ASSESSMENT OF FUEL MANUFACTURING SAFE OPERATING ENVELOPE

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ABSTRACT

In a previous work, the range of fuel manufacturing parameters was reviewed. This paper models that deduced range with ELESTRES. The purpose is to establish quantitatively the fuel parameters that lead to bounding predictions of fuel centreline temperature, volume average temperature, free inventory fraction and element average sheath strain. This will establish the analysis range for fuel and hence the Safe Operating Envelope (SOE) for fuel. The first application of this work will be to revisit the implication of considering a range of fuel conditions on accident consequences. At present, the PLGS '97 Safety Report assesses accident consequence based on only a nominal fuel type that was defined around 1980. The second application will be to assess the need to retain the bundle mass limit in our Fuel Tender Document.

INTRODUCTION

An investigation into the variation in fuel parameters over the range of fuel manufacturing tolerances was performed at PLGS. This analysis has yielded a set of input files that will be used in all future safety analysis to envelope the range of fuel conditions. It also provides information useful to define the sensitivity of fuel behaviour to variations in manufacturing parameters.

A total of 25 ELESTRES input files were prepared. There was a base case, cases designed to maximize and minimize the U-mass and cases which vary individual parameters such as UO_2 density, sheath thickness and pellet roughness. For a complete more complete description of the cases refer to Table 1.

The results of the ELESTRES runs were examined for the following variables that are significant to safety analysis:

Volume Average Temperature
Centreline Temperature
Average Sheath Strain
Free Inventory Fraction
Pellet End Interfacial Pressure
Mid-Pellet Interfacial Pressure

From these results it was possible to generate ELESTRES input files which maximize and minimize the volume average temperature, centreline temperature, average sheath strain and free inventory fraction. Similar input files were not generated for the interfacial pressure parameters due to the non-linear nature of their behaviour. These ELESTRES input files will be archived and can then be used in future safety analysis to define the fuel manufacturing envelope.

METHOD

Code Version

The version of ELESTRES which was used in this assessment is ELESTRES M13B.8-PLGS (Reference [1]). This version of ELESTRES was created by porting ELESTRES M13B.8 (References [2], [3], [4] and [5]) to the IBM PC platform and compiled with the Lahey FORTRAN 90 Compiler (revision A). No changes were made to the calculational capabilities or solution techniques in the version documented in the references given. Therefore testing of this version of the code consisted of running two example cases and comparing the results to those obtained from ELESTRES M13B.8 runs performed on an SGI workstation.

ELESTRES provides a 1-D radial thermal model of a CANDU fuel element, combined with a 2-D radial/axial elastic-plastic stress strain model of a single half-pellet. ELESTRES is not capable of modelling the impact of the following manufacturing parameters outlined in Reference [6]:

- endcaps and end pellets (except for the axial clearance)
- cut-off pellets (ELESTRES accepts an integer number of pellets all of the same length
- variable pellet lengths in a single element
- sheath ovality
- endplates
- spacer and bearing pads
- HAZ distribution
- Be chemical composition and braze characteristics
- end-flux peaking

In addition, due to assumptions in the ELESTRES model, the effect of changes in the following cannot be modelled:

- effects of variations in UO_2 pore size on material properties
- effects of variations in UO_2 O/U ratio on material properties

In the authors' opinion, the only variations discussed above which are likely to have any noticeable impact on the results are the effects of endcaps and end pellets and cut-off pellets, within the defined SOE.

Assumptions

Parameters are assumed to be variable only within the ranges outlined in Table 1 of Reference [6]. In addition to the restrictions implied by the modelling limitation outlined above (*i.e.* it is assumed that there are no cut-off pellets), the following assumptions are to be made in the ELESTRES assessment:

- Axial clearance = sheath length + weld groove depth - fuel support height - fuel stack length
- Diametral clearance = sheath ID - pellet OD
- Fuel element fill occurred at 0.1013 MPa pressure
- Fuel and sheath surface roughness can vary between 0.0 and 8.0 μm, with a nominal value of 0.5 μm
- Sheath-to-coolant heat transfer coefficient = 50.0 kW/m²·K
- Coolant temperature = 562.0 K
- Coolant pressure = 10.7 MPa
- Fuel is natural U only
- Only radial cracking of fuel pellets is modelled (default option in ELESTRES)
- Default values of all fuel and sheath properties are used
- Fuel follows the licensing power/burnup curves [7] which assumes a fixed ring-to-ring power profile (found in Table 9). Note that each case will be assessed with a power history appropriate for each fuel ring.

Data

A total of 25 cases are examined. Selection of the cases was guided by the definition of a set of 5 ELESIM input files for cases representing the breadth of the envelope in Reference [6].All of the data used in this assessment is reported in Reference [6], although in some minor cases, the specific numbers vary due to one of two reasons. Some numbers differ due to differences between ELESTRES and ELESIM, and a review of Reference [6] with AECL staff revealed a number of misinterpretations and inconsistencies in the information in Reference [6]. The following is a summary of cases in which the data used for this assessment is different from that outlined in Reference [6]:

1. It is impossible to have a nominal value of LE and of the Standard Pellet Length while maintaining an integer value of NP. Therefore, the number of pellets implied by LE, the standard pellet length, and the end pellet length is rounded to the nearest integer. Stack lengths are controlled using 'cut-off pellets' but the computer model does not allow for this level of detail. Note that the value suggested in IR-03553-10 rev. 0 for NP is different because ELESIM assumes single-dished pellets and ELESTRES allows explicit modelling of double dished pellets.

2. In IR-03553-10 rev. 0, the suggested values of FGV are calculated for each case presented. However, ELESIM & ELESTRES both support specifying the pressure of the fill gas at 293 K. This input option is used for this work. It is assumed that the fuel manufacture was such that the element was sealed at atmospheric pressure and ELESTRES is allowed to calculate the volume. These volumes will be examined in the outputs.

3. For the variable SRFS (sheath inside surface roughness), Reference [6] does not provide a range, just the nominal value. The range 0 to 0.8 μm along with the nominal value of 0.5 μm for this variable used in this assessment is from Reference [8].

4. ELESTRES has an input group, IGROUP=11, which is not available in ELESIM. In it, the variables NDISH, PELGAP, WCHAM, HCHAM, SYIELD, RR1 and PINK are set. For this work:

   NDISH=2 (double dished pellets)

   PELGAP=0.0 (models pellet-to-pellet interaction)

   $$WCHAM = \frac{(Diam\ of\ Pellet - 2 * Chamfer\ Radius)}{2}$$

   $$HCHAM = WCHAM * TAN(RADIANS(CHAMFER\ ANGLE))$$

   The balance of the variables will be left at their ELESTRES default values.

5. The maximum value of HA (axial gap) used in this study is less than that used in Reference [6]. It is believed that the value in Reference [6] is in error.

6. There are also a small number of variables whose values appear to have been rounded off in Reference [6]:

   Stack Length (cases 2 through 5)

   Axial Clearance (Case 2 and 4)

   Sheath Thickness (Case 2)

   These values will not be rounded off in this study to maintain numerical consistency.

The power burnup histories used in this analysis were taken from the fission product inventory update [9] for a 935 kW bundle.

Application

A total of 25 ELESTRES input files were prepared. The first file was generated from the nominal values given in Table 1 of Reference [6] and is referred to as the 'base case'. The next two cases (cases 2 and 4) maximize and minimize parameters in order to maximize the bundle uranium mass followed by two cases, (3 and 5) which will minimize the U-mass. The next 16 cases (11 through 28) will examine individual parameters such as UO_2 density, sheath thickness and pellet roughness. For a complete description of the cases refer to Table 1.

The generation of the safety analysis 'Historical' case will be performed by incorporating the values from Table 11 in Reference [6], which was reproduced from the 1993 PLGS Safety Report. The following parameters will be assumed to be at their nominal values in order to generate the ELESTRES input file:

Sheath Thickness	Volume of Fill Gas
Fraction of He	Heat Transfer Coefficient
Sheath Roughness	Fuel Roughness
Coolant Temperature	Coolant Pressure
Grain Size	Enrichment

The documentation of the assessment will include reporting of the variation in the following parameters for all of the cases assessed:

1. Fuel volume average temperature (important for assessing reactivity feedback)
2. Fuel centreline temperature (important for assessing impact on LOCAs, RIAs)
3. Fuel average sheath strain (important for assessing likelihood of NOC failures and the sheath failures during accidents)
4. Free inventory fraction (important for assessing the burst release during accidents where a burst release is possible)
5. Pellet end interfacial pressure (important for trip coverage and bowing)
6. Mid-Pellet interfacial pressure (important for trip coverage and bowing)
7. Bundle Mass (a common measured parameter during fuel manufacture)

Each of the parameters that are included in this assessment are defined below.

Volume Average Temperature:	The temperature of the fuel element calculated on a volume average basis (K). The number of finite-difference annuli used in this analysis was the default of 100.
Centreline Temperature:	The temperature of the fuel element at the centre location (K). This is independent of axial position.
Average Sheath Strain:	This value was calculated after ELESTRES was run by summing 1/3 of the plastic sheath strains at the pellet end location (circumferential ridge) and 2/3 of the plastic sheath strains at the pellet mid-plane location (%). This calculational approach was adopted to be consistent with [10] and [11].
Free Inventory Fraction:	The percentage of total fission gases (active and inactive) produced that is released out of the fuel into the fuel element internal free voidage (%).
Pellet End Interfacial Pressure:	Pellet to sheath inside surface interfacial pressure at the pellet end location (MPa).
Mid-pellet Interfacial Pressure:	Pellet to sheath inside surface interfacial pressure at the Mid-pellet location (MPa).
Bundle Mass:	This value was calculated using two methods. The first evoked a method described in Appendix B of [6] and the second used the ELESTRES output UO_2 mass for the element (converting it to U mass and a bundle basis). The ELESTRES UO_2 mass is calculated by summing the UO_2 in each annuli in the GEO subroutine [12] (kg U).
Free Volume:	The calculation within ELESTRES for the volume for storing free gas is based on the total voidage available for storing fission gas (mm^3/K) and the average pellet surface temperature (K) and the sheath inside temperature (K).The units for free volume are (mm^3)

RESULTS

The 21 ELESTRES input files (described in Table 1) were generated as described above and submitted to ELESTRES M13B.8-PLGS [1] to be run. The input files were submitted with 4 power burnup histories, each of which models a different ring of elements. Due to the higher powers in the outer elements they are chosen for the determination of the bounding cases when examining temperatures, sheath strains and free inventories. The input files for the other elements were submitted to ELESTRES M13B.8-PLGS to generate a complete bundle model in the event that these are useful at a later date. The output files for the 21 cases where compiled into an EXCEL worksheet where the results were tabulated and compared. Each of the parameters described in the introduction is plotted along with the base case for each output file in Figures 1 through 30 of Reference [13].

The ELESTRES output files were also examined for the bundle U-mass predicted by the code and the free volume at the end of the run. The bundle U-mass values reported by ELESTRES are presented in Table 2 of Reference [13] along with the values calculated from the input parameters by the method described in Appendix B of Reference [6].

Selection of Bounding Conditions

The generation of Figures 1-30 and Figures 39-42 in Reference [13] made it possible to determine the contributions of the various input parameters on the volume average temperature, centreline temperature , average sheath strain and free inventory fraction. As expected, it was found that a case that maximized volume average temperature also maximized centreline temperature and free inventory fraction. The mid-pellet and pellet end interfacial pressure were not considered in this form of the analysis due to its non-linear behaviour.

I. In order to maximize volume average temperature:
- Cases 2R, 22 and 11 show the pellet diameter should be maximized and the diametral clearance should be minimized
- Cases 2 and 2R show that the axial gap should be minimized
- Cases 13 and 23 show that the density should be minimized
- Case 16 shows that the sheath roughness should be maximized
- Case 27 shows that the fuel roughness should be minimized
- Case 28 shows that the grain size should be minimized
- Cases 15 and 25 show that the Helium gas fraction is not significant

II. In order to maximize centreline temperature:
- As expected the cases which maximized volume average temperature also maximize centreline temperature

III. In order to maximize free inventory fraction:
- As expected the cases which maximized volume average temperature and centreline temperature also maximized the free inventory fraction
- Case 15 shows that the Helium gas a minor affect on free inventory and in order to maximise the free inventory fraction the Helium in the fill gas should be minimized

IV. In order to maximize the average sheath strain:
- Cases 2R, 22 and 11 show the pellet diameter should be maximized and the diametral clearance should be minimized
- Cases 2 and 2R show that the axial gap should be minimized
- Cases 13 and 23 show that the density should be maximized
- Case 16 shows that the sheath roughness should be maximized
- Case 27 shows that the fuel roughness should be minimized
- Case 28 shows that the grain size should be minimized
- Cases 15 and 25 show that the Helium gas fraction is not significant

V. In order to minimize volume average temperature:
- Cases 5R, 12 and 21 show the pellet diameter should be minimized and the diametral clearance should be maximized
- Cases 5 and 5R show that the axial gap should be maximized
- Cases 13 and 23 show that the density should be maximized
- Case 26 shows that the sheath roughness should be minimized
- Case 17 shows that the fuel roughness should be maximized
- Case 18 shows that the grain size should be maximized
- Cases 15 and 25 show that the Helium gas fraction is not significant

VI. In order to minimize centreline temperature:
- As expected the cases which minimized volume average temperature also minimize centreline temperature

VII. In order to minimize free inventory fraction:
- As expected the cases which minimized volume average temperature and centreline temperature also minimized the free inventory fraction
- Case 15 shows that the Helium gas a minor affect on free inventory and in order to maximise the free inventory fraction the Helium in the fill gas should be maximized

VIII. In order to maximise the average sheath strain:
- Cases 5R, 12 and 21 show the pellet diameter should be minimized and the diametral clearance should be maximized
- Cases 5 and 5R show that the axial gap should be maximized
- Cases 13 and 23 show that the density should be minimized
- Case 26 shows that the sheath roughness should be minimized
- Case 17 shows that the fuel roughness should be maximized
- Case 18 shows that the grain size should be maximized
- Cases 15 and 25 show that the Helium gas fraction is not significant

Definition of Nominal Fuel Type

For future analysis we define a 'nominal' fuel type to be used along with these bounding cases in future analysis. The nominal case is presented in Table 4. The Base Case in the ELESTRES analysis used a range of fuel roughness and sheath roughness of 0.0 to 0.8 with a nominal value of 0.5. The nominal value for this analysis should have been 0.4. The Nominal Case uses 0.4 as its nominal value of fuel roughness and sheath roughness, this is the only difference between the Base Case and the Nominal Case.

Recommended Bounding Cases

From these results the following ELESTRES input files were generated by using the appropriate value (maximum, minimum or nominal) for the parameters in the input files:

I. NOMINAL.TXT – Nominal Case

II. MAX-TEMP.TXT – Maximize Volume Average & Centreline Temperature & Maximize Free Inventory Fraction
III. MAX-STRAIN.TXT – Maximize Average Sheath Strain
IV. MIN-TEMP.TXT– Minimize Volume Average & Centreline Temperature & Minimize Free Inventory Fraction
V. MIN-STRAIN.TXT Minimize Average Sheath Strain

These files are presented in Tables 4 through 8 of Reference [13]. The results of running these input files with ELESTRES M13B.8-PLGS [1] show the maximum and minimum volume average temperatures, centreline temperatures, average sheath strains and free inventory fractions and are presented in Figures 1 through 4.

Observations

Note that the physics Design Manual (DM) quotes a zero reactivity change at a volume average temperature of 1209 K (936 °C), the maximum volume average temperature for the base case was found to be 1311 K (1038 °C) and the bounding volume average temperature was 1481 K (1208 °C). Since fuel temperature is accounted for in the core physics representation, this may affect the accuracy of these models.

The melting temperature for stochiometric UO_2 is 3116 K (2843 °C) so the nominal case has a margin of 984 ° to melting and the bounding case has a margin of 820 °.

At a normal burnup of 180 MWhr/kgU the sheath strain for the nominal case is –0.1% and +1.4 % for the bounding case.

The 'Historical' input files which were derived in [6] from existing safety analysis were also submitted to ELESTRES M13B.8-PLGS [1] to be run. A comparison of the historical case to the nominal case is included in Figures 1 though 4 and show similar results for volume average temperature, centreline temperature and free inventory fraction. The average sheath strain for the historical case is approximately 0.5% higher due to the small axial and radial gaps.

CONCLUSIONS

1. A suite of five ELESTRES input files (the nominal case and the four limiting cases) have been identified to provide future safety analysis with a range of outputs for volume average temperature, centreline temperature, average sheath strain and free inventory fraction which covers the manufacturing variations. These bounding cases (the results of which are presented in Figures 1 through 4) are intended to be used in all future safety analysis.

2. The historical case and the base case have similar results for volume average temperature, centreline temperature and free inventory fraction. The historical case did exhibit slightly higher average sheath strains over the base case.

3. The interfacial pressures for the cases were plotted because of their impact on heat transfer and fuel rigidity but due to the scatter in the results a bounding case could not be determined.

4. The bundle mass reported by ELESTRES and that calculated by the method reported in appendix B of Reference [6] are consistent. The range of bundle masses considered in this report (18.58 - 19.85 kg U/bundle with the nominal case being 19.2) is bounding for the range of U-masses currently in the core at PLGS (18.9-19.2 kg U/bundle [14]).

5. The highest volume average temperature over all cases and burnups predicted by ELESTRES for the manufacturing range was 1481 K (1208 °C). The PLGS physics Design Manual (DM) quotes a zero reactivity change at 1209 K (936 °C).

6. The highest centreline temperature over all cases and burnups predicted by ELESTRES for the manufacturing range was 2296 K (2023 °C) which is below the UO_2 melting point of 3116 K (2843 °C). This represents in a reduction in the margin to melting of 166 ° from the historical case which had a margin of 820 °.

7. The highest free inventory fraction over all cases and burnups predicted by ELESTRES for the manufacturing range was 26.3 %.

8. The highest average sheath strain over all cases and burnups predicted by ELESTRES for the manufacturing range was +1.33 % at 180 MWhr/kg (this value was continuing to rise with increased burnup – see Figure 3).

9. The results indicate that the nominal fuel model defined here behaves essentially the same as the 'historical' nominal case, but it is apparent that our existing safety analysis does not take into account the range of manufacturing conditions.

REFERENCES

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Table 1: Description of the ELESTRES Runs

Case	Description
Base Case	All variables at their nominal values as given in Table 1 of Reference [6] with the exceptions noted in Section 2.4
2	Maximum fuel mass, minimum axial/radial clearances (cf. Case 2 in Reference [6])1
3	Maximum clearances, minimum fuel mass (cf. Case 3 in Reference [6])
4	Minimum element diameter and axial/radial clearances, maximum fuel mass (cf. Case 4 in Reference [6])
5	Minimum element diameter and fuel mass, maximum axial/radial clearances (cf. Case 5 in Reference [6])
2 Rho	Case 2 with the nominal density
3 Rho	Case 3 with the nominal density
4 Rho	Case 4 with the nominal density
5 Rho	Case 5 with the nominal density
11	Maximum pellet size (max length & diameter, minimum dish size and minimum chamfer)
12	Maximum diametral and axial gaps[1]
13	Maximum UO_2 density
14	Maximum sheath thickness
15	Maximum fraction of He in fill gas
16	Maximum sheath roughness
17	Maximum fuel roughness
18	Maximum UO_2 grain size
21	Minimum pellet size (min length & diameter, maximum dish size and maximum chamfer)
22	Minimum diametral and axial gaps
23	Minimum UO_2 density
24	Minimum sheath thickness
25	Minimum fraction He in fill gas
26	Minimum sheath roughness
27	Minimum fuel roughness
28	Minimum UO_2 grain size

[1] Note: all of the input files will be based on the Base Case except for the variables described in the Table

Figure 1: Maximum and Minimum Volume Average Temperature

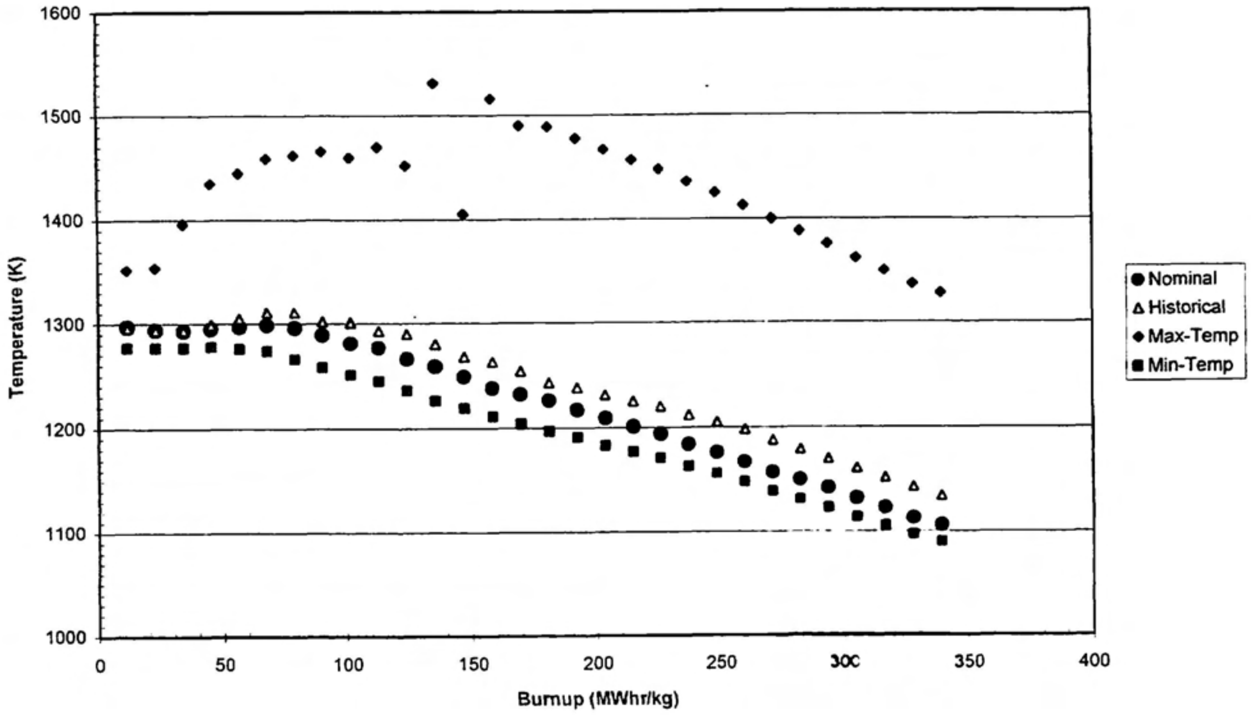

Figure 2: Maximum and Minimum Centreline Temperature

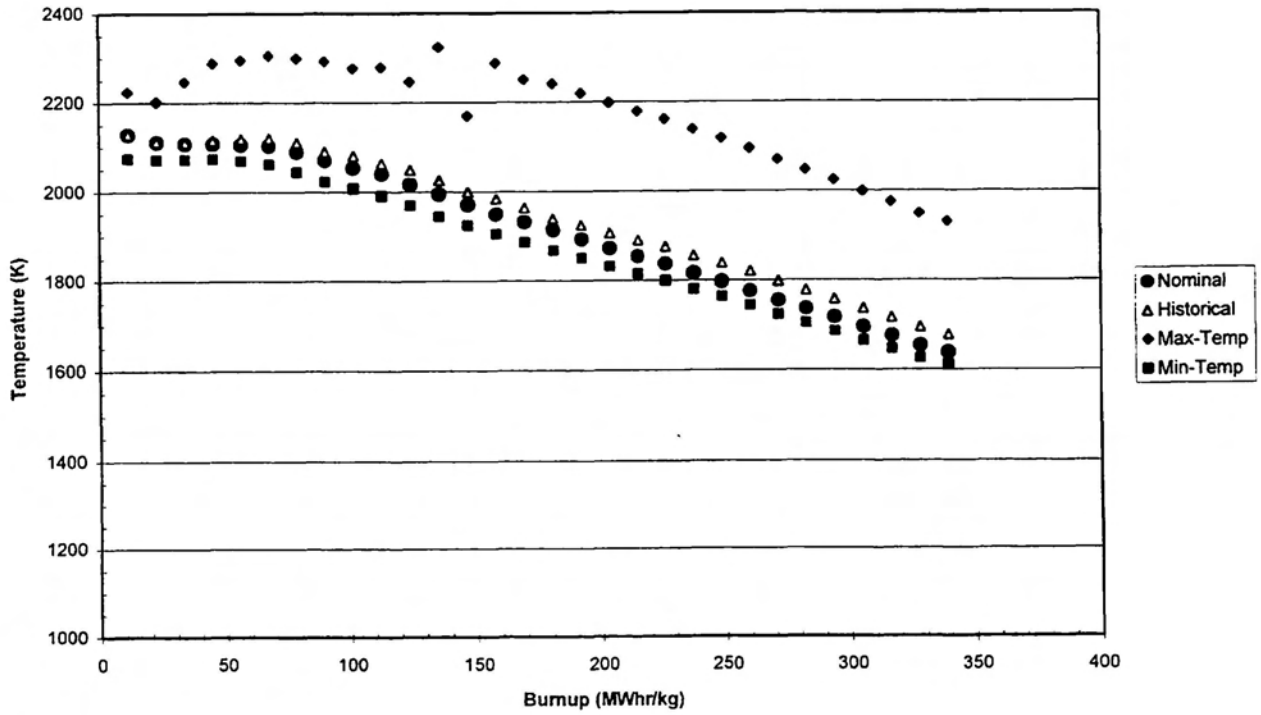

Figure 3: Maximum and Minimum Average Sheath Strain

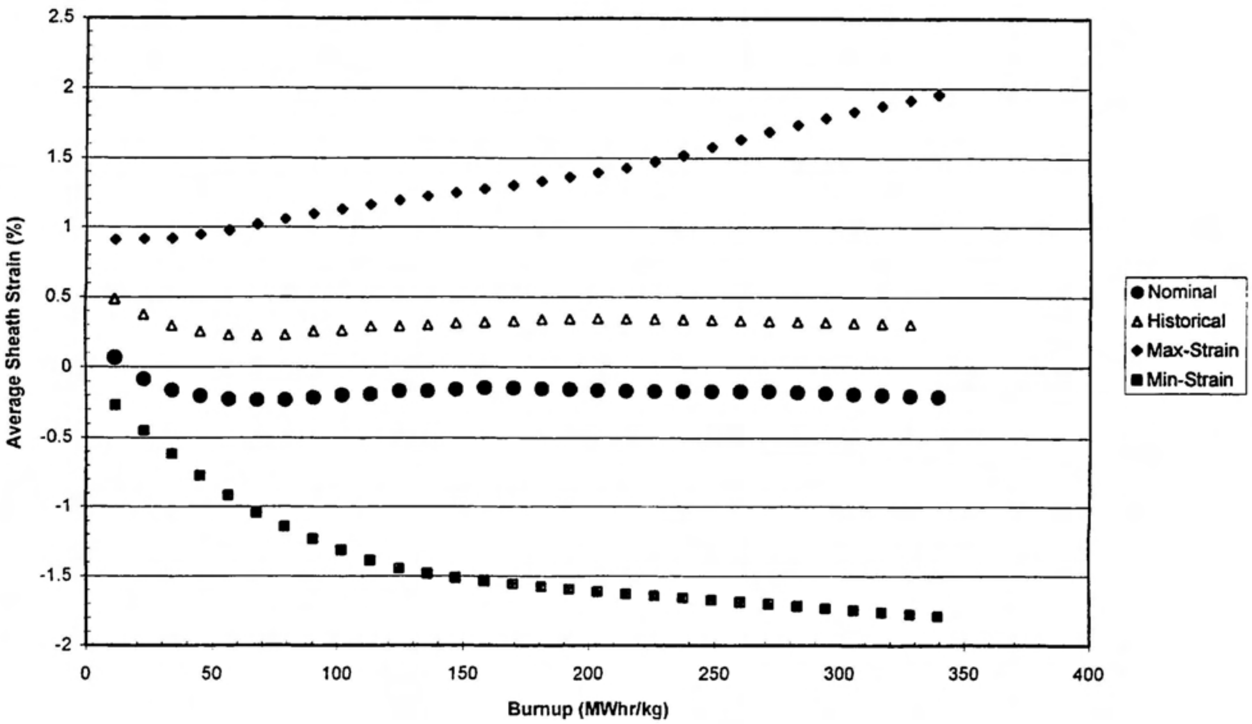

Figure 4: Maximum and Minimum Free Inventory Fraction