

A STATISTICAL ASSESSMENT OF CANDU FUEL MANUFACTURING PARAMETERS AND THEIR IMPACT ON IN-REACTOR PERFORMANCE DURING TRANSIENT CONDITIONS

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ABSTRACT – Probability distributions are fitted to actual fuel manufacturing datasets provided by Cameco Fuel Manufacturing, Inc. They are used to generate input for ELOCA, an industry-standard fuel performance modeling code that predicts fuel element behaviour under transient conditions. The chosen accident for this study is a hypothesized 80% Reactor Outlet Header break LBLOCA. 10^5 simulations are conducted, and it is shown that the distributions of key output quantities are well below the limit values established by industrial acceptance criteria, implying the existence of margin in the current design. The results of this probabilistic study are then compared with those of a deterministic case, and the contrast between the two methods is quantified.

Introduction

Given the constantly evolving nuclear power industry in Canada and elsewhere, improving the utilization of nuclear fuel and simultaneously ensuring its safe operation is of paramount importance to the realization of cost-effective, robust, and efficient nuclear power plants. Fuel failures invariably result in fission product release into the coolant, and consequently have a significant operational impact on the station. It is therefore prudent that all areas of nuclear fuel performance are clearly evaluated and understood. One such area, which is the focus of this work, is fuel reliability. Quantifying normal variances in fuel manufacturing parameters and processes, and analyzing the follow-on effects of these variances in terms of in-reactor performance, allows for greater fidelity in fuel design and safety analysis.

This study involves the analysis of real manufacturing datasets, using a proven simulation tool, in order to demonstrate that fuel performance margins exist. Using this methodology, it is then possible to make a realistic prediction regarding the probability of unsatisfactory fuel performance through the examination of multiple failure mechanisms – something that has not yet been quantified in the CANDU industry. The intent is to afford valuable information to industry professionals during the development of design criteria and/or the conduct of safety analyses.

This approach has previously been utilized to quantify fuel performance margins for a fuel element under Normal Operating Conditions (NOC) [1]. The results of that study show that, using the industry-standard modeling code ELESTRES, no fuel failures are predicted in 10^5 trials, and the probability of the limit values being exceeded is less than 10^{-30} . This paper presents an expansion on that work to investigate fuel element performance in response to one particular design based accident – a Large Break Loss of Coolant Accident (LBLOCA) based on an 80% Reactor Outlet Header (ROH) break.

1. Background

Cameco Corporation, a CANDU fuel manufacturer in Canada, has provided relevant datasets that describe the behaviour of current manufacturing processes. Through statistical analysis, appropriate probability distributions for important CANDU fuel manufacturing parameters are established. These distributions are then randomly sampled and the resultant input vectors are submitted to two industry-standard fuel performance modeling codes. This paper discusses the simulation results for the second of these codes, ELOCA, which models the thermo-mechanical response of a CANDU fuel element during transient (accident-type) conditions [2]. The code output is then statistically analyzed to establish reliability. This allows for fuel performance predictions to be based on many years of real data as opposed to selected limit values.

1.1 Fuel Performance

Fuel performance has been a highly recognized strength of CANDU reactors, with less than 0.1 percent of fuel bundles containing or developing defects [3]. This low defect rate is a result of element and bundle designs that meet or exceed all regulatory and operational requirements, and manufacturing processes that produce fuel well within those design specifications.

In contrast with other reactor types, one unique advantage of the CANDU design is that on-power refueling is possible. Hence, most defects are discovered by operators before they are large enough to pose a serious concern and therefore the defective bundle can be removed in the normal fashion while the reactor is at power. However, in situations where multiple defects are in the core simultaneously, or when defects are sufficiently large that a critical regulatory limit for the coolant radioactivity could be reached, reactor shutdown is required [3]. Due to the economic and operational consequences of such a scenario, one of the primary goals of any nuclear fuel design or operating procedure is reaching a situation where there are zero defects. As mentioned previously, CANDU fuel technology has come very close to meeting this standard, however defects do still occur and generating stations require mechanisms to both detect and locate them.

It is unlikely that fuel defects will ever be eliminated entirely from CANDU reactors. This will necessitate the continued improvement of detection systems, computer modeling, manufacturing technologies and operating procedures. However, another area for development is fostering a better understanding of the root causes of fuel defects. This study centers upon defining existing fuel performance margins based on current designs and manufacturing capabilities. This will allow for any future endeavours aimed at minimizing defects to be focused in the correct direction.

1.2 Chosen Transient

There are a number of transient states possible in a CANDU reactor, and these must be carefully and thoroughly assessed by the nuclear generating station to ensure employee and public safety. One of the extreme types of accidents postulated for a CANDU reactor is the Large Break Loss of Coolant Accident (LBLOCA), in which coolant flow is significantly reduced due to a significant rupture in the Primary Heat Transport System (PHTS). The coolant rapidly escapes into the containment structure, allowing heat to build up around the fuel bundles and causing them to fail, resulting in the potential for the release of radioactive fission products [4]. In order to mitigate the

possibly drastic consequences of such an accident, CANDU reactors have multiple independent safety systems included in their design, including separate shutdown systems and an emergency core cooling system to deal with the excess heat.

The accident chosen for this study is a hypothesized 80% Reactor Outlet Header (ROH) break, one of the more serious transient states conceived for a CANDU reactor [4]. This scenario involves a rapid depressurization of the coolant coinciding with a spike in temperature and reactor power, which causes a trip to shut down the reactor. The temperature eventually levels out after the safety systems are engaged. This is an important transient for reactor safety analyses, as it results in a very high energy pulse. Although other LBLOCA accident scenarios that result in a higher net energy deposit into the fuel have been hypothesized, ELOCA transient data are not available for those cases at this time. In this study, it is assumed that the emergency core cooling systems are online and completely functional.

1.3 ELOCA (Element Loss of Coolant Analysis)

ELOCA refers to a computer code that models the thermo-mechanical response of a CANDU fuel element during transient (accident-type) conditions [2]. Calculations are performed to account for fuel melting, swelling and cracking, as well as sheath deformation and cracking and changes to the internal gas pressure within the fuel element.

For its input, the ELOCA code requires element history data, normally provided by the NOC code ELESTRES, as well as data describing the transient case to be modeled, including coolant pressure and temperature history. Quantities that are calculated at each time step include the fuel centerline temperature, the true sheath hoop strain, the internal gas pressure, and the number of oxide cracks.

ELOCA uses a one-dimensional model to calculate the temperature distribution of the fuel element, with newer versions of the code allowing the user the option of a two-dimensional model. The two-dimensional model allows for the inclusion of circumferential variations in the fuel temperature [5].

Thermal expansion of the sheathing is modeled using empirical correlations from the MATPRO database [6, 7]. Cases of fuel-to-sheath radial contact and pellet-to-pellet axial contact are considered, and interfacial pressure values are determined. Sheath plastic deformation is examined using a micro-structural model that accounts for grain size, phase changes, re-crystallization and creep [5].

Under transient conditions, sheath failure can occur as a result of high internal pressure within the fuel element or by some form of sheath oxidation, or by a combination of both [2]. ELOCA models a variety of sheath failure mechanisms, including sheath failure due to overstrain from internal gas pressurization, low ductility, beryllium-assisted crack penetration, oxygen embrittlement, overstrain under oxide cracks, high strain rates, and high fuel enthalpy [7].

1.4 Acceptance Criteria

The fuel performance code discussed previously models CANDU reactor operation under transient conditions. The output it provides allows fuel designers to draw valuable conclusions without

having to conduct extensive in-reactor testing, with all its resource and safety implications. The simulated fuel performance calculated by the code is compared to predefined acceptance criteria.

Although the regulator stipulates reactor shutdown limits based on fission product isotope concentrations in the coolant, acceptance criteria are largely station-specific, and are based on a variety of factors. For the purposes of this paper, generic acceptance criteria to quantify acceptable versus unacceptable fuel performance are described. In general, the fuel element is considered intact if the following criteria are met [3, 8]:

1. No UO₂ Melting. The centerline temperature of the fuel element must not exceed the UO₂ melting temperature of 2840°C.
2. No Excessive Strain. The uniform sheath strain of the element must not exceed 5% for sheath temperatures less than 1000°C or 2% for sheath temperatures higher than 1000°C.
3. No Oxygen Embrittlement. The oxygen concentration must not exceed 0.7 weight percent over half of the sheath thickness.

2. Input Generation

Three files are required as input for the ELOCA code. The first specifies some values for internal parameters of the ELOCA code and is supplied with the code package. These values can be changed, however for the purposes of this study the default values are used. The second input file describes the transient to be modeled by the code, including coolant conditions and code execution options. A number of test cases are supplied with the code package, including the 80% ROH break scenario used in this study. The final input file provides the element history data to the code. This file is generated as part of the ELESTRES (NOC) code output. This file was extracted for each case from the NOC study previously conducted [1]. What follows is a description of how the original ELESTRES input files were generated.

2.1 Data Collection

Over the course of several visits to Cameco Fuel Manufacturing, Inc. (CFM), a CANDU Fuel manufacturer in Canada, sufficient data were collected to complete this study. Datasets were assembled from records detailing the most recent three year period. This is deemed appropriate as manufacturing processes have evolved over the years and the study is aimed at assessing *current* industrial conditions.

The majority of datasets can be directly related to the code input parameters. Others are indirectly related, meaning code parameters are determined by their mathematical relationships with values from the datasets. Information pertaining to some parameters was not available, either because the manufacturer did not possess sufficient data at the time of collection, or more commonly, used alternative control procedures to direct parameter measurement, including visual inspection or range gauge testing. For some of these parameters, the manufacturer was able to provide a tolerance range of minimum and maximum values. In these cases, a Normal distribution is assumed to describe the parameters. For other parameters, the manufacturer provided a limit value as specified

in the manufacturing drawing or the fuel specification. Sufficient data have been collected to describe the remainder of the parameters, and probability distributions are fitted to each.

2.2 Distribution Fitting

Using the Probability Paper Plotting method [9], probability distributions are fitted to each parameter. This is done by evaluating the goodness of fit of a number of suspected distributions to the datasets collected at CFM. The results are given in Table 1. As expected, the majority of the parameters are successfully described by the Normal and/or Log-Normal probability distributions, which are commonly associated with manufacturing processes.

Table 1 – Distribution Fitting Summary

Parameter	Data Points	Coefficient of Variation	Chosen Distribution	R²
Pellet Diameter	1920	0.00027	Log-Normal	0.961
Dish Depth	900	0.06973	Log-Normal	0.914
Land Width	897	0.03938	Log-Normal	0.967
Pellet Density	1618	0.00186	Normal	0.992
Sheath Thickness	834	0.00474	Log-Normal	0.973
Helium Fraction of Fill Gas	111	0.02825	Log-Normal	0.977
Pellet Grain Size	362	0.14855	Log-Normal	0.969
Sheath Yield Stress	822	0.05252	Normal	0.998
Weld Displacement	400	0.01904	Weibull	0.978
Sheath Outer Diameter	834	0.00025	Log-Normal	0.935
Sheath Inner Diameter	834	0.00030	Log-Normal	0.976

A limiting factor in this analysis is the quantity of data points included in each dataset. Logically, the more data points available, the more accurate a distribution fitting exercise will be. However, sufficient data were obtained to establish a detailed understanding of how each parameter is behaving, and the corresponding coefficient of determination (R²) values of the linear regression analyses yield a high degree of confidence in the distributions selected.

The Coefficients of Variation (COV) in Table 1 indicate the relative variability of each parameter across its dataset. This is simply the ratio of a parameter's standard deviation to its mean, meaning a lower COV is indicative of a tighter distribution, and therefore a lower degree of randomness. Although no hard rules exist when classifying a parameter as a random versus non-random variable, a parameter with a COV of much less than 1% would be suspect of not being sufficiently random to have an impact on the system across its acceptable range of values. This would imply that parameters such as Sheath Thickness and Pellet Diameter are not varying sufficiently to impact fuel performance. From a design and manufacturing perspective, this is a positive result.

However, other parameters, such as Pellet Grain Size and Dish Depth, show a higher COV and thus a higher degree of randomness. This is not necessarily a cause for concern, as this degree of randomness is often acceptable if the parameter is practically difficult to control and if its impact is assessed to be minimal for a particular tolerance level.

Distributions are selected for each parameter based on the least squares regression analysis methodology [10]. The higher coefficient of determination (R^2) value is the deciding factor. As shown in Table 3, the parameter labeled Weld Displacement is best described by the Weibull distribution. This distribution type is normally used to describe ageing phenomena (such as the degradation of reactor components over time), and therefore intuitively seems like a questionable choice for a manufacturing parameter. However, due to its shape and scale parameters, it is a flexible distribution that can sometimes be used to describe other variables. The Log-Normal distribution is also a good fit for this parameter, and it is likely that if a sufficiently large dataset were obtained, the Log-Normal distribution would prove to be a better fit.

2.3 Monte Carlo Simulation

Many engineering applications involve several random variables with differing distributions. The statistical mechanics involved in such situations quickly become difficult, or even impossible, to solve analytically, making numerical approaches necessary [11]. As the number of variables increases, so too does the number of dimensions of their combined probability distribution.

This can be overcome through the use of simulation. If the distribution of a variable is known, albeit with specified statistical uncertainty, then values for the variable can be generated at random using a computer. If this is done for each variable in a set of random variables, then a possible combination of values for those variables has been randomly generated. If this process is repeated several times, then valuable and accurate knowledge of the combined distribution of the variables can be obtained. This process of simulating random events using a computer is commonly referred to as Monte Carlo Simulation (MCS).

First, random numbers from the uniform distribution on the unit interval (zero to one) are generated using a random number generator. Random values from any distribution can then be constructed using the *Inverse CDF Method* [12]. This is based on the fact that any value from the uniform distribution on the unit interval can be equated to a probability value from any distribution, as the probability also ranges from zero to one. Therefore, the i^{th} value of a random variable x , x_i , can be generated by equating its Cumulative Distribution Function (CDF), $F(x_i)$, to a random number generated from the uniform distribution, u_i :

$$u_i = F(x_i) \quad (1)$$

$$x_i = F^{-1}(u_i) \quad (2)$$

Some distributions have analytical expressions for the inverse CDF, F^{-1} , and others must be solved numerically. This transformation process is shown graphically in Figure 1.

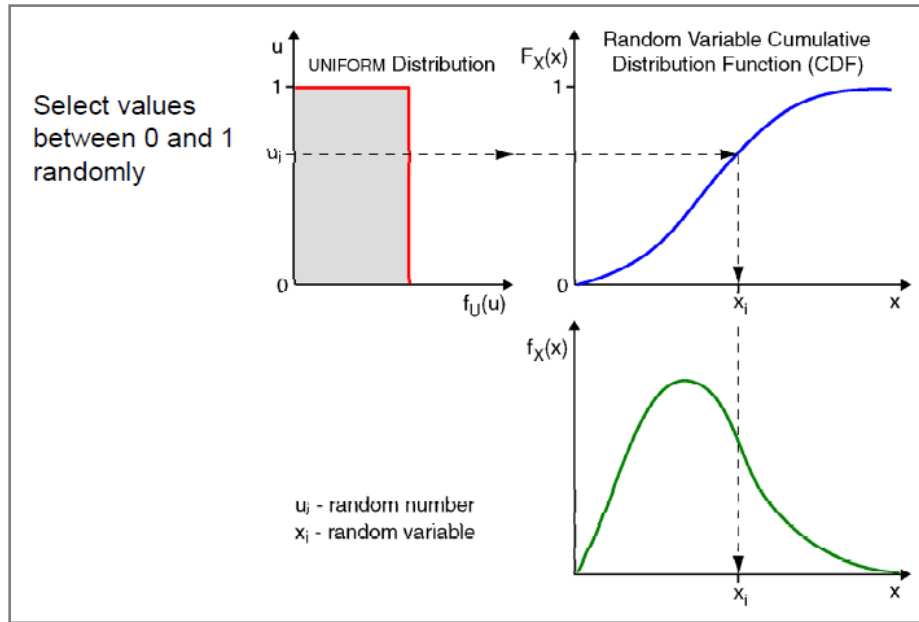


Figure 1 – A Schematic on the Inverse CDF Method (Reproduced with permission from Pandey [12])

This process is repeated for all of the input parameters being studied. 10^5 input vectors are generated and supplied to the ELESTRES code, and the corresponding element history data file for each case is supplied as input to the ELOCA code.

3. ELOCA Simulation Results

The primary outputs examined in this simulation set are fuel centerline temperature and sheath hoop strain. Other, less significant outputs are also examined, but are not included in this paper. The maximum values for each of these variables for each simulation run are read into a spreadsheet and then statistically analyzed. What follows is a detailed analysis of the results for each variable with respect to the acceptance criteria described in Section 1.4.

3.1 Fuel Centerline Temperature

Fuel centerline temperature is assessed for the relative change, if any, when the fuel is exposed to the ROH break LBLOCA. The expectation is that there should be little to no change in the fuel centerline temperature statistics. A significant increase in value indicates a failure to remove excess heat sufficiently quickly. Table 2 shows statistics for fuel centerline temperature from 10^5 ELOCA trials simulating the 80% ROH break.

As with the NOC case, the results indicate that failure due to fuel melting is a very unlikely occurrence, as the failure criterion is 134 standard deviations away. The spread of the data is slightly larger than the NOC case (77 °C versus 53°C), however considering the rapid changes in coolant conditions it is surprising how small the change actually is.

Table 2 – Fuel Centerline Temperature Statistics Obtained Through 10⁵ ELOCA Simulations

Mean	1741.2 °C	Minimum Value	1704.5 °C
Standard Deviation	7.9 °C	Maximum Value	1781.8 °C
Coefficient of Variation	0.00454	Range	77.3 °C
Second Moment	3.0×10^6	Number of σ from Failure	134

The resultant maximum fuel centerline temperature statistics obtained from 10⁵ ELOCA trials are found to be best represented by the Log-Normal distribution, with an R^2 value of 0.9999. This distribution and a histogram of the output data is given in Figure 2. From this distribution, the probability of the centerline temperature exceeding 2840 °C is found to be less than 10⁻³⁰. This indicates the presence of design margin when considering realistic manufacturing parametric values and a simulation of the given LBLOCA.

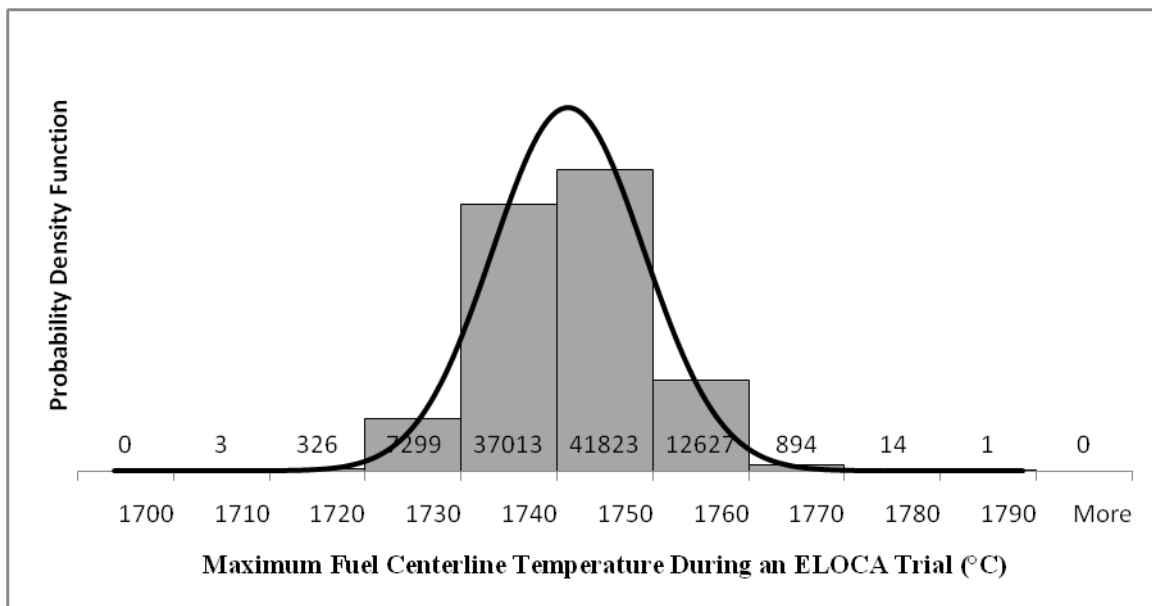


Figure 2 – Distribution of ELOCA Output – Fuel Centerline Temperature (°C)

3.2 Sheath Hoop Strain

The maximum true sheath hoop strain is evaluated to determine the likelihood of exceeding the failure criterion for “no excessive strain.” For the NOC case, the sheath temperature remains sufficiently low that the 5% criterion can be used for determining whether an element has failed due to sheath overstrain. However, during the transient case this limit value cannot be used. During the transient, the coolant temperature increases to nearly 1200 °C, meaning that the appropriate limit value is actually 2% sheath strain.

Table 3 outlines the sheath hoop strain statistics observed. The maximum value through all trials is slightly higher than the NOC case (1.398% versus 1.350%), which is 9 standard deviations from the 2% limit value. A larger spread in the data can be noted, evidence of the magnified output variation the transient conditions cause.

Table 3 – Sheath Hoop Strain Statistics Obtained Through 10⁵ ELOCA Simulations

Mean	1.081%	Minimum Value	0.438%
Standard Deviation	0.067%	Maximum Value	1.398%
Coefficient of Variation	0.062	Range	0.961%
Second Moment	1.173	Number of σ from Failure	9

The maximum sheath strain data are found to best agree with the Normal distribution, with an R^2 value of 0.9851. This distribution is illustrated in Figure 3. Using this distribution, the probability of exceeding the 2% sheath strain limit criterion is less than 10^{-30} , again implying the presence of margin. For the manufacturer, this helps to confirm that the fuel currently being produced is controlled sufficiently to negate the possibility of any normal perturbations in manufacturing processes contributing to a fuel failure during one of the design-based accidents.

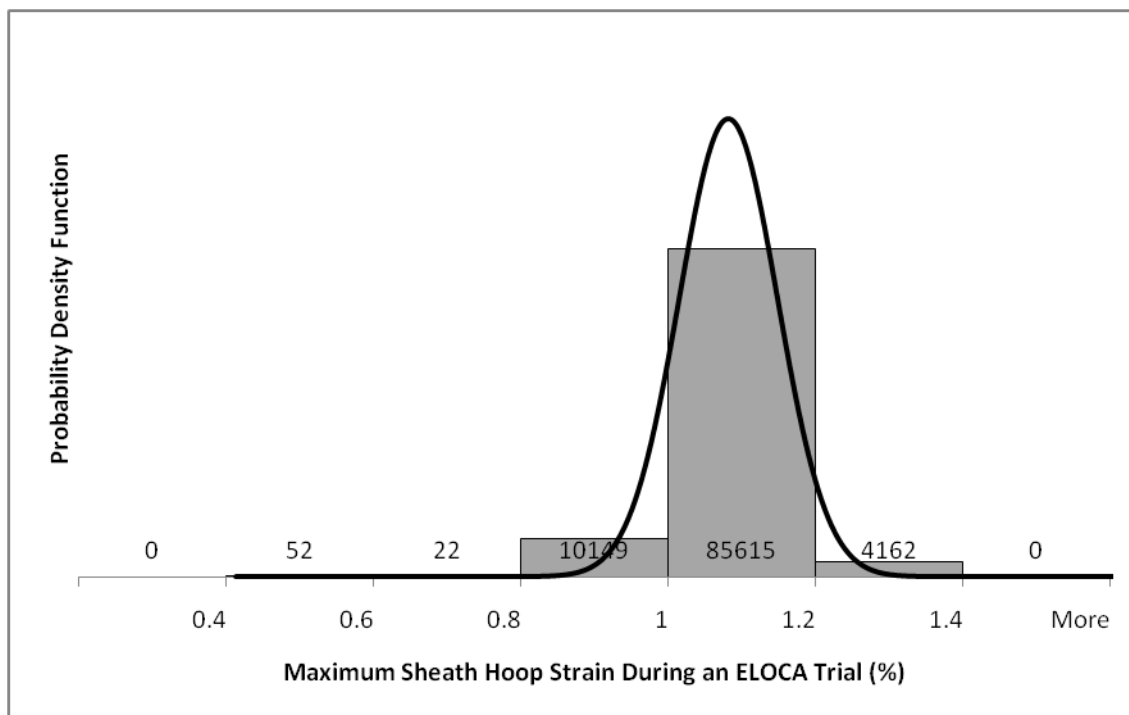


Figure 3 – Distribution of ELOCA Output – True Sheath Hoop Strain (%)

3.3 Oxygen Embrittlement and Oxide Cracks

Two oxygen-related failure mechanisms are examined. The first, oxygen embrittlement, occurs primarily upon rewet following a LOCA. If the dissolved oxygen concentration in the sheath

exceeds 0.7 percent by weight, its ductility is likely to be sufficiently affected such that it may not remain intact upon rewet [3, 7, 13]. ELOCA assumes that the oxygen concentration in the sheath during a transient is determined via zirconium oxidation on the outside surface, followed by oxygen diffusion from that oxide layer into the α and β zirconium layers. The 0.7% criterion is assessed at the sheath mid-plane through the solving of diffusion equations and with knowledge of oxide layer thickness from a proven model [7]. In 10^5 ELOCA trials, there are no instances of failure by this mechanism, and there are insufficient data available in the code output to draw any meaningful conclusions with regards to the impact of manufacturing parametric values on dissolved oxygen concentration in the sheath.

The second oxygen-related phenomenon is failure due to oxide cracks. An oxide layer forms on the outside surface of the sheath. This layer is brittle, and cracks can form at strains lower than the 2% limit assessed for Zircaloy. The growth of these cracks can reduce the local sheath thickness and result in higher than normal localized sheath strains, potentially resulting in element failure [7]. A one-dimensional crack formation and propagation model is utilized by ELOCA to assess the number and size of oxide cracks. Again, in 10^5 trials, zero oxide cracks are formed, meaning no conclusions can be drawn, other than the fact that normal element manufacturing variances appear to have no impact on oxide crack formation while under the transient evaluated.

4. Limit of Operating Envelope (LOE) Benchmark

The conditions described in the Monte Carlo Simulation (MCS) exercise above are deemed to be a realistic representation of currently manufactured fuel elements, as the full range of potential input values are deduced directly from manufacturing data. Due to time and resource constraints, as well as the requirement for the nuclear industry to remain conservative in its estimation of such conditions, this type of approach is not taken in industry. The LOE approach is instead adopted, where all manufacturing parameters are assumed to be at their respective limit values. This creates a “worst-case” estimation for input conditions, and the resultant model output values are then assumed to be the worst possible prediction of in-reactor fuel performance. To determine how the MCS study compares to a traditional LOE approach, a benchmark case is constructed.

With LOE data unavailable, input parameters are given maximum or minimum values according to the conditions that would most likely promote fuel failure. For each parameter, if a limit value is not given by the manufacturer, a reasonable value at the appropriate edge of the parameter’s dataset is selected. These values are used to create an input file for the code package, and the case is simulated.

The benchmark case is subjected to a postulated 80% ROH break LBLOCA transient, with identical transient data to those utilized during the MCS study. The results are given in Table 4, along with the mean and maximum cases observed during MCS. The same ELOCA output quantities are examined as those presented for the MCS exercise. Mean and maximum values obtained from MCS are also given for comparison.

The data in Table 4 show that the benchmark case produces more severe output conditions than a typical case, as the values of both output quantities are greater than the mean values obtained

through MCS. They are also significantly greater than the maximum values obtained through 10^5 MCS trials, revealing the disparity that exists between the two methods.

Table 4 – A Comparison of ELOCA Results for the LOE Benchmark Case and the MCS Study

Output Quantity	Benchmark Maximum	MCS Mean Value	MCS Maximum
Maximum Fuel Centerline Temperature (°C)	1848.9	1741.2	1781.8
Maximum Sheath Hoop Strain (%)	2.168	1.081	1.398

Interestingly, the benchmark case produces a value for fuel centerline temperature that is nearly 70 °C larger than the MCS maximum. This can be largely attributed to the fact that the density of the fuel pellet is minimized, greatly reducing its thermal conductivity. The value obtained of 1848.9 °C is still 125 standard deviations from failure when compared with the MCS transient output distribution, however this large discrepancy between the two methods illustrates the benefit of utilizing more realistic estimates for the values of manufacturing parameters, particularly pellet density.

The maximum sheath hoop strain observed during the transient for the benchmark case is 2.168%, which is substantially greater than the mean value obtained via MCS of 1.081% as well as the maximum MCS value of 1.398%. In addition, considering the high temperature conditions of the transient, this value appears to exceed the acceptance criterion for sheath strain. When examining the output file, it is noted that the 2% criterion is exceeded for roughly 12 seconds near the end of the transient. The maximum sheath temperature during that 12 second period is 962.9 °C, meaning that the 5% criterion for low temperature conditions still applies, with failure being 42 standard deviations removed. Although this confirms that failure does not occur, the fact that sheath strains above 2% are observed exemplifies the sometimes grave predictions that come with deterministic safety analysis.

5. Conclusions

The MCS exercise presented in this paper makes use of the ELOCA code to offer insight into how current, as-manufactured CANDU fuel reacts to a hypothesized LBLOCA – an 80% ROH break. Similar to the NOC case previously documented [1], there are no fuel failures predicted by the simulation exercise. However, there is a noticeable spread in the output data which, although not large, allows for a measurable cause-and-effect relationship between manufacturing variance and in-reactor fuel performance to be defined. This spread in data is larger than that of the NOC case for most output quantities, due to the rapidly changing conditions during a LBLOCA accident.

The probability of industrial acceptance criteria being exceeded during the transient examined is found to be less than 10^{-30} for both fuel melting and sheath strain. In addition, oxygen-related failures are not observed throughout the course of this work. When comparing the results of this study to a typical LOE benchmark, the contrast is appreciable. This study implies that margin exists

within the current fuel design and manufacturing domains, suggesting current specification limits can potentially be relaxed on some parameters if a need arises.

There are limitations to the methodology. Namely, only one transient is studied, and only one simulation code is employed. The simulation code, ELOCA, is part of the Industry Standard Toolset and was chosen for that reason, as well as the fact that its computational demand lends itself toward large-scale simulation exercises. The examination of other design based accidents, as well as the use of other fuel codes with more complex models, would be of benefit to expand this study.

6. References

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