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ASSESSING THE IMPACT OF THE 37M FUEL BUNDLE DESIGN ON FUEL SAFETY PARAMETERS

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ABSTRACT – To improve the critical heat flux and margin to fuel dryout in aging CANDU nuclear generating stations, the 37-element bundle design ("37R" fuel) has been modified by reducing the central fuel element diameter, producing the modified "37M" fuel bundle. The codes FACTAR_SS, ELESTRES, ELOCA-IST, and SOURCE have been used to compare fuel temperature, fission gas release, and element integrity in 37R and 37M fuel bundles for Bruce Power nuclear reactors. The assessment demonstrated that, relative to 37R fuel bundles, using 37M fuel bundles does not significantly impact the existing safety margins associated with fuel temperature, fission gas release, and element integrity during design basis accidents.

Introduction

The Heat Transport System (HTS) in CANDU (CANada Deuterium Uranium) nuclear reactors is aging resulting in reduction in the Critical Heat Flux (CHF), which in turn reduces the margin to fuel sheath dryout. It is necessary to mitigate HTS aging effects in order to continue to operate at current channel power levels through to pressure tube end of service. The modified 37 element fuel bundle, or 37M bundle, features a centre element with a smaller sheath outside diameter than that of the regular, or 37R, bundle. This feature allows more coolant to flow through the centre of the bundle, increasing the CHF of the 37M bundle and thus increasing the overall margins to critical channel power relative to the 37R bundle. In preparation for the use of 37M fuel in operating Bruce Power units, it is necessary to assess the impact of the 37M bundle on fuel safety parameters during normal operation and accident scenarios. The focus of this paper is to compare fission gas release and element integrity margins in 37M and 37R fuel bundles.

1. Method and Assumptions

Two assessments are presented in this paper:

- Fission product assessment comparing fission gas release from 37M and 37R fuel using the FACTAR_SS [1], ELESTRES [2], and SOURCE [3] codes
- Element integrity assessment comparing fuel temperature and sheath strain for 37M and 37R fuel using the ELESTRES and ELOCA-IST 2.1c [4] codes

1.1 Fission Product Assessment

The fission product assessment is performed at normal operating conditions (NOC) for a bundle at end-of-dwell (EOD). For both a 37M and a 37R bundle, the outer ring element, intermediate element, inner element, and centre element of the bundle are assessed. The fission gas production under NOC constitutes the inventory available for release during accidents due to the short duration of the accidents compared to the duration of NOC. Hence, any difference in fission gas inventory between 37M and 37R fuel under NOC is considered representative of the difference in releases under accident conditions.

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In order to perform an assessment of the distribution of fission products (FPs), it is necessary to be able to model the fuel temperatures. The distribution of FPs within the various regions of a fuel element (pellet grains, grain boundaries, and pellet-to-sheath gap) is affected by the temperature distribution within the fuel element. FACTAR_SS and ELESTRES are the computer codes used to predict the conditions within individual fuel elements under steady-state conditions. The SOURCE code uses the outputs of FACTAR_SS and ELESTRES to predict the fission product distribution.

The irradiation histories for the 37M and 37R bundle elements were calculated using FACTAR_SS. Figure 1 shows the power-burnup envelopes for the 37M and 37R outer elements.

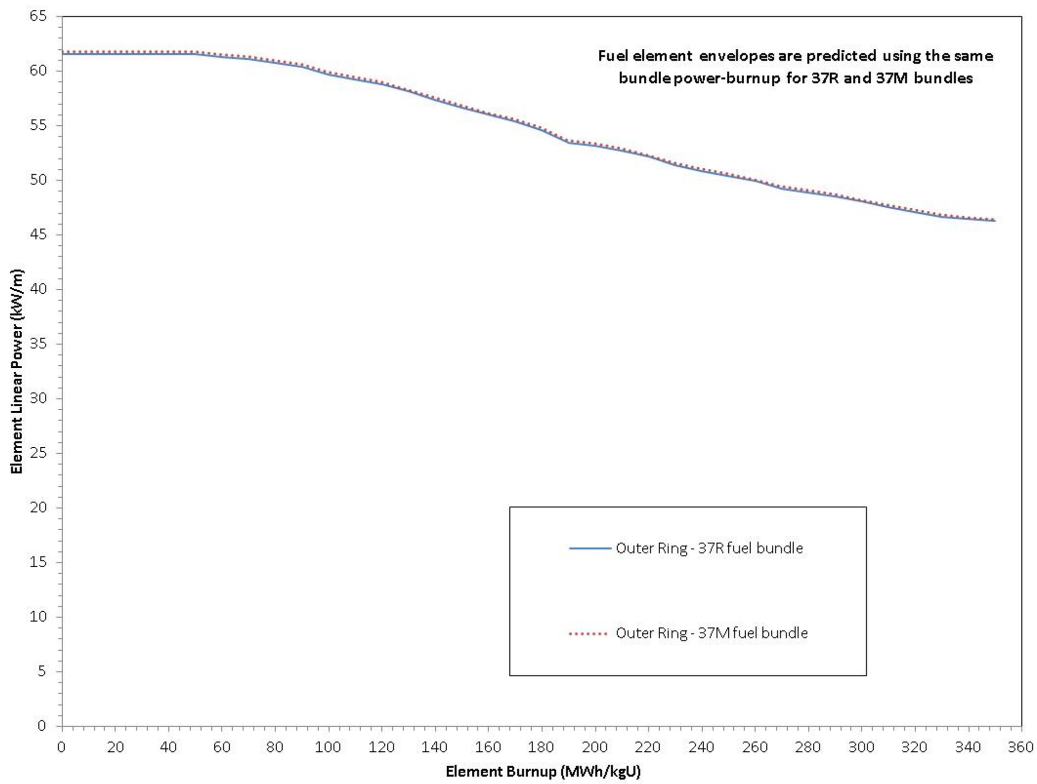

Figure 1: Power-burnup histories used for 37R/37M outer elements

The coolant temperature, coolant pressure, and sheath-to-coolant heat transfer coefficient are assumed to be the same for both 37M and 37R fuel. For these thermal hydraulic (TH) conditions and the irradiation histories given by the FACTAR_SS code, ELESTRES was executed and the results were passed to SOURCE. For each isotope fission product distribution predicted by SOURCE, the release fraction from the fuel at the end of irradiation was calculated as:

$$f_{isotopic} = \frac{I_{Gap} + I_{FS}}{I_{TOT}} \quad (1)$$

where,

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$f_{isotopic}$ = fractional fission product release from fuel for a given isotope,
I_{Gap} = inventory of fission gas isotope in the fuel-to-sheath gap,
I_{FS} = inventory of fission gas isotope on the fuel surface,
I_{TOT} = total inventory of fission gas isotope in the fuel element (i.e., in the fuel matrix, grain boundaries, fuel surface, and fuel-to-sheath gap)

1.2 Element Integrity Assessment

This assessment examines the thermal-mechanical responses of the centre and outer elements of 37M and 37R bundles under the same TH boundary conditions for the following two accident scenarios:

- Large Break Loss Of Coolant Accident (LBLOCA)
- Loss Of Flow (LOF) Accident

The assessment was performed for bundle burnups of 50 and 215 MWh kgU^{-1}. The thermal-mechanical behaviour of the fuel elements during NOC is determined using the ELESTRES 1.2 [2] code for the steady state irradiation histories given by Figure 1. The steady state and transient TH boundary conditions are assumed to be the same for 37M and 37R fuel. The thermal-mechanical behaviour of the fuel elements during accident conditions is determined using the ELOCA-IST 2.1c code [4] for the same relative power transient conditions.

For each case, the 37M and 37R centre and outer elements at the low and high bundle burnups up to the end of the transient (i.e., 60 seconds or up to the fuel sheath failure time) were compared based on the following parameters:

(a) The difference in the fuel sheath temperature during the transient.
(b) The difference in the fuel centreline temperature during the transient.
(c) The difference in the fuel sheath hoop strain during the transient.
(d) The time of fuel sheath failure (if any) and the failure mechanism.
(e) The difference in the peak oxygen concentration at the sheath mid-thickness during the transient.

These are the main parameters of interest for fuel safety analysis as they impact the fuel element integrity during the accident. To predict the sheath failure time (if any), the following fuel sheath failure thresholds are tracked by the ELOCA-IST code ([5], [6]):

(a) Sheath overstrain using a failure limit of 5%.
(b) Beryllium Assisted Crack Penetration which occurs when the failure probability exceeds 95%.
(c) Athermal sheath strain which occurs when the athermal strain reaches 0.4% and the volume fraction of the re-crystallized alpha-Zr-4 phase is more than 95%.
(d) Oxidation embrittlement which occurs when the oxygen concentration at the sheath mid-thickness exceeds 0.7wt%.
(e) Fuel centreline melting at 2840ºC
(f) Fuel sheath melting at 1760ºC

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2. Results and Discussion

2.1 Fission Product Assessment

The ELESTRES and SOURCE results showed higher fission gas release fractions for the outer, intermediate, and inner elements of the 37M bundle compared to the 37R bundle, while showing lower fission gas release fractions for the centre element. These results are to be expected since the change in power distribution in the 37M bundle results in higher element power ratings in the outer, intermediate, and inner elements of the 37M bundle compared to the 37R bundle for the same bundle power (as seen in Figure 1 for the outer element). Since the largest difference is found in the outer elements, the isotopic release fractions calculated using equation (1) for the outer elements of the 37M and 37R bundle are compared in Table 1 below.

Table 1: 37M/37R SOURCE Isotopic Inventory for Outer Element at end-of-dwell

Isotope	Difference in Release Fractions (37M - 37R)
Cs-134	0.004
Cs-137	0.004
Te-129m	0.004
Xe-131m	0.005
I-131	0.002
Xe-133	0.001
Te-132	0.001
Te-131m	0.000
I-133	0.001
Xe-135	0.000
I-135	0.001
Kr-85m	0.001
Xe-135m	0.17E-03
Rb-88	0.18E-03
Kr-88	0.16E-03
I-134	0.12E-03
Te-131	0.11E-03
Te-133m	0.09E-03
Cs-138	0.09E-03
Te-134	0.08E-03
Rb-89	0.06E-03
Te-133	0.05E-03
Xe-138	0.05E-03
Rb-90m	0.27E-04
Xe-137	0.25E-04
Kr-89	0.23E-04

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The experimental uncertainty in the measured fractional release of the fission gas is estimated to be in the range of 10% based on [7]. As can be seen in Table 1 above, the maximum difference in fission gas release fractions between 37M and 37R fuel is 0.005, an order of magnitude smaller than the estimated SOURCE uncertainty. Based on this comparison, it is concluded that the impact of 37M fuel on fission gas release is small.

2.2 Fuel Temperature and Element Integrity Assessment

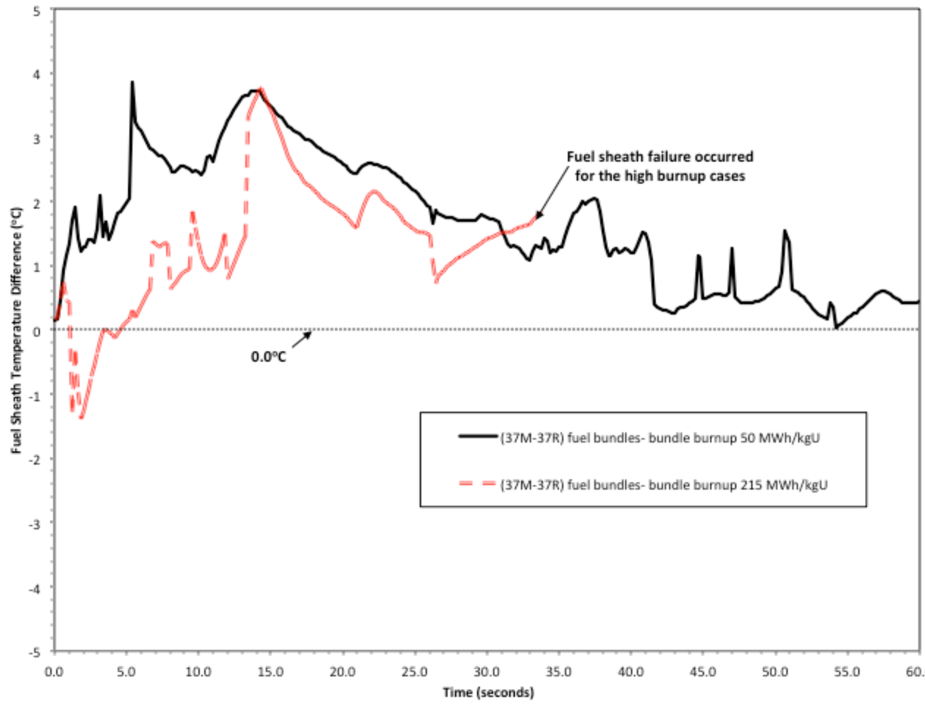
The ELOCA-IST code results generally showed higher sheath temperature, fuel temperature, and sheath hoop strain for the outer element of the 37M bundle compared to the 37R bundle, while showing lower sheath temperature, fuel temperature, and sheath hoop strain for the centre element.

Figure 2 below shows the difference in sheath temperature for the outer element of the 37M and 37R bundle. While the temperature of the 37M outer element sheath is higher, this temperature difference remains within 4ºC; i.e., ~0.4% of the 37R sheath temperature. As this difference is smaller than the ELOCA-IST code uncertainty (2σ), which is estimated to be in the range of ±5%, there is no impact on the margin for element integrity.

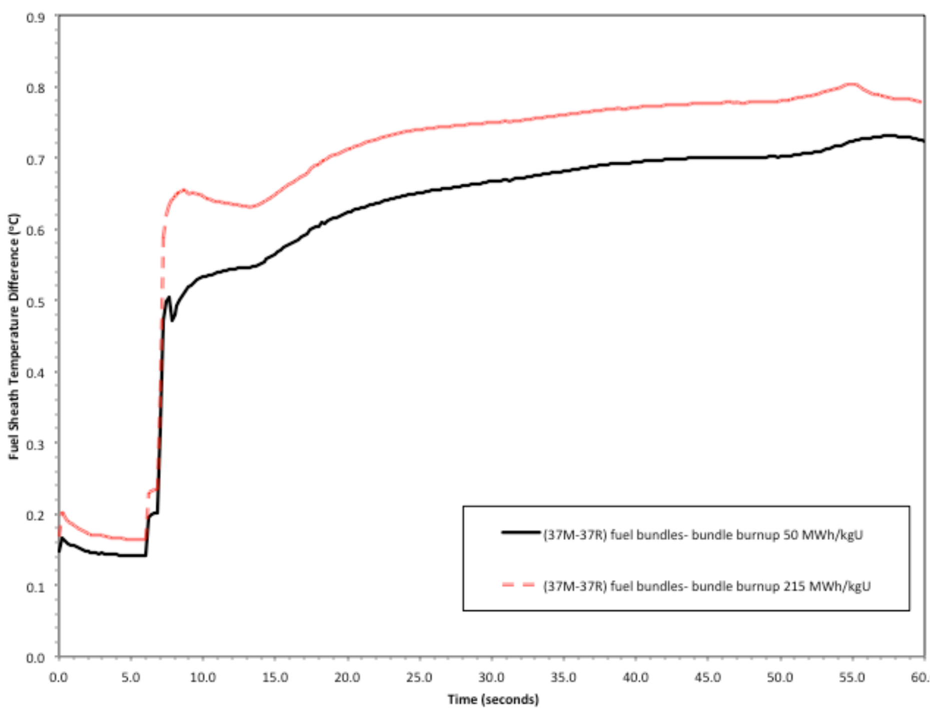
Figure 3 below shows the difference in fuel centreline temperature for the outer element of the 37M and 37R bundle. While the temperature of the 37M outer element sheath is higher, this temperature difference remains within 10ºC; i.e., ~0.6% of the 37R sheath temperature. As this difference is smaller than the estimated ELOCA-IST code uncertainty (2σ) of ±5%, there is no impact on the margin for element integrity.

Figure 4 shows the difference in sheath hoop strain for the outer element of the 37M and 37R bundle. The difference in the sheath hoop strains is small and is in the range of 0.006% to 0.067% or equivalently 0.44% to 2.35% relative to the 37R sheath hoop strain.

For the LOF case, the peak hoop strains of the 37R and 37M outer elements were well below the failure criterion of 5% and a large margin to failure due to sheath overstrain will be maintained for the outer element when 37M fuel is implemented. For LBLOCA, the difference in the sheath hoop strain did not significantly impact the fuel sheath failure time as the 37M fuel failed less than 1 second earlier than the 37R fuel as shown in Table 2 below for the high-burnup LBLOCA case. For the low-burnup LBLOCA case and the high- and low-burnup LOF cases, there was no difference in the failure times for 37M and 37R fuel. Table 2 also confirms that there is no difference in the oxygen concentration in the 37M and 37R fuel sheath.

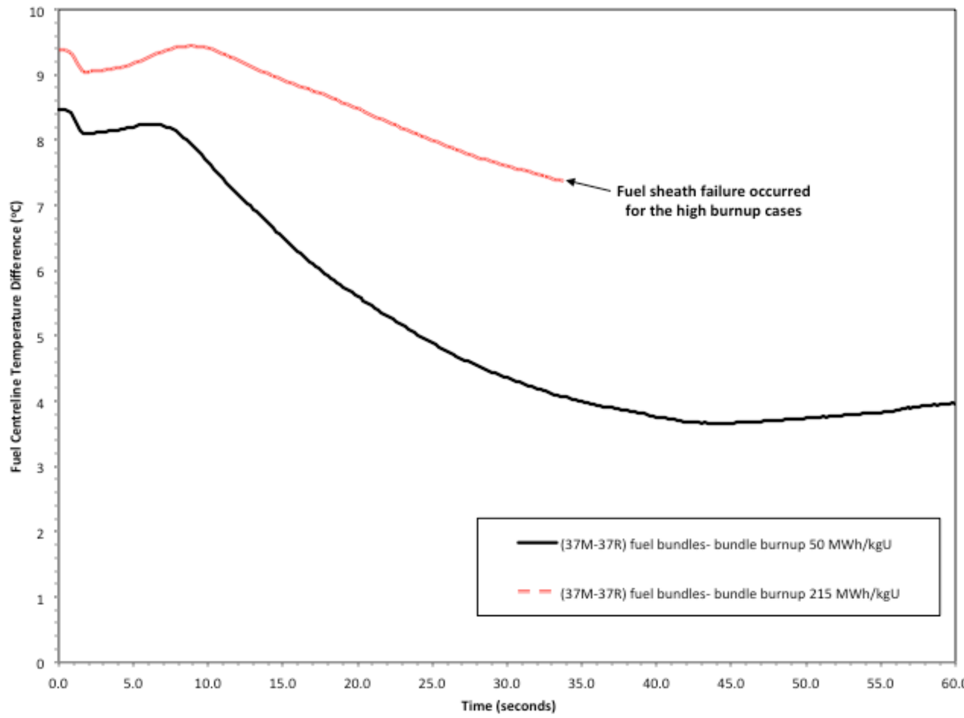


(a)

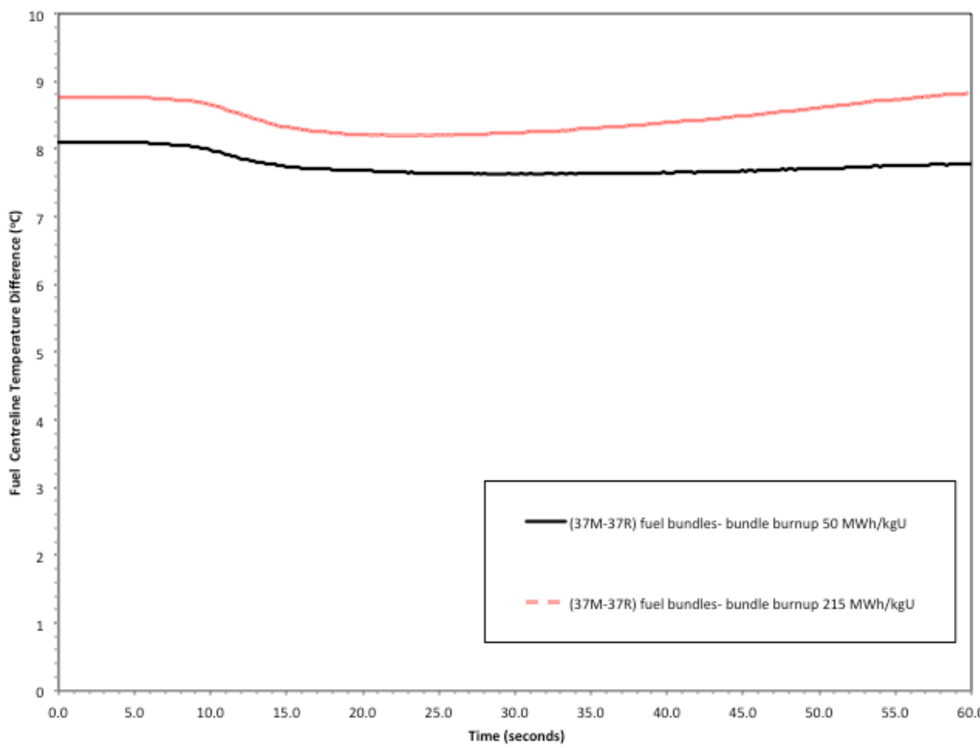


(b)

Figure 2: Comparison of outer element fuel sheath temperature transients for 37R/37M fuel bundles for the (a) LBLOCA and (b) LOF case at 50 MWh kgU^{-1} and 215 MWh kgU^{-1}



(a)



(b)

Figure 3: Comparison of outer element fuel centreline temperature transients for 37R/37M fuel bundles for the (a) LBLOCA and (b) LOF case at 50 MWh kgU^{-1} and 215 MWh kgU^{-1}

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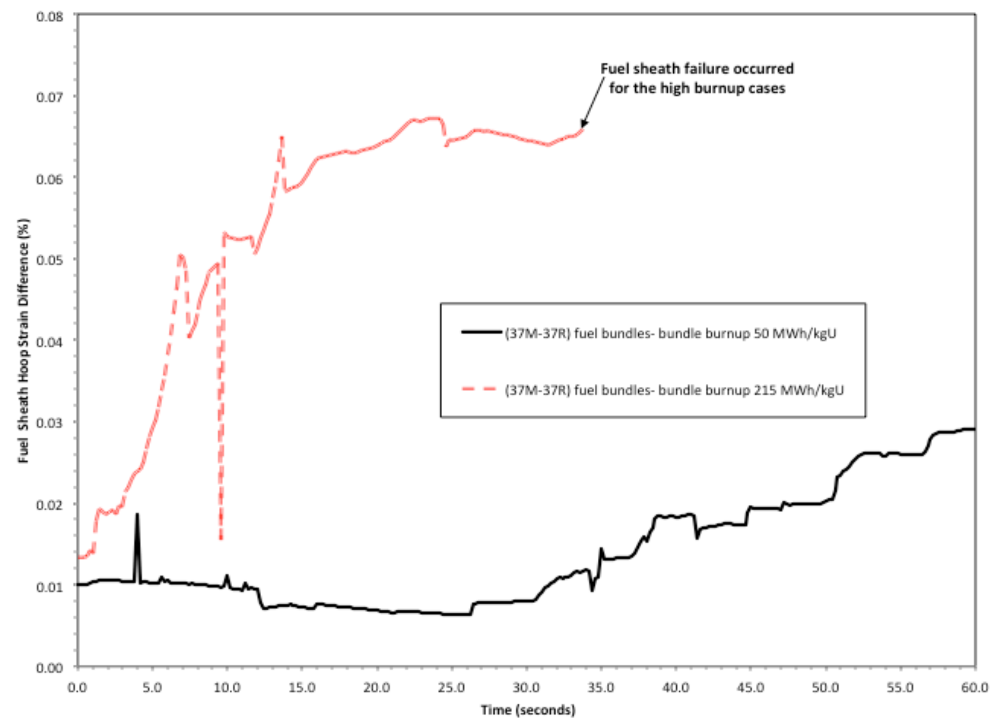
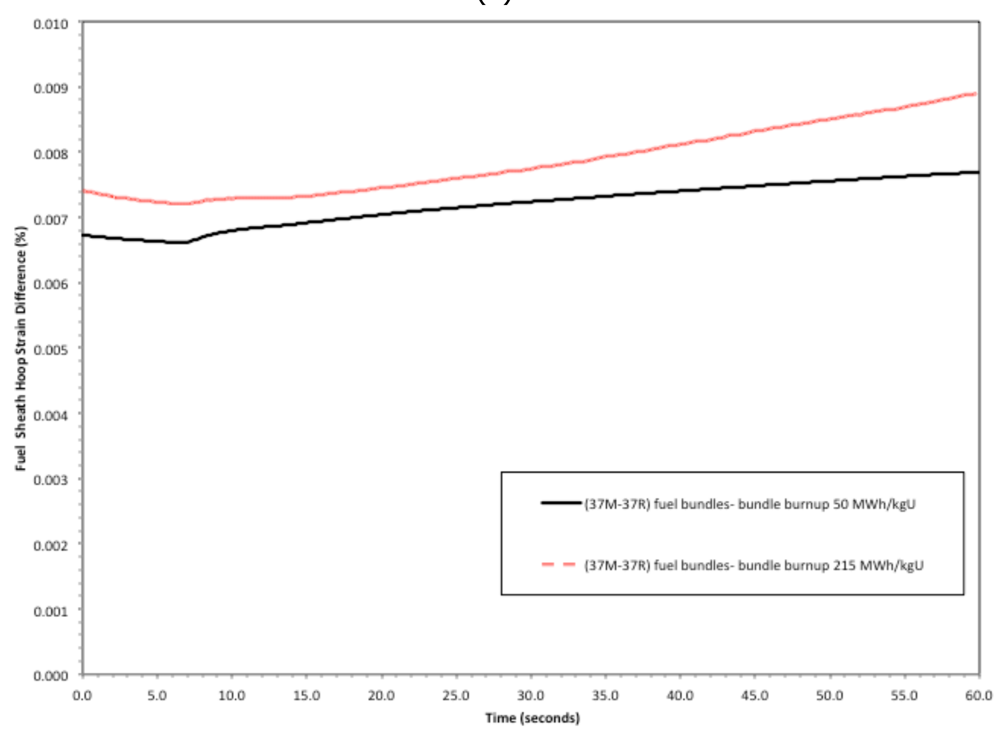


(a)



(b)

Figure 4: Comparison of outer element fuel sheath hoop strain transients for 37R/37M fuel bundles for the (a) LBLOCA and (b) LOF case at 50 MWh kgU^{-1} and 215 MWh kgU^{-1}

Table 2: Comparison between the time of sheath failure or fuel centerline melting and the oxygen concentration at the sheath mid-thickness for the outer element of 37R/37M

Case / Parameter*	LBLOCA – 50 MWh kgU^{-1}		LBLOCA – 215 MWh kgU^{-1}		LOF –50 MWh kgU^{-1}		LOF – 215 MWh kgU^{-1}	
	Max/Min difference during transient**	Max/Min relative difference during transient (%)***	Max/Min difference during transient**	Max/Min relative difference during transient (%)***	Max/Min difference during transient**	Max/Min relative difference during transient (%)***	Max/Min difference during transient**	Max/Min relative difference during transient (%)***
Time of sheath failure or fuel centreline melting (s)	None	-------	-0.75 **37R:** Failure at 34.55 seconds (overstrain) **37M:** Failure at 33.8 seconds (overstrain)	-2.17	None	-------	None	-------
Oxygen concentration at the sheath mid-thickness (wt%)	0.00/0.00	No difference	0.00/0.00	No difference	0.00/0.00	No difference	0.00/0.00	No difference

*In case of fuel sheath failure or fuel centreline melting the parameters are reported up to the failure or melting time not for the whole transient

**The difference is defined as $37M\ Parameter - 37R\ Parameter$

***The relative difference is defined as $100\text{x}\,\frac{37M\ Parameter - 37R\ Parameter}{37R\ Parameter}$

Therefore, Figures 2, 3, and 4, as well as Table 2 confirm that the 37M fuel has no impact on element integrity margins.

3. Summary and Conclusions

The 37M fuel design features a smaller centre element diameter to allow additional coolant flow through the bundle, thereby increasing the Critical Heat Flux in the channel relative to the 37R bundle. A comparison of fission gas release from 37R/37M under NOC was performed for outer/intermediate/inner/centre fuel elements. The ELESTRES and SOURCE results showed that the only fission product gas release of any significance was from the outer element for both 37R and 37M fuel. The SOURCE analysis demonstrated that any differences in fission gas release between 37R and 37M fuel are very small, below 0.01 fraction of the total fission product inventory for the outer fuel elements. It is therefore concluded that the change in fuel design has only a small impact on fission gas release.

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To investigate the impact of the 37M bundle on the fuel element integrity during accidents, the centre and outer element thermal-mechanical responses for the 37M and 37R bundles were examined using the ELESTRES and ELOCA-IST codes under the same TH boundary conditions for a LBLOCA and a LOF case. The reduction in the 37M centre element power resulted in lower fuel sheath temperature, fuel centreline temperature, and sheath hoop strain compared to the 37R centre element. The increase in the 37M outer element power resulted in slightly higher fuel sheath and fuel centreline temperatures compared to the 37R outer element temperatures (i.e., an increase of less than 10^{o}C or 0.6%). The temperature differences between the two bundles do not impact the margins of fuel pellet and sheath integrity. The outer element sheath hoop strain of the 37M bundle was always higher than that of the 37R bundle due to the difference in the element power and temperature. However, this difference was small and it did not affect the failure time (i.e., the 37M outer element failed earlier than the 37R outer element by less than 1 second) and will not increase the number of outer fuel element failures.

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