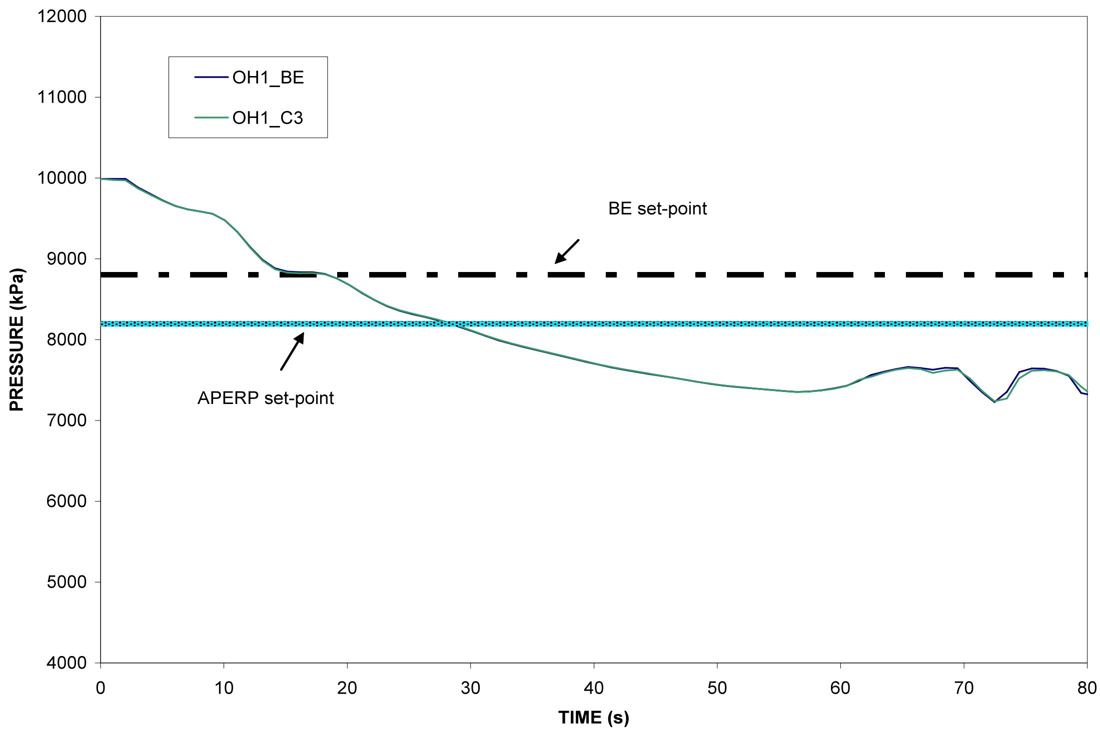

Figure 3 - 5% RIHB - OH1 pressure transient

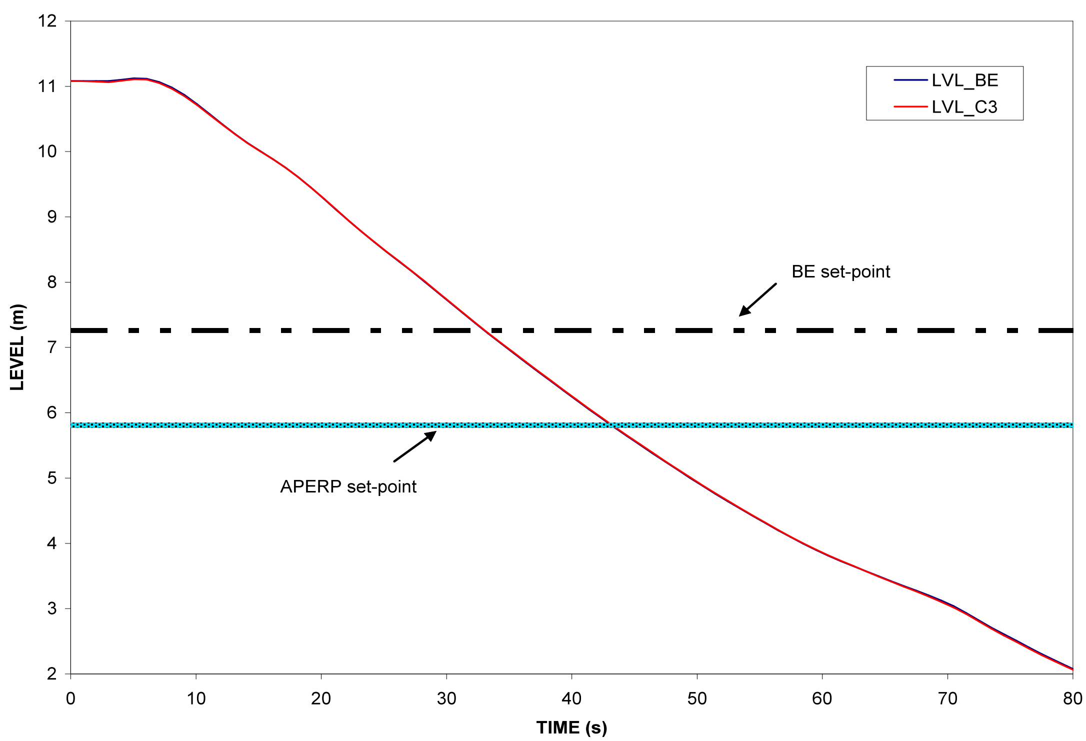

Figure 4 - 5% RIHB - Pressurizer liquid level transient

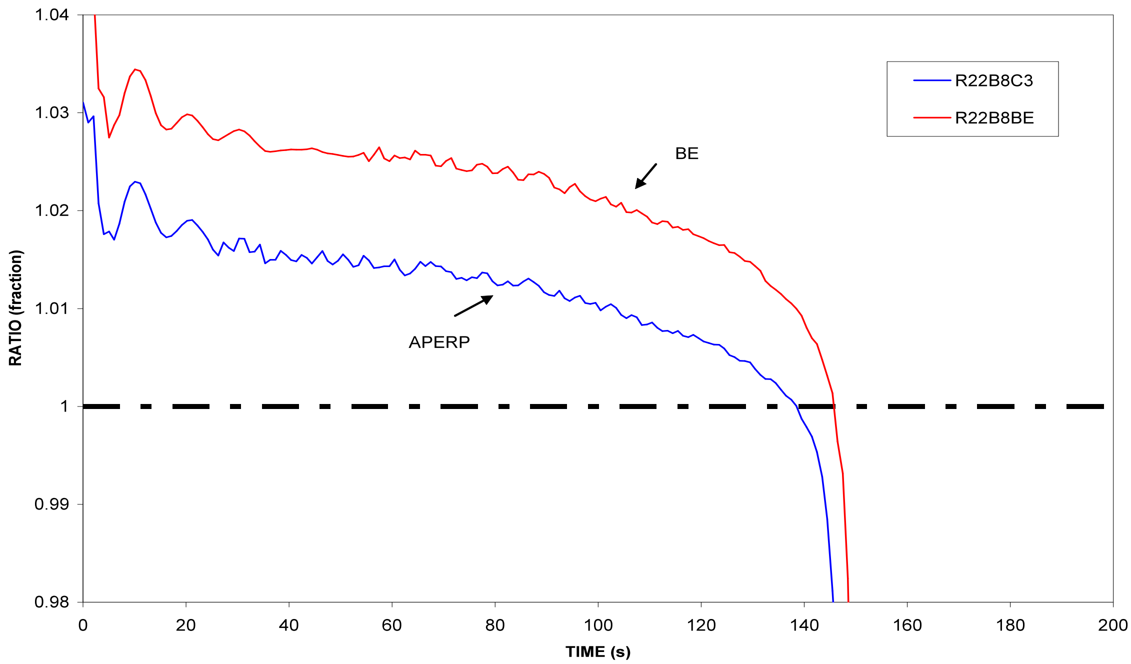

Figure 5 - T_{CHF}/T_{WALL} Ratio - 2.5% RIH Break

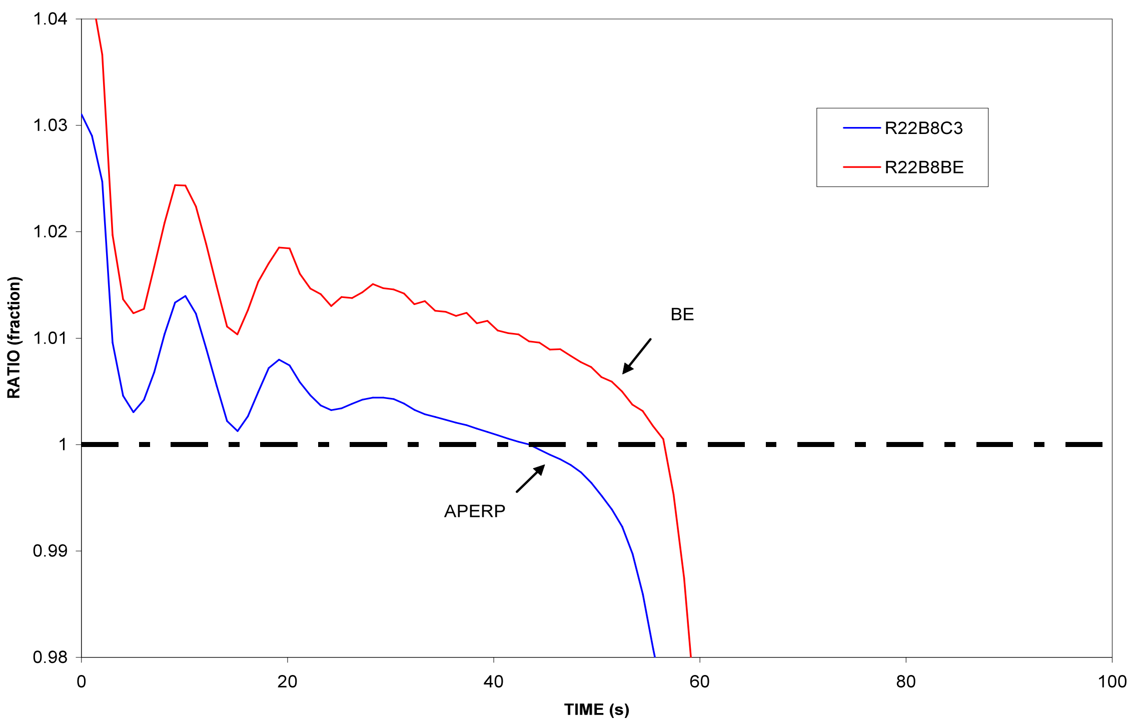

Figure 6 - T_{CHF}/T_{WALL} Ratio - 5% RIH Break

6. References

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