Design and Safety Assessment of Slightly Enriched Fuel Elements for CANDU Reactors

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Summary

Fuel with very slight enrichment allows for an increase in the number of full power days for a 37-element fuel bundle. Consequently sheath strain, FGR, and fuel temperature are affected. The goalis to confirm that safety margins could be maintained, with some minor fuel design enhancements. The effect of selected design parameters on safety margins has been assessed. Asystematic design study confirms thatsheath strain and FGR could be maintained, when compared with thecurrent predicted values. It was found that current manufacturing parameters are fully capable to maintain safety margins for a desired enrichment of 0.75% Uranium-235. Three enhanced fuel designs have also been presented which reduce the effects of enrichment.

1. Introduction

Current CANada Deuterium Uranium (CANDU) reactors use natural uranium (NU) as fuel,which is comprised of 0.715% Uranium-235 (U-235) and 99.285% Uranium-238 (U-238)[1]. On-power refueling is necessary to maintain long-term core reactivity for CANDU reactors. This puts pressure on the fuel handling department when the fueling machine is under maintenance or unavailable. If the period between fuelling could be increasedby approximately 10 days on average, it would alleviate this pressure and result in other potential benefits to CANDU reactors in Canada and around the world.

2. Objectives

Previous work has demonstrated thata slight increase of U-235 in the fuel results in a significantimprovement in the useful life of the bundle relative to the enrichment.An enrichment of 0.75% U-235 would be sufficient to meet station requirements to increase the fuel life cycle by at least 10 additional full power days (FPD) with no negative impact on criticality[1]. The objectives of this paper are to assess the effects of very slightlyenriched fuel bundle on safety and to demonstrate the existing fuel design envelop is sufficient to maintain the safety margins while increasing the number of FPD for a 37-element fuel bundle.

3. Design

3.1 Acceptance Criteria

The following two conservative acceptance criteria defined by the United States Nuclear Regulatory Commission (USNRC)[2] and considered by the CSNC have been set as the constraints:

- No UO_2 centreline melting which occurs at 2840°C
- Maximum Sheath strain cannot exceed 1%

The designs must also minimize the quantity of fission gas released into the fuel-sheath gap by not exceeding the quantities produced in the current NU design.The goal is to present an enhanced fuel element design that would allow for the very slight enrichment of fuel while keepingdesign enhancements as simple as possible such that it could be easily implemented. There are many design variables to consider within a fuel element.The density of fuel pellets and pellet grain sizeare the focus as they determine the thermal conductivity and the subsequent fission gas release (FGR)[3]. The total internal void within a CANDU fuel element has also beenconsidered as it accommodates FGR.

3.2 Design Parameter Variance

Fuel pellet density, grains size, and the axial gap were all independently varied on a scale of the standard deviation, σ, in current manufacturing values shown in Table 1[4]. Each parameter was independently varied from the current mean by ±3 σ. The effectthroughouta typical CANDU burnup history was simulated using ELESTRES-IST (ELEment Simulation and sTRESes – Industry Standard Tool). This is the current industrial tool used to predict the on-power axisymmetric, thermal, micro-structural, and mechanical behavior of a CANDU fuel element[5].

Table 1: Mean values and standard deviation of specified fuel manufacturing parameters.

	Pellet Density (g/cm^3)	Pellet Grain Size (μm)	Axial Gap (mm)
Mean Value	10.626	8.226	2.902
σ	0.020	1.222	0.263

The sensitivity of these parameters on sheath strain, centreline temperature, and FGR throughout the CANDU burnup history is shown in Table 2. The variance ofthe parameters also demonstrated similar trends for enrichments as high as 0.91%.

Table 2: The maximum values of the of safety constraints throughout the burnup historydue to achange of ±3σ in selected fuel designparameters.

		Maximum Sheath Strain (%)	Maximum Fission Gas Release (%)	Maximum Centreline Temperature (^{o}C)
Mean Values		0.884	11.3	1750
Pellet Density	-3σ	0.720	12.2	1770
	+3σ	1.040	10.5	1740
Pellet Grain Size	-3σ	0.915	12.7	1770
	+3σ	0.836	11.0	1740
Axial Gap	-3σ	0.896	11.3	1750
	+3σ	0.823	11.5	1750

4. Methodology: Thermomechanical Behaviour

4.1 Heat Conduction

The temperature and heat flux in the pellet are critical in understanding every physical property of the fuel. Heat is generated inside the fuel, transported to the outer surface of the fuel, and finally through the sheath to the coolant. Consideration of the thermal interaction between the fuel and cladding is an important factor in determining the fuel temperature profile. The temperature drop across the fuel-to-sheath gap can be calculated as[6]:

$$\Delta T_{gap} = \frac{P_{lin}}{2\pi r_{gap}}\left(\frac{1}{h_T}\right) \quad (1)$$

Where ΔT_{gap} is the temperature difference, P_{lin} is the linear power, r_{gap} is the radius from the fuel centre to the gap, and h_T is the total heat transfer coefficient between the fuel and cladding. This can be represented as the sum of three different components:

$$h_T = h_S + h_g + h_r \quad (2)$$

Where h_S is the heat conduction due to solid-solid contact between the fuel and cladding, h_g is the conduction through gas in the gap and h_r is the radiative transfer from the fuel to cladding. Heat transfer due to radiation is very small relative compared to the other two terms and can be neglected. The density impacts the thermomechanical behaviour of the fuel and cladding due to their influence on heat transfer and fission gas production in the fuel.

4.2 Fission Gas Release

The heat conduction, h_g, through gas in the gap is dependent on the composition of the gas mixture. The stable release of fission product gases from the fuel pellets determines this composition of the gas mixture, and likewise the pressure on the cladding. The rate of release of fission product gases to the grain boundary within the fuel is dependent on the grain diameter. The accumulation of gases on the grain face eventually leads the growth of bubbles which form tunnels to the surface of the fuel[6].

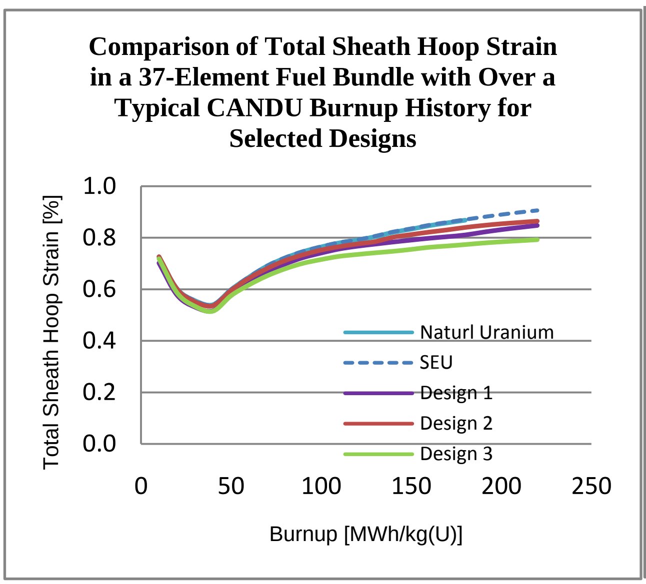
5. Results and Discussion

Three enhanced designs have been proposed in effort to reduce the maximum sheath strain and FGR back to values currently predicted using NU. The proposed designs have been based on the results found through parameter variance and design simplicity. Figure 1 shows a comparison of the sheath strain andFGR for all the proposed designs throughout an extended burnup. This is compared to what is predicted to occur using current manufacturing valueswith NU and 0.75% U-235.

<u>Design 1</u>
Increase the axial gap by 3σ, this correlates to an additional 0.789 mm in the gap. This decreases sheath strain by accommodating the additional fission product that is released into the void, but it does not help in the reduction of FGR itself, as expected. It is proposed as this is the simplest and most feasible parameter to vary during bundle assembly.

<u>Design 2</u>
Increase the average pellet grain size by 2σ, or 2.444μm. This slight increase is sufficient to meet the goals to reduce sheath strain and FGR to the original quantities. The drawback is the manufacturing process is more complex to adjust, and consequently it may be more complicated to implement.

<u>Design 3</u>
Reduce density by 1σ, or 0.020 g/cm^3. This reduces sheath strain but has an adverse effect on FGR. To offset the increased FGR, an increase in grain size by 3σ is necessary. The result of this design is a reduction in sheath strain but the adjusted grain size was not sufficient to negate the effects on FGR from density. This outcomeis becausedensity has a stronger effect on FGR thangrain size when adjusted simultaneously. It was found that this approach was not effective or practical to implement.



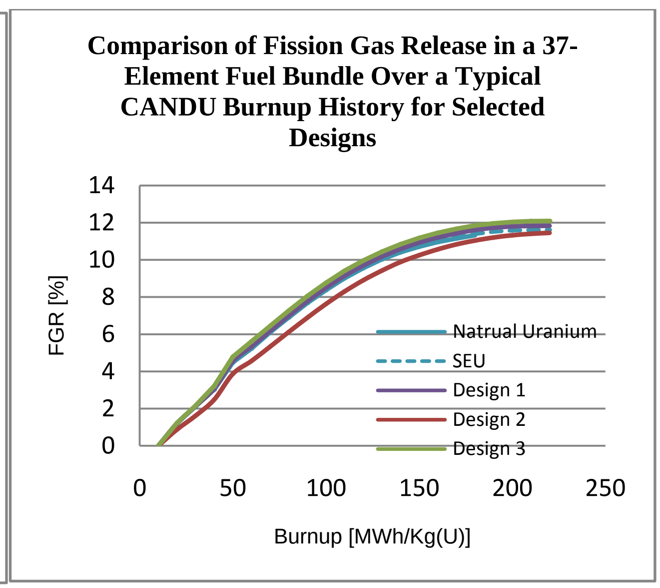


Figure 1: Comparison of the enhanced fuel designs and the current manufacturing parameters for NU and a very slight enrichment of 0.75% U-235. Graph a) on the left presents the sheath strain as a percentage of the change from the original cladding shape throughout a typical burnup. Graph b) on the right presents the FGR as a percentage of the gas composition within the internal void throughout a typical CANDU burnup history.

6. Conclusion

A consequent of extending the number of full power days for a 37-element fuel bundle by very slight enrichment isan increase on the maximum sheath strain, FGR, and a very slight variance in temperature. Nevertheless,is was found through using ELESTRESto view the impact on safety margins over an extended burnup that the current manufacturing parameters are capable are fully capable to maintain safety margins set by the USNRC while using fuel enriched of 0.75 wt% U-235. That is no fuel melting and sheathing strain never exceeds 1%.

Three enhanced fuel designs have been presented, all resulted in a sufficient reduction in sheath strain, but had varying effects on FGR. The results show that an increase in the pellet grain size of 2.444 μm (Design 2) would be sufficient to reduce the effects of 0.75% U-235 enrichment and return sheath strain and FGR to current values. Variation of grain size may present challenges during manufacturing. With this in mind an alternative solution would be to reduce the axial gap by 0.789 mm (Design 1). This is a simple method to reduce sheath strain andprovide sufficient spacing for the additional fission gases to accumulate. These are two possible design enhancements capable ofmaintaining sheath strain and FGR at the same level as the NU fuel design, and thus allow an increase in the fuel life cycle by at least 10 additional full power days.

7. References

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