FUEL SHEATH INTEGRITY FOR FUEL BUNDLES AT DECAY POWER LEVELS AT 600°C IN STEAM

P.J. REID

ALARA Research, Inc.
975 First Avenue, Saint John, NB, Canada E2M 4N9

and R.A. GIBB

Point Lepreau Generating Station
P.O. Box 10, Lepreau, NB, Canada E0G 2H0

1. INTRODUCTION

During the 1995 outage at Point Lepreau Generating Station (PLGS), the fuel channels underwent a Spacer Location And Relocation (SLAR) procedure. The SLAR tool is used during the defuelling of the channel. However, this tool restricts coolant flow in the channel. It was possible that the fuelling machine ram could have become jammed during this process, inhibiting flow in the fuel channel. To determine the possible consequences of this, an assessment was made of the heatup rate of the fuel bundles at decay powers in stagnant coolant[1]. The goal was to determine a waiting period to allow for decay heat sources to diminish before beginning SLAR such that the maximum bundle temperature would not exceed a pre-defined limit. An interim limit of 600°C was initially used. The work reported in this paper addresses whether that limit can be supported. The goal was to ensure that there will be no fuel failures for the set of possible scenarios.

While this analysis was undertaken for the accident scenario described above, it is generally applicable for any situation in which a bundle which is at decay power levels is expected to heat up in steam to temperatures up to 600°C at low system pressures. Although the bundle temperature transients used in this analysis are derived from Reference [1], the failure times are so long with respect to the heatup times that small variations in bundle heatup rates will have negligible impact on the predicted sheath failure time.

There are two potential failure mechanisms of concern for this type of scenario. The first is over-strain due to the internal fission gas pressure in the fuel element, which could fail the fuel element at elevated temperatures. The second possible mechanism of sheath failure is embrittlement due to oxidation, where the oxidation is sufficiently advanced that brittle sheath fracture would be expected upon rewet.

Both of these processes are also of concern after the postulated accident has ended. If the fuel sheath remains intact during the accident, it could nonetheless be too severely oxidized to withstand subsequent normal operation, or to remain intact during defuelling from the channel. Also, if the sheath has strained significantly during the postulated accident, dryout powers could be affected. Sheath strain could also cause the fuel to experience higher temperatures, due to the larger than nominal fuel-to-sheath gap. Either one of these factors will affect any subsequent operation of the reactor with the fuel in question.

Based upon the above considerations, time limits are determined in this document which define the length of oxidation at 600°C after which fuel element failures or significant impact on dryout powers and fuel temperatures would be expected upon subsequent normal operation of the bundles. Another time limit is determined which defines the length of time after which failures would be expected upon subsequent handling of the fuel bundles (*i.e.* during defuelling). And finally, time limits defining the duration of oxidation after which fuel element failures could occur either during rewet or due to sheath overstrain are established.

2. OXIDATION EMBRITTLEMENT

2.1 Methodology

To determine whether a fuel element has oxidized sufficiently that it may not survive subsequent operation, or defuelling, or indeed the rewet process which must occur to terminate the accident, recourse is taken to experimental data. The measure used to define the impact of oxidation on the likelihood of sheath failure is the absorbed energy to fracture (AEF). This measure defines the toughness of a material, and is the energy which must be applied per unit area to fracture the material. AEF decreases with increasing brittleness.

Reference [2] examines the impact of Zircaloy oxidation in steam on embrittlement. The experimental data points can be fitted to curves of the form $AEF = A \cdot e^{-B \cdot \delta} + C$, where AEF is the absorbed energy to fracture (J/cm²), δ is the oxide thickness (μm) and A, B and C are constants. Reference [2] proposes two limits for use in analysis of oxidation embrittlement. The first is a limit on AEF for subsequent handling, the other is a limit on AEF for embrittlement failure upon rewet. The recommendation is 20 J/cm² AEF for subsequent handling of parent or B-HAZ material and 10 J/cm² AEF for embrittlement failure upon rewet. The dependence of AEF on oxidation is different for parent and B-HAZ material. This means that parent material can oxidize to a greater extent than B-HAZ before being embrittled to the same degree.

Reference [2] does not provide an oxidation limit beyond which subsequent operation should be avoided. However, such a limit can be derived. The measurements of AEF for zero oxidation for both parent and B-HAZ material has an experimentally measured variation which is reported in Reference [3]. The assumption is made that a bundle can be operated after oxidation as long as the best estimate of AEF is not less than the 1-sigma lower limit of the AEF for unoxidized material.

These limits correspond to 5.6 μm oxidation for parent material and 6.3 μm oxidation for B-HAZ material. The amount of oxidation required to embrittle Zircaloy when oxidized in steam is much less than is required for oxidation in air. This is because of the effect of dissolution of hydrogen in the Zircaloy substrate in the steam oxidation case, which decreases the ductility of the fuel sheath.

Reference [2] provides data for oxidation rates in air and steam at 600°C. In the temperature range considered in the analysis in this document, the oxidation of Zircaloy exhibits linear kinetics, after a short period of cubic growth. This cubic growth period ends as oxide cracking begins to occur (also referred to as breakaway oxidation), leading to linear kinetics. Correlations are presented to determine the oxide growth on parent and B-HAZ material in Reference [2], and the growth rates determined there are used in this analysis. The initial period of cubic oxidation is ignored, as it is small compared to the oxidation times considered here.

Reference [2] does not provide oxidation rate data for temperatures below 600°C. For this analysis, the sensitivity to temperature is examined. In order to determine the oxidation rate for Zircaloy at temperatures of 500°C and 500°C, the oxidation rates measured for Zircaloy in steam in the temperature range 600°C - 750°C are extrapolated using a logarithmic fit. In order to account for the uncertainty inherent in extrapolating these oxidation rates, the oxidation rates used for this analysis at 550°C and 500°C are the extrapolated rates plus a $3 \cdot \sigma$ uncertainty allowance.

Using the oxide growth rates and the limiting oxide thicknesses from the experimental data on embrittlement, the elapsed time until reaching the oxidation limit for failure on subsequent operation, subsequent handling or rewet can be determined for a range of temperatures between 500°C and 600°C. Note that the fuel sheaths will have a small initial oxide layer thickness before heatup begins. A nominal initial oxide thickness of 1 μm is assumed in this analysis.

2.2 Results

Figure 1 shows the limits imposed by oxidation embrittlement of B-HAZ and parent material at 600°C for subsequent operation, subsequent handling (*i.e.*, defuelling) and rewet, respectively. In all cases, the limiting material is the B-HAZ material. The fuel would be expected to survive rewet as long as the oxidation at 600°C did not last longer than 59.1 hours. The fuel would be expected to survive defuelling without failing as long as the duration of oxidation at 600°C did not exceed 36.1 hours. The fuel would be expected to be able to operate normally without any appreciable performance deterioration as long as the oxidation period at 600°C did not exceed 5.0 hours.

Figures 2 and 3 show the same limits for oxidation rates extrapolated at the $3 \cdot \sigma$ limit of uncertainty to 550°C and 500°C, respectively. At 550°C the time limit for rewet failure is 8.0 hours, the time limit for failure on handling is 2.4 days and the time limit for rewet failure is 3.9 days. At 500°C these time limits increase to 20.2 hours, 6.1 days and 9.9 days, respectively.

3. SHEATH STRAIN

3.1 Methodology

The second mechanism which is of concern with respect to fuel integrity during the postulated accident is sheath strain failure due to internal gas pressure. As the sheath heats up, its tensile strength decreases. Also important is differential thermal expansion between the fuel and the sheath, which reduces the available free volume to hold the fission products. Finally, the increase in temperature results in an increase in pressure of the fission gas. These processes result in a simultaneous increase in pressure and decrease in sheath strength which will lead to sheath deformation. Sheath strain under such conditions can lead to strain failure by local overstrain or by high strain rate. High strain rate failure is typically invoked at strain rates of 10 s^{-1}. Sheath failure by overstrain will occur when local strains reach 15%-100%, depending on the heatup rate, the sheath temperature, the oxidation state, etc.

The calculation performed for this analysis gives average sheath strain, not local strain. Sheath failure by overstrain will be assumed to occur when the average sheath strain reaches 5%. Since the strain process is very slow in this scenario, the strain is expected to be very uniform. Therefore, the use of a 5% average strain as a failure criterion should result in an underestimate of the time to failure.

In order to determine the time to reach 5% average sheath strain, recourse was taken to conditions determined with calculations based upon ELESIM-II mod10, version 1.2[4] and to a small utility program called CREEP which incorporates thermal expansion correlations[5] with creep data from Reference [6]. CREEP was developed because ELESIM is incapable of modelling changes in thermal hydraulic boundary conditions and analysis with ELOCA would take excessive amounts of computer time for the long duration transients of many days which are considered here. A brief description of CREEP follows.

CREEP takes initial conditions of fuel element dimensions and internal gas pressures from an ELESIM-II mod10 output file and transient boundary conditions of fuel and sheath temperature and system pressure from its own input file. Using correlations from References [5] and [6], CREEP determines the evolution of internal gas pressure and fuel element dimensions. The processes of radial creep due to the pressure and due to thermal expansion are both assessed, with user-defined criteria for time step selection. This last allows the user to ensure that a converged solution is achieved. CREEP does not credit the effect of oxide strengthening on creep rates. This will result in an under-prediction of time to failure.

In order to determine the shortest possible time interval to sheath failure, the ELESIM-II mod10 analysis used a fuel element which follows the overpower envelope, with maximum possible UO_2 density and minimum possible dimensional clearances. Two different histories were considered. The first is for the outer element of a bundle which has achieved 200 MW·h/kgU burnup, while a second ELESIM case for a very high burnup bundle, 400 MW·h/kgU, was also performed.

The two burnups selected are justified based upon the fact that, as of 14 February 1995, only 94 bundles in the core had burnups above 200 MW·h/kgU (*i.e.*, outer element burnup of ~230 MW·h/kgU), the burnup achieved in the lower burnup ELESIM run. All bundles in core except those whose burnups are above 200 MW·h/kgU can be represented by that one ELESIM run for the purposes of this analysis. Therefore, this ELESIM run should apply to all but ~2% of the channels in the core. The other channels can be represented by the higher burnup case. Note that the highest burnup bundle as of 14 February was 280 MW·h/kgU, which is significantly below the 400 MW·h/kgU burnup indicated by the high burnup ELESIM run.

The CREEP runs were performed using a temperature history which is based on the temperature transients from Reference [1]. The temperatures shown here are pro-rated for cases with other maximum temperatures. Maximum temperatures of 450°C, 500°C, 550°C, 575°C and 600°C were used. The bundle heats up to maximum temperature in ~21 minutes. As will be seen, sheath failure takes place for elapsed times on the order of days by overstrain, so the amount of time spent in the heatup phase is not a critical parameter. The thermal hydraulic analysis produced only predicted fuel temperatures, so in most cases, the fuel and sheath temperatures are assumed to be identical. However, a sensitivity study is performed to assess the impact of a cooler sheath, since this would be predicted to occur. Calculations indicate that the difference between the fuel and sheath would be expected to be in the range of 4.5°C to 32°C for a bundle at 200 MW·h/kgU which had followed the overpower envelope and achieved a maximum temperature of 600°C at decay power levels with a system pressure of 0.14 MPa.

The time step selection in CREEP is defined in all of the analyses performed such that the maximum change in sheath strain due to internal gas pressure is limited to 10^{-4}, the maximum allowed change in sheath temperature in a single time step is 100.0°C and the largest allowable time step irrespective of other limitations is 1000.0 s.

The system pressure used in the CREEP covered a range of pressures which were intended to represent pressures for various possible situations, from a channel in the top of the core with the PHTS drained to the headers up to the system being pressurized such that the boilers can act as a heat sink. The pressures used are 0.14 MPa, 0.2 MPa, 0.3 MPa, 0.5 MPa and 1.1 MPa. No pressures higher than 1.1 MPa were assessed, since failure times at this pressure were >115 days for all maximum temperatures examined.

For fuel in channels which experience heatup in steam for extended periods but does not fail, some sheath strain will still have occurred. When the reactor is returned to power, the sheath strain could adversely affect the critical channel power (CCP). This concern has been addressed in Reference [7], which performed calculations with NUCIRC version MOD 1.501 and ASSERT-4 version 2. The NUCIRC calculations include the impact of increases in sheath diameter in a single channel on CCP. This calculation did not include the impact of the larger fuel element diameter on CHF and showed that the reduction in CCP was linearly dependent on the increase in fuel diameter, with a 1% increase in sheath diameter for all fuel in the channel being equivalent to a 2.2% penalty in CCP. The ASSERT-4 calculations examined the impact of the increase in sheath diameter on CHF. These calculations, however, indicate that the margin to dryout increases with sheath strain (MCHFR =

1.006 for nominal sheath dimensions, MCHFR = 1.051 for 1% sheath strain). The ASSERT-4 calculations apparently do not model the effect of element-to-element gap on CHF. Therefore, it is recommended that the NUCIRC results be used.

The impact of fuel sheath strain of up to 5% on fuel temperatures is assessed by repeating the lower burnup ELESIM run with an initial fuel to sheath gap of 400 μm, which corresponds to 5% sheath strain. The power/burnup history indicated here is of a fuel bundle following the licensing overpower envelope, so this will show the maximum possible impact of operation of fuel with sheath strains just short of failure. The operational parameters of concern for assessment of the impact are fuel centreline temperature, fission gas release and sheath strain.

3.2 Results

Table 1 shows the earliest possible time to predicted sheath failure by overstrain for a bundle which followed the overpower envelope to a maximum burnup of 200 MW·h/kgU, for a range of maximum fuel/sheath temperatures and system pressures. The earliest failure is predicted to be at 3.0 d, in the scenario in which the system pressure is 0.14 MPa and he maximum achieved temperature is 600°C.

The subroutine which calculates the creep rate of the sheath has an uncertainty which means that the prediction is good to within a factor of 1.0377 ± 0.3632. This implies that the 3-sigma limit of the creep rate would be determined by multiplying the predicted creep rate by a factor of 2.127. Table 2 shows the earliest time to sheath failure using this large uncertainty assessment for the creep rate of the sheath. It shows that the earliest failure is predicted to be at 1.4 d.

Only a very small percentage of bundles will have burnups in excess of those assumed in the runs reported in Tables 1 and 2. In order to determine the sensitivity of the predicted time to failure on the peak burnup, the runs reported in Table 1 were performed using the higher burnup ELESIM case. Table 3 shows that the earliest time to failure reduces from 3.0 d to 2.0 d.

In order to determine the sensitivity of the predicted time to failure to the assumption on the fuel-to-sheath temperature difference, a run was performed which was based upon the most limiting of the runs shown in Tables 1, 2 and 3. This is the case with system pressure of 0.14 MPa, maximum fuel and sheath temperature of 600°C, 3·σ limit on sheath strain rates and a bundle burnup of 200 MW·h/kgU. The sheath temperatures in the run were reduced so that there was a 25°C temperature difference between the fuel and the sheath throughout the transient. Hence, temperature transient for the fuel had a maximum value of 600°C, with the peak sheath temperature reaching 575°C. This case resulted in sheath failure being predicted at 4.0 d. In contrast, the case with maximum fuel and sheath temperatures of 600°C had failure at 1.4 d and the case with maximum fuel and sheath temperature of 575°C had a predicted failure at 4.4 d. This result indicates, as would be expected, that the sheath temperature is more important than the fuel temperature in these calculations, but that the fuel temperature has a non-negligible impact. The result also indicates that using a sheath temperature equal to the predicted fuel temperature results in an under-prediction of the time to failure, so the uncertainty in the sheath temperature is dealt with conservatively in this analysis.

According to the analysis described in Section 2, return to power would result in the possibility of sheath failure by embrittlement after 5.0 hours, 8.0 hours or 20.2 hours for maximum fuel and sheath temperatures of 600°C, 550°C or 500°C, respectively. Examination of CREEP results for the corresponding cases with a 3·σ allowance for creep rate uncertainty indicates that by the time at which subsequent operation could result in fuel failures, the sheath strains are in the range 1.4% - 3.0%. Therefore, in the event of an accident which does not result in sufficient oxidation to embrittle the sheath beyond the limit for subsequent operation, the CCP for the affected channel should be reduced by 6.6%. A reduction in a single channel's CCP would have to be allowed for in the ROP trip setpoint. In most cases, a penalty in this setpoint results in a requirement to reduce reactor power. Due to the strong economic penalties associated with this, it may have been deemed preferable to defuel a channel whose fuel had experienced heatup to these temperatures in steam.

In order to assess the impact of returning to power with strained fuel sheaths, Figures 4, 5 and 6 show comparison of various critical parameters for the case with 5% initial strain and no initial strain. Fuel temperatures are higher by up to 175°C and fission gas release is approximately doubled in the case with 5% initial strain because the differential pressure across the fuel sheath is insufficient to close the radial gap. These effects are acceptable, however, since the predicted fission gas release is within levels which have been observed in CANDU fuel, fuel temperatures do not approach fuel melting and fuel sheath strains are compressive.

4. SLAR EXPERIENCE

The analysis reported in this paper was made use of during the 1995 outage at PLGS. On August 8, 1995, the SLARing of channel O01 had been completed and the fuel had been returned to the channel when the fuelling machine guide sleeve became jammed. Due to this problem, the channel closure plug at the inlet end of the channel could not be replaced.

In order to rectify this problem, it was proposed to drain channel O01, manually replace the closure plug and then re-fill the channel. This process was estimated to take ~30 minutes (in fact, the channel was drained for a total of 39 minutes). However, it was necessary to ensure that fuel sheath integrity would not be compromised during the drain and that subsequent fuel performance would not be affected.

The situation considered in the analysis reported in this paper is not identical to what occurred in channel O01, since this analysis considers oxidation in steam rather than in air. However, since oxidation in steam is more limiting in terms of elapsed time to reach the various embrittlement criteria, applying this work to the actual situation was conservative.

It was estimated that the peak steady-state temperature which would be achieved by the hottest bundle in channel O01 was 245°C and that it would take ~4 hours to reach this temperature. Therefore, in the time interval in which the channel drain occurred, heatup was to a much lower temperature of ~65°C. However, even if the channel were to reach the much higher temperature of

500 °C, the analysis presented in this paper indicated that 5% sheath strain would not occur until a time interval of >115 days and the embrittlement due to oxidation would not cause problems in subsequent operation until 20.2 hours had passed at 500 °C. Based on this information, it was possible to quickly come to the conclusion that the proposed procedure for replacing the closure plug did not impose any risk of sheath failure due to sheath strain nor did it pose any risk of sufficient oxide embrittlement that there were any concerns for subsequent operation.

5. CONCLUSIONS

The analysis of sheath embrittlement due to oxidation in steam at 600 °C shows that there would be no embrittlement resulting in significant degradation in operating margin as long as the oxidation *period* were less than 5.0 hours. The fuel would be expected to survive normal defuelling as long as the oxidation period is less than 36.1 hours. The fuel would not be expected to fail on rewet as long as the oxidation period is less than 2.5 days. For oxidation at 550 °C, these times increase to 8.0 hours, 2.4 days and 3.9 days, respectively. At 500 °C, the corresponding limiting times are 20.2 hours, 6.1 days and 9.9 days, respectively.

Analysis presented in this paper indicates that immediate sheath failure by overstrain could also occur in this scenario. For the most restrictive conditions of sheath temperature and system pressure considered in this analysis (maximum temperature of 600 °C and system pressure of 0.14 MPa), a fuel element would have 3.0 days (72 hours) until the earliest possible time of failure by overstrain. If the fuel bundle burnup is in excess of 200 MW·h/kgU, this time would be reduced to 2.0 days. The failure time by overstrain for a specific scenario can be determined by examination of either Table 1 or Table 3. If a large uncertainty in the sheath strain rate is desired, the failure times due to Table 2 can be used instead of the failure times due to Table 1.

Table 4 shows the time to reach the various different failure criteria for various temperatures for a bundle whose burnup is less than 200 MW·h/kgU with a system pressure of 0.14 MPa for a range of maximum sheath temperatures. Similar failure times for different bundle burnups, system pressures and uncertainty allowances for sheath strain can be obtained by replacing the times for immediate sheath strain failure by the appropriate data from Tables 1, 2 or 3.

This indicates that, for the specific scenario of the fuelling machine ram becoming stuck during SLARing in the upcoming outage, the 600 °C maximum temperature can be supported. The proviso is that, if the fuelling machine ram is not freed before the times indicated above are exceeded, fuel sheath failures could occur either immediately, on fuel rewet, during subsequent fuel handling or on return to power, depending on the time limit exceeded. Note that, if the oxidation lasts for longer than 5.0 hours with a maximum sheath temperature of 600 °C, it is not recommended to re-irradiate the fuel bundles due to the potential oxidation embrittlement of the fuel sheath, even though the sheath would not be expected to fail.

If the oxidation period is less than 5.0 hours and the decision is made to re-irradiate the fuel bundles, consideration of the impact of the sheath strain which would have occurred indicates that the critical channel power of the channel would drop by up to 6.6%. This would likely lead to the necessity to impose penalties on the ROP trip setpoint. Such a penalty would likely result in a requirement to operate the reactor at reduced power. In this case, the economic penalty may be such that the choice would be made to defuel the channel. Another impact of the sheath strain will be to increase fuel centreline temperature by up to 175°C and to increase fission gas release by up to a factor of 2. Increases in the parameters by this amount should not preclude safe operation. Note that operating the fuel below license limit powers will ameliorate the impact of the sheath strain on fuel temperatures and fission gas release.

The analysis performed for this paper was applied during the 1995 PLGS outage. Because of problems replacing the channel closure plug on channel O01, it was necessary to drain the channel and replace the closure plug manually. This analysis was used to demonstrate that the procedure did not result in any threat either to fuel sheath integrity or to subsequent return to power for the fuel in channel O01.

6. REFERENCES

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		Maximum Temperature (°C)				
		600	575	550	500	450
System Pressure (MPa)	0.14	3.0 d	9.3 d	30.4 d	>115.0 d	>115.0 d
	0.2	3.5 d	10.8 d	35.5 d	>115.0 d	>115.0 d
	0.3	4.6 d	14.3 d	47.5 d	>115.0 d	>115.0 d
	0.5	9.3 d	30.2 d	105.5 d	>115.0 d	>115.0 d
	1.1	>115.0 d	>115.0 d	>115.0 d	>115.0 d	>115.0 d

Table 1: Minimum Time to Sheath Failure by Overstrain for Various Maximum Temperatures and System Pressures (nominal sheath strain rates, 200 MW·h/kgU bundle)

		Maximum Temperature (°C)				
		600	575	550	500	450
System Pressure (MPa)	0.14	1.4 d	4.4 d	14.3 d	>115.0 d	>115.0 d
	0.2	1.6 d	5.1 d	16.7 d	>115.0 d	>115.0 d
	0.3	2.2 d	6.7 d	22.3 d	>115.0 d	>115.0 d
	0.5	4.4 d	14.2 d	49.4 d	>115.0 d	>115.0 d
	1.1	>115.0 d	>115.0 d	>115.0 d	>115.0 d	>115.0 d

Table 2: Minimum Time to Sheath Failure by Overstrain for Various Maximum Temperatures and System Pressures ($3 \cdot \sigma$ limit on sheath strain rates, 200 MW·h/kgU bundle)

		Maximum Temperature (°C)				
		600	575	550	500	450
System Pressure (MPa)	0.14	2.0 d	6.2 d	20.4 d	>115.0 d	>115.0 d
	0.2	2.3 d	7.1 d	23.3 d	>115.0 d	>115.0 d
	0.3	2.9 d	9.0 d	29.8 d	>115.0 d	>115.0 d
	0.5	5.1 d	16.2 d	55.3 d	>115.0 d	>115.0 d
	1.1	>115.0 d	>115.0 d	>115.0 d	>115.0 d	>115.0 d

Table 3: Minimum Time to Sheath Failure by Overstrain for Various Maximum Temperatures and System Pressures (nominal sheath strain rates, 400 MW·h/kgU bundle)

		Maximum Temperature (°C)		
		600	550	500
Sheath Failure Mode	Embrittlement Failure on Operation	5.0 h	8.0 h	20.2 h
	Embrittlement Failure on Handling	36.1 h	2.4 d	6.1 d
	Embrittlement Failure on Rewet	2.5 d	3.9 d	9.9 d
	Sheath Strain Failure Immediately	3.0 d	30.4 d	>115.0 d

Table 4: Time to Reach Various Fuel Sheath Failure Criteria for a Range of Maximum Temperatures (Immediate sheath strain failure times are the shortest times from Table 1)

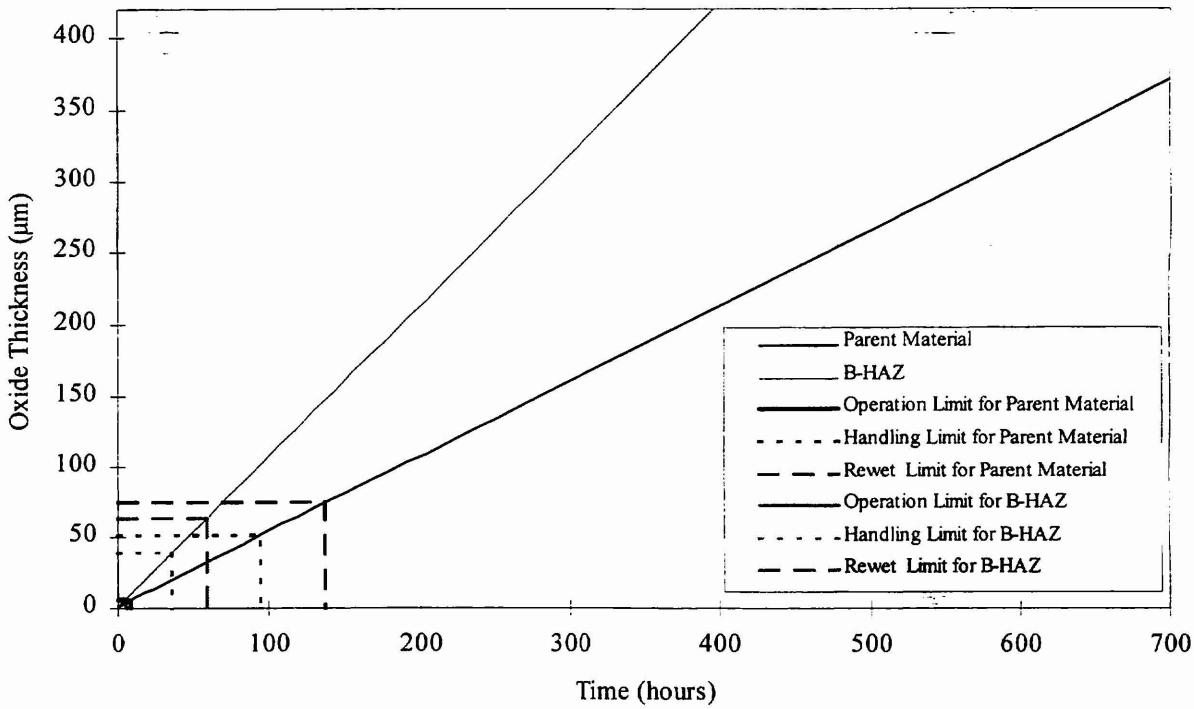

Figure 1: Oxide Growth for Parent and B-HAZ Material at 600°C, Showing Limits for Oxide Growth

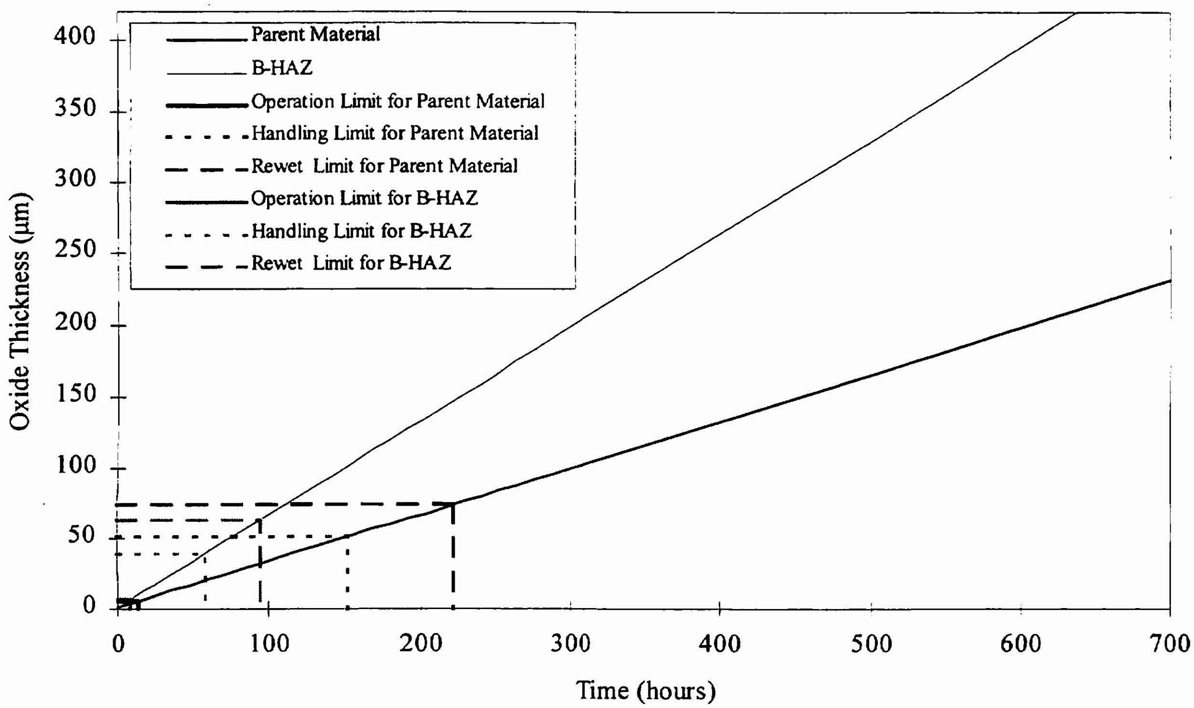

Figure 2: Oxide Growth for Parent and B-HAZ Material at 550°C, Showing Limits for Oxide Growth

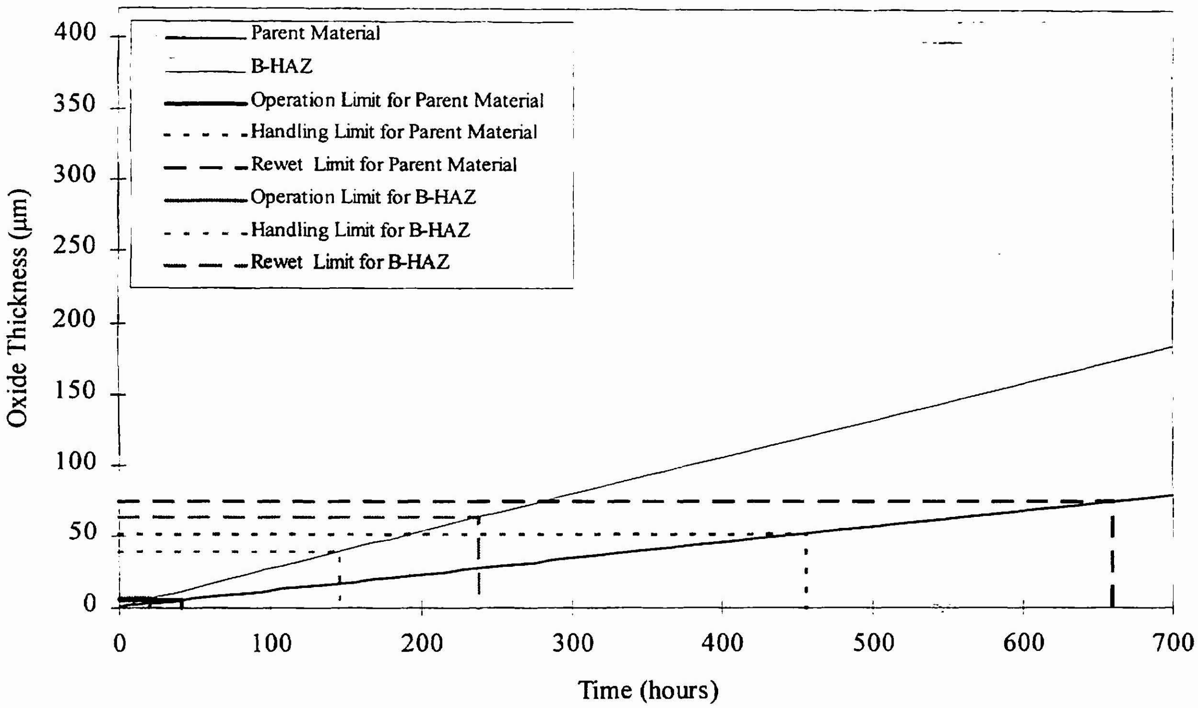

Figure 3: Oxide Growth for Parent and B-HAZ Material at 500°C, Showing Limits for Oxide Growth

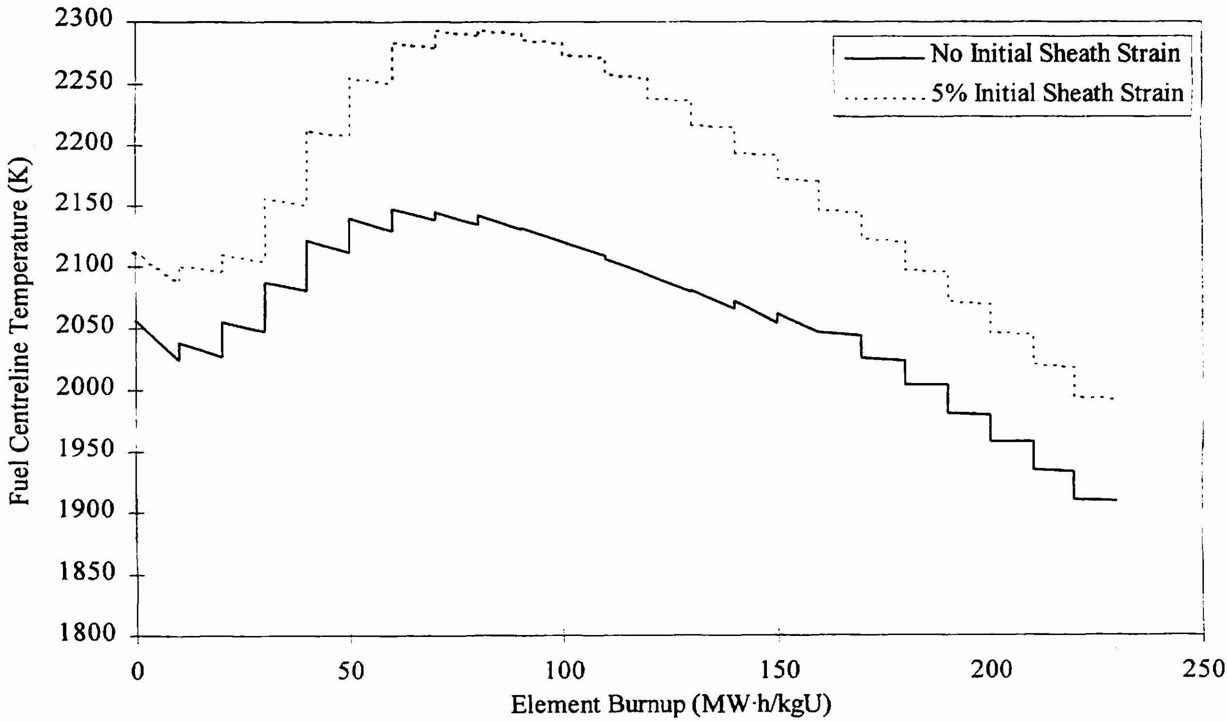

Figure 4: Impact of 5% Initial Sheath Strain on Fuel Centreline Temperatures during Operation at Licensing Envelope

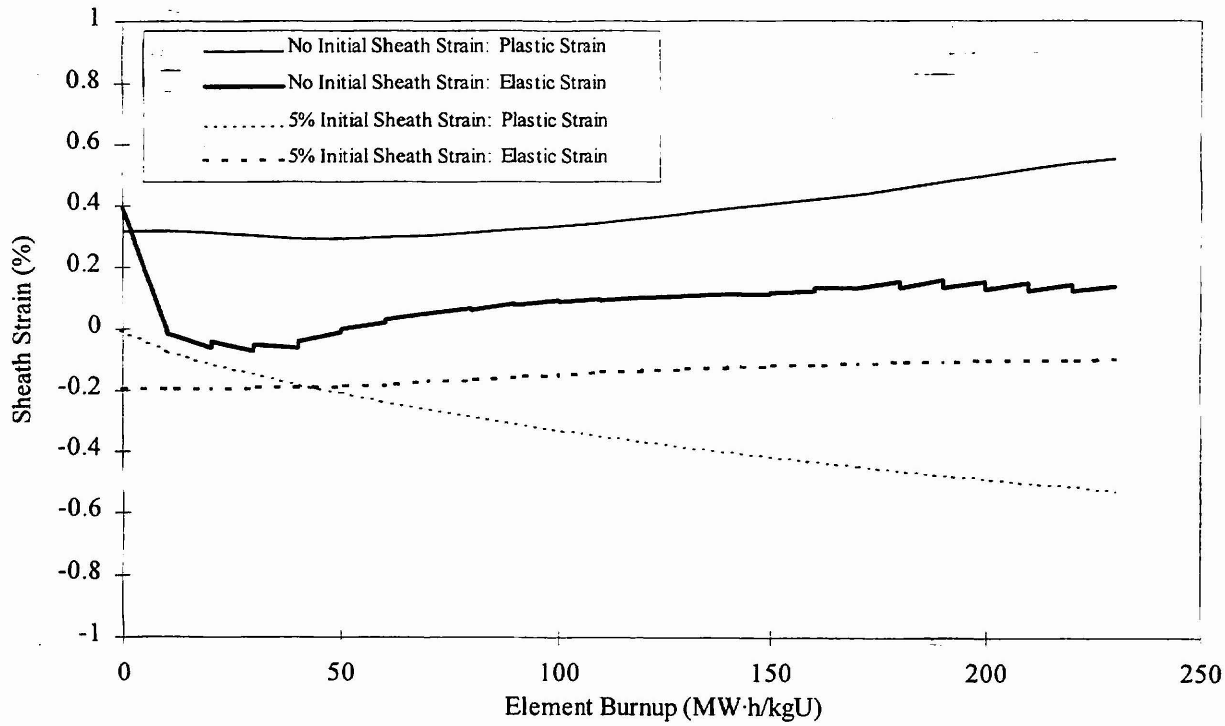

Figure 5: Impact of 5% Initial Sheath Strain on Fuel Sheath Strains during Operation at Licensing Envelope

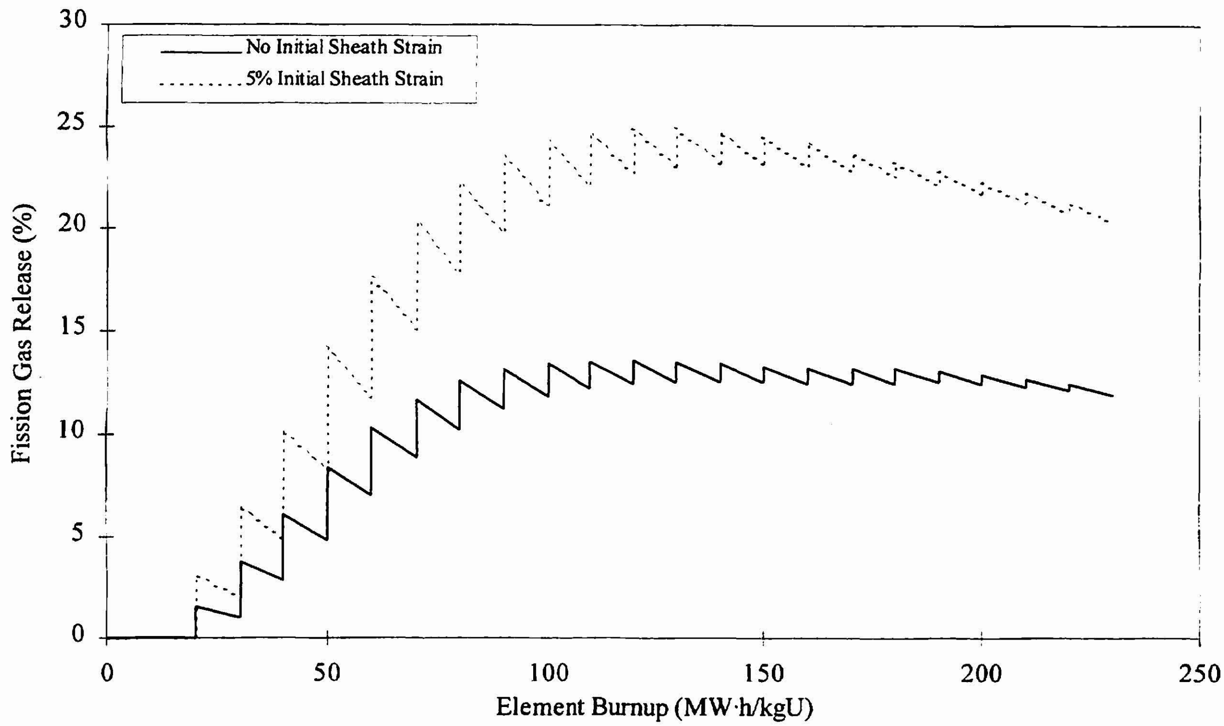

Figure 6: Impact of 5% Initial Sheath Strain on Fission Gas Release during Operation at Licensing Envelope