

Upgrading Potential of a CANDU 6 Reactor with CANFLEX Fuel - A Safety Analysis Perspective

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ABSTRACT

CANFLEX® (CANDU FLEXible fuelling) fuel bundles with natural uranium have reduced outer element linear powers as well as higher dryout powers, providing an opportunity to increase the power output of the CANDU 6 reactor. In this study, consequences of a postulated large loss of coolant accident (LOCA) were used as an indicator to determine the power increase. The power-uprating potential was determined by increasing the power in a CANFLEX-fuelled reactor to the point where the predicted consequences, in terms of calculated fuel failures and pressure tube strain, are the same as the consequences for a 37-element fuelled reactor operating at current nominal powers.

1. INTRODUCTION

This paper presents the single channel analysis performed to determine the increase in nominal reactor power for a full core of CANFLEX-NU fuel so that the consequences of postulated large break loss of coolant accidents (LOCAs) are not increased relative to a 37-element fuelled core. An analysis of the consequences of a large break LOCA will provide a limit on the reactor power increase from the current nominal power. Because of the lower outer element linear power ratings of CANFLEX fuel, as compared with those of 37-element fuel, there is a potential for an increase in reactor power without a decrease in safety margins. The hydraulic properties of CANFLEX fuel are essentially equivalent to the hydraulic properties of 37-element fuel (to within 1%) [1], therefore, full circuit simulations were not performed for this analysis.

1.1 Analysis Approach

To determine the approximate magnitude of the power increase, single channel analyses were performed for two large break LOCA scenarios with shut down systems and emergency core cooling (ECC) available; these scenarios were a 35% reactor inlet header (RIH) break and a 100% reactor outlet header (ROH) break. The 100% ROH break was chosen because this break size leads to the greatest number of predicted fuel failures in a 37-element fuelled core. The 35% RIH break was chosen because it leads to the greatest amount of pressure tube ballooning contacts with the calandria tube in a 37-element fuelled core.

Two high power channels, 7.3 MW licensing limit (with the assumption that there two bundles at their licensing limit of 935 kW) and 6.83 MW were used for this uprating analysis. These channel powers were increased, and the consequences of a large

break LOCA were assessed at each increase in power while constant header-to-header boundary conditions were maintained for the steady-state and transient calculations.

1.2 Acceptance Criteria

The power of the CANFLEX channel was increased until the point where the following primary criterion was met:

- 1) The amount of pressure tube/calandria tube contact of a CANFLEX fuelled channel equals the amount of contact of a 37-element fuelled channel.

Two other secondary criteria were also considered:

- 1) The number of fuel failures for a CANFLEX fuelled channel equals the number of fuel failures for 37-element fuelled channel.
- 2) The fission product release from the fuel to sheath gap of CANFLEX fuel equals the gap release from 37-element fuel.

1.3 Behaviour

The sequence of events that occur after a large break LOCA such as reactor trip, loop isolation, ECC initiation, pump trips, etc., will not vary significantly for a full core of CANFLEX fuel. The channel and system thermalhydraulics for a full core of CANFLEX fuel will not differ significantly from the thermalhydraulics for a full core of 37-element fuel. The reason for this similarity is that the channel flows as a function of pressure drop for CANFLEX fuel are within approximately 1% of the value for a channel with 37-element bundles [1].

2. ANALYSIS METHODS AND ASSUMPTIONS

2.1 Power Pulse Analysis

A 100% pump suction pipe (PSP) break power pulse for a full core of CANFLEX fuel was applied to the 35% RIH and 100% ROH break thermalhydraulic boundary conditions. The power pulse for the 100% PSP break is greater in amplitude than the power pulse for either the 100% ROH or 35% RIH breaks and thus will provide upper bounds on the fuel and fuel channel behaviour during both accident scenarios. To provide a consistent basis for comparison, the 100% PSP power pulse, as calculated for a 37-element fuelled core, was applied to the thermalhydraulic boundary conditions for the 35% RIH and 100% ROH breaks for 37-element fuel; the same methodology and tools were used as those that were used for the full core CANFLEX 100% PSP power pulse calculation.

The power pulse analysis was performed using coupled CATHENA-RFSP simulations of the system response after break initiation [2,3]. The thermalhydraulic circuit model used in the power pulse calculations is a full circuit two-

loop representation of a typical CANDU-6 primary heat transport system (PHTS). The model is identical to the standard model used in the assessment of 37-element bundles, except that the fuel string thermalhydraulic parameters correspond to those of the CANFLEX bundles; a critical heat flux (CHF) correction factor was used for CANFLEX fuel [1]; pressure tube creep was only considered for the power pulse calculations.

2.2 Single Channel Analysis Methodology

The single channel analysis was performed using the CATHENA computer code [2]. The analysis used previously calculated header boundary conditions obtained from the Wolsong 2/3/4 CATHENA full circuit calculations of 35% RIH and 100% ROH large break LOCA's. The single channel thermalhydraulic analysis was performed for a high power channel (channel O6) using two axial bundle power distributions: a 7.3 MW (licensing limit) channel, with two bundles (bundles 6 and 7) operating at 935 kW (licensing limit); and a 6.83 MW channel where the high power, mid-channel bundles operate at 784 kW. Table 1 provides the axial power distribution for the 7.3 and 6.83 MW channels. Table 2 provides the radial power distribution for both the 37-element and CANFLEX bundles.

2.3 Fuel Methodology

The ELESTRES computer code was used to determine the initial fuel conditions [4] for both the 37-element and CANFLEX fuel. The CANFLEX fuel elements, as well as the 37-element fuel elements, are assumed to follow the 37-element outer element over-power curve for a 935 kW fuel bundle; scaled accordingly to each ring of fuel elements.

The ELOCA computer code [5] was used to calculate the fuel temperature as well as the thermo-mechanical behaviour of the fuel during the transient. The initial conditions for the ELOCA calculations were provided by the ELESTRES computer code, and the transient simulations were performed using the transient thermalhydraulic boundary conditions obtained from the CATHENA single channel simulations. Sheath failures are assumed to occur if the ELOCA results indicate that any of the following failure criteria are satisfied:

- i. 2% sheath hoop strain and sheath temperatures greater than 1000°C,
- ii. 5% sheath hoop strain at any sheath temperature,
- iii. fuel centre-line melting (greater than 2840°C),
- iv. oxygen concentration in the sheath greater than 0.7 weight% over at least half of the cladding thickness, and
- v. probability of beryllium-braze assisted cracking greater than 1%.

These failure criteria are applied to both the 37-element fuel and CANFLEX fuel. Failure mechanisms (i), (ii) and (iii) are the most relevant sheath failure mechanisms for a large break LOCA analysis. Failure criteria (iv) and (v) are more

applicable when the sheath remains at high temperatures for prolonged periods of time, which are not expected during a large break LOCA having ECC available.

3. ANALYSIS RESULTS

The primary acceptance criterion was applied to the 35% RIH accident analysis, and the secondary acceptance criteria were applied to the 100% ROH accident analysis. This approach was taken because no pressure tube/calandria tube contact is expected to occur for the 100% ROH and no fuel element failures are expected for the 35% RIH analysis.

3.1 35% RIH Break

3.1.1 7.3 MW Channel

The CANFLEX fuelled high power channel was increased in power until the first acceptance criterion was met. At 106.5% (7.77 MW) of nominal channel power the pressure tube contacted the calandria tube at five axial locations, which is equivalent to the 37-element fuelled channel operating at nominal power.

Figures 1 and 2 present results of the ELOCA calculated fuel centre-line temperature and internal gas pressure transients used to analyze the performance of the CANFLEX fuelled channel. Figures 1 and 2 have been plotted for the 37-element case at 100% power and for the CANFLEX fuelled channel operating at 100% and 106.5% power for the highest temperature bundle (bundle position 7). From these figures it can be seen that even at the elevated power of 106.5% of nominal, the centre-line temperature and internal gas pressure are lower for CANFLEX fuel than those of 37-element fuel.

The CATHENA calculated temperature transient of the pressure tube is shown in Figure 3 for bundle position 7 for the 37-element fuelled channel, as well as the CANFLEX fuelled channel at 100% and 106.5% of nominal power. It can be seen that the peak pressure tube temperature is higher for the 37-element case than for either of the CANFLEX cases.

3.1.2 6.83 MW Channel

The 6.83 MW channel was used as a more 'reactor typical' high power channel and was investigated for the 35% RIH accident scenario using only the first acceptance criterion. No pressure tube/calandria tube contact was calculated for either the 37-element or CANFLEX fuelled channels operating at 6.83 MW. The powers in both channels were increased until first contact was predicted, at 106.5% power for the 37-element fuelled channel and at 116.5% power for the CANFLEX fuelled channel. The results indicate that CANFLEX fuelled channel would have an up-rating potential of 10% when compared to the 37-element fuelled channel. For the power at which first contact is predicted to occur, Figure 4 compares the fuel centre-line temperatures for the two fuel types. This figure illustrates that, even at higher relative powers, fuel centre-line

temperatures for CANFLEX fuel are lower, as compared with those of the 37-element fuel.

3.2 100% ROH Break

Fuel element failures were assessed using the 100% ROH accident scenario at the elevated power levels. For channel powers up to 106.5% nominal power, no fuel CANFLEX element failures were predicted to occur. Figure 5 is a plot of the fuel centre-line temperature, and Figure 6 is a plot of the internal gas pressure. For both of these transients, the calculated temperatures for the CANFLEX fuelled channel are lower than the calculated temperatures for the 37-element fuelled channel.

In terms of the available fission product gap inventory for release after sheath failure, CANFLEX fuel has a lower inventory, as shown in Figure 7. This lower inventory, combined with greater margin to fuel failure, will result in lower fission product release.

4. CONCLUSIONS

From the analysis of a 35% RIH break, the power in a 7.3 MW channel within a full core of CANFLEX fuel can be increased to 106.5% nominal power at which the extent of pressure tube/calandria tube contact is approximately equal to that of the 37-element fuelled channel. In the 6.83 MW channel case for the 35% RIH accident scenario, the power within the channel could be increased to 116.5% of nominal power before the pressure tube is calculated to contact the calandria tube. Similarly, the 37-element fuelled core operating with a high power channel of 6.83 MW could be increased to 106.5% before first contact, leaving a 10% margin between the two fuel types for the more typical 6.83 MW channel. In terms of determining the uprating potential of CANFLX fuel, the 35% RIH break is more limiting than the 100% ROH break.

The consequences during a 100% ROH large break LOCA were investigated at the up-rated powers, calculated in the 35% RIH analysis. No fuel element failures were calculated to occur for the CANFLEX fuelled channel. In addition, CANFLEX fuel element centre-line and sheath temperatures during the 100% ROH accident are either less than or comparable to those of the 37-element fuelled channel. Because of the flatter radial element power distribution of the CANFLEX fuel bundle, fission product release will also be lower for CANFLEX than for 37-element fuel.

The conclusion of this study is that there is uprating potential available with a CANFLEX fuelled core, and the consequences of a large break LOCA for the up-rated CANFLEX core would be no worse than the consequences after a large break LOCA for a 37-element fuelled core at nominal power.

5. REFERENCES

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2. B.N. Hanna, "CATHENA: A Thermalhydraulic Code for CANDU Analysis", Nuclear Engineering and Design, 180 (1998) 113-131.
3. B. Rouben, "Overview of Current RFSP-Code Capabilities for CANDU Core Analysis", AECL-11407, 1996 January.
4. M. Tayal, "Modelling CANDU Fuel Under Normal Operating Conditions: ELESTRES Code Description", AECL-9331, 1987 January.
5. H.E. Sills, "ELOCA Fuel Element Behaviour During High-Temperature Transients", AECL-6357, 1979 March.

Table 1 - Axial (Bundle) Power Distribution in the 7.3 MW and 6.83 MW Channels (kW)		
Bundle Position	7.3 MW	6.83 MW
1	111.8	170.7
2	406.1	402.6
3	619.7	581.7
4	761.4	709.0
5	874.0	737.1
6	935.0	783.8
7	935.0	782.8
8	875.6	737.6
9	744.9	710.0
10	577.5	603.4
11	363.8	426.6
12	95.3	181.4

Table 2 - Radial Power Distribution for the 37-Element and CANFLEX Fuel Bundle (Plutonium Peak)		
	Element Ring	Element Power
37-Element	Centre	0.7613
	Inner	0.8051
	Inter.	0.9206
	Outer	1.131
CANFLEX	Centre	1.0325
	Inner	1.0800
	Inter.	0.8707
	Outer	1.058

Figure 1 - 35% RIH Break Fuel Centre-Line Temperatures for 37-Element Fuel at 100% Power and CANFLEX Fuel at 100% and 106.5% Power for the 7.3 MW Channel

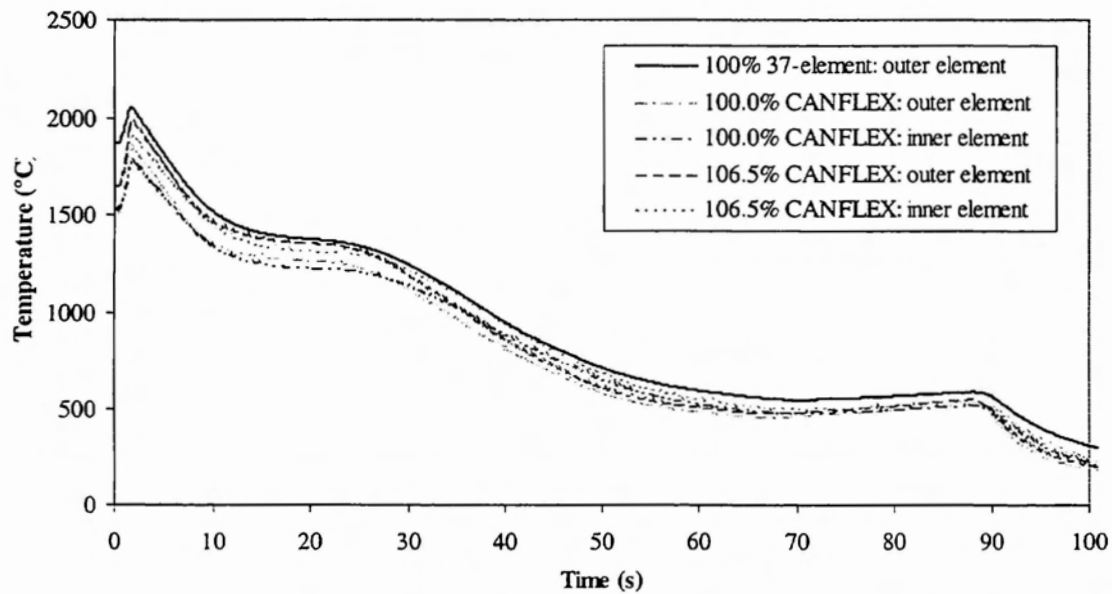


Figure 2 - 35% RIH Break Internal Gas Pressure for 37-Element Fuel at 100% Power and CANFLEX Fuel at 100% and 106.5% Power for the 7.3 MW Channel

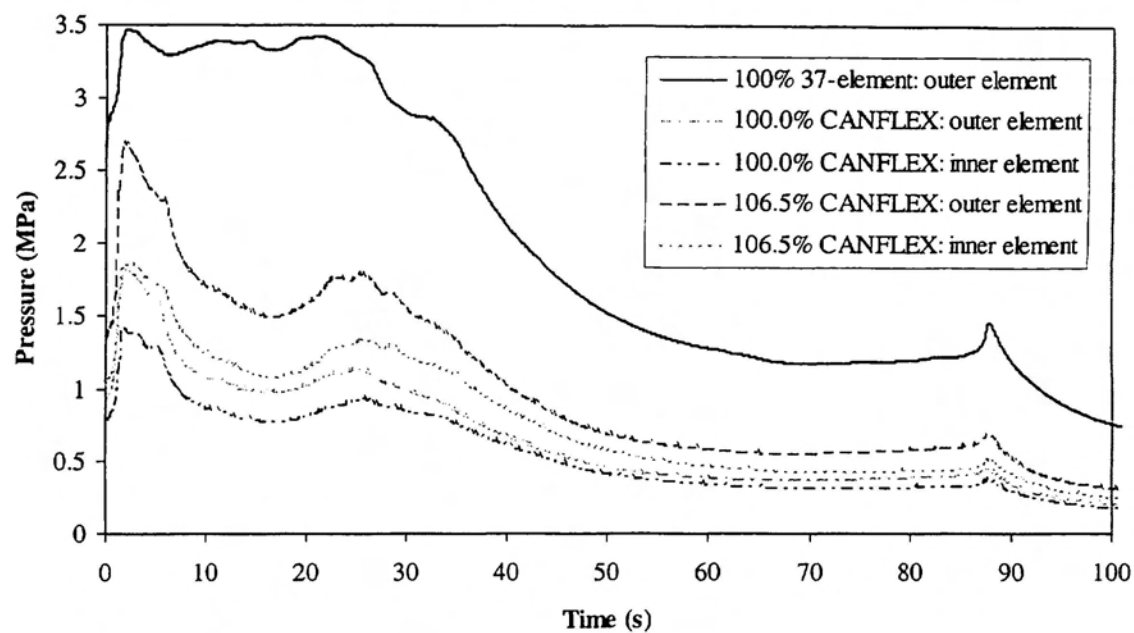


Figure 3 - 35% RIH Pressure-Tube Temperature for 37-Element Fuel at 100% Power and CANFLEX Fuel at 100.7% and 106.5% Power for the 7.3 MW Channel

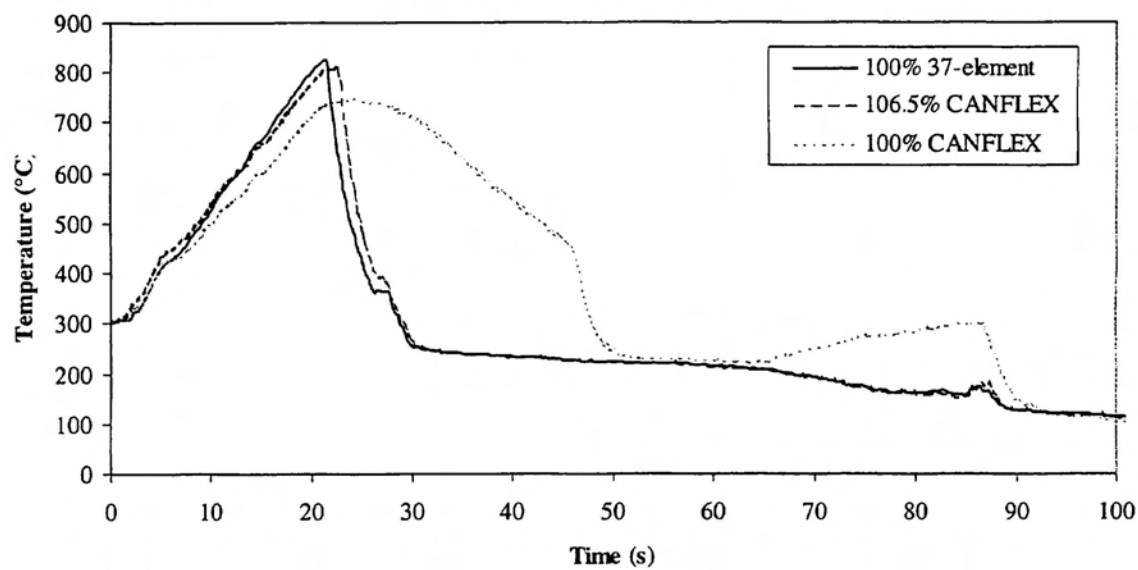


Figure 4 - 35% RIH Fuel Centre-Line Temperature for 37-Element Fuel at 106.5% Power and CANFLEX Fuel at 116.5% Power for the 6.83 MW Channel

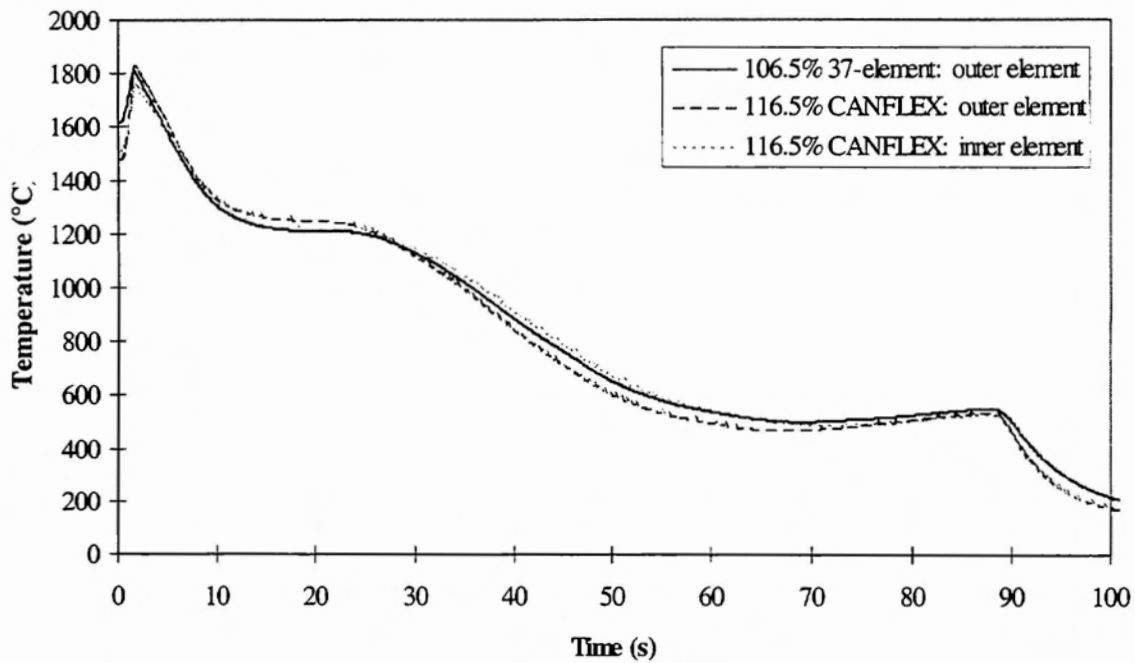


Figure 5 - 100% ROH Fuel Centre-Line Temperature for 37-Element Fuel at 100% Power and CANFLEX Fuel at 100% and 106.5% Power for the 7.3 MW Channel

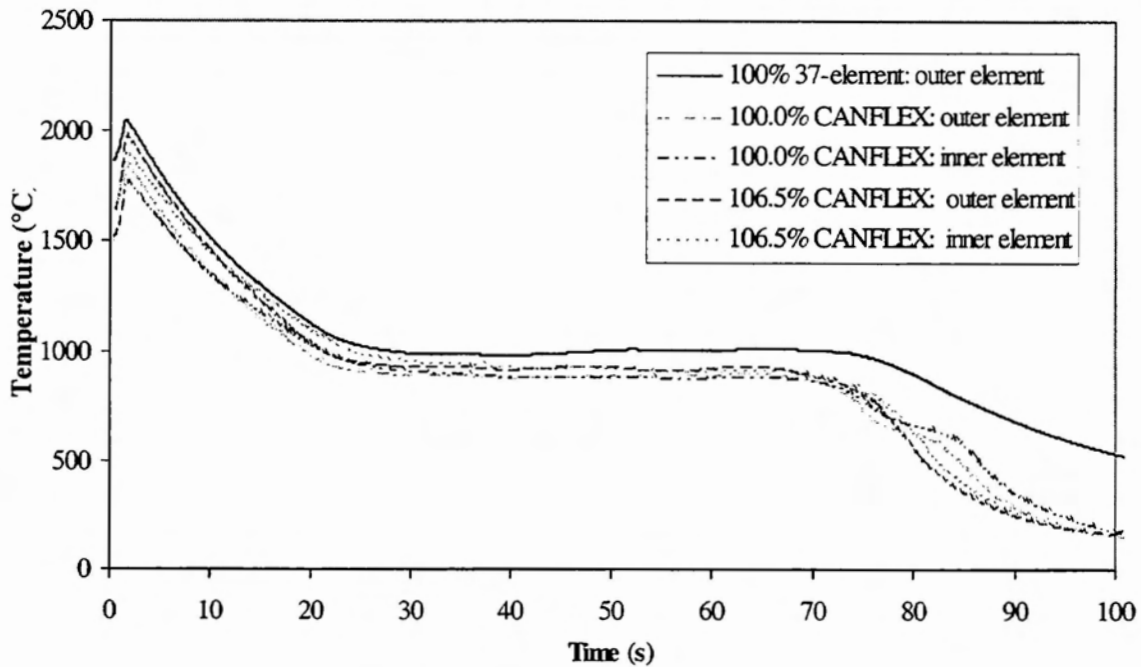


Figure 6 - 100% ROH Internal Gas Pressure for 37-Element Fuel at 100% Power and CANFLEX Fuel at 100% and 106.5% Power for the 7.3 MW Channel

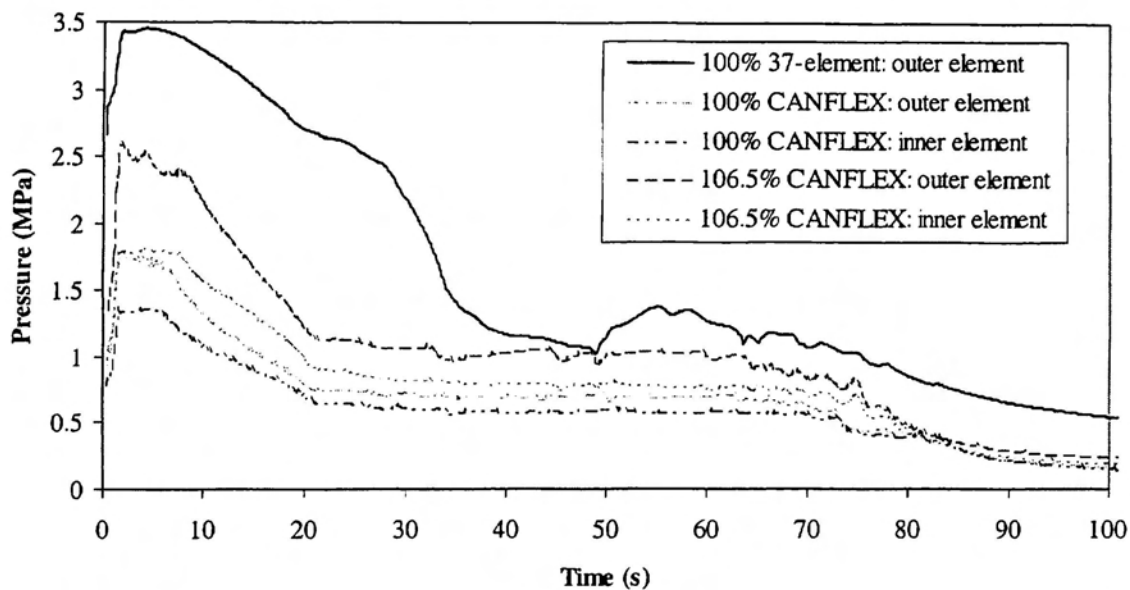


Figure 7 - Comparison of Fission Product Gap Inventories for 37-Element Fuel at 100% Power and CANFLEX Fuel at 100% and 106.5% Power

