MODIFIED 37-ELEMENT BUNDLE DRYOUT

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Abstract

The Heat Transport Systems (HTS) of the Canadian nuclear reactors are ageing. One of the effects of ageing is the non-uniform change in the dimension of the reactor pressure tubes through the mechanism of diametral creep. The mechanism has the global effect of increasing channel flows and decreasing the reactor header-to-header pressure drop. However, the increased flow is not distributed uniformly through the fuel bundle cross-section because the bundle tends to settle at the bottom of the pressure tube leaving a crescent shaped space on the top. This portion experiences the bulk of the increased flow, as it offers the path of least hydraulic resistance. As a result of this flow bypass, the coolant flows through some of the interior-subchannels of the fuel bundle are reduced. For a given flow, inlet temperature and exit pressure, flow bypass in the top of the channel reduces flow from the interior subchannels and consequently reduces the Critical Heat Flux (CHF).

To recover some of the reduction in dryout power, OPG started a program in 2004 to examine possible modifications to the reference 37-element bundles that may result in an increase in dryout powers for the uncrept and crept pressure tube. Under accident conditions, where CHF is a concern, the ideal design is one where all fuel elements reach dryout at the same time. The ASSERT subchannel code [1] was used to explore potential modifications to the 37-element bundle that may result in increased dryout powers in an uncrept and crept pressure tube. In addition analysis of post-dryout tests in 37-element bundle [2] were examined to explore the potential of increasing the dryout power of the reference 37-element bundle by slightly modifying the bundle geometry. A small reduction of the centre element in the bundle was selected as an approach to enhance the dryout power of the bundle. CHF tests of the modified bundle were performed [3]. The measurement confirmed that the modified bundle has higher dryout powers than the reference bundle.

Keywords: CHF, Modified 37-Element Bundle Design.

1.0 Description of CANDU Channels

A general view of a CANDU fuel channel is shown in Figure 1 and Figure 2. The UO_2 fuel pellets are contained within Zircaloy-4 fuel sheaths which are grouped into fuel bundles. A 37-element fuel bundle is shown in Figure 1. The spacing between the fuel elements in the bundle is maintained by spacer pads that are brazed onto the Zircaloy-4 sheaths. The fuel bundles are contained within a Zr-2.5wt%Nb pressure tube which is surrounded by a Zircaloy-2 calandria tube. The spacing between the pressure tube and the calandria tube is maintained by an Inconel or Zircaloy garter spring. Spacing between the fuel elements and the pressure tube is maintained by bearing pads that are brazed onto the fuel sheaths.

The Heat Transport Systems (HTS) of the Canadian nuclear reactors are ageing. One of the effects of ageing is the non-uniform change in the dimension of the reactor pressure tubes through the mechanism of diametral creep. As pressure tube diametral creep increases, the changes in geometry alters the fuel-cooling behaviour. Specifically, pressure tube diametral creep increases the available coolant flow area and consequently decreases the channel resistance to flow. This has the global effect of increasing channel flows and decreasing the reactor header-to-header pressure drop. However, the increased flow is not distributed uniformly through the fuel bundle cross-section because the bundle tends to settle to the bottom of the pressure tube leaving a crescent shaped space above as shown in Figure 3. This portion experiences the bulk of the increased flow, as it offers the path of least hydraulic resistance. As a result of this flow bypass, the coolant flows through some of the interior-subchannels of the fuel bundle are reduced. For a given flow, inlet temperature and exit pressure, flow bypass in the top of the channel reduces flow from the interior subchannels and consequently reduces the Critical Heat Flux (CHF).

CHF measurements performed at Stern Labs using uncrept and 3.3% and 5.1% maximum creep pressure tubes confirmed the drop in dryout power with the increase in pressure tube creep.

2.0 Canadian Utilities Effort to Enhance CHF of the 37-Element

To recover some of the reduction in dryout power due to pressure tube creep, Ontario Power Generation (OPG) started a program in 2004 to examine possible modifications to the reference 37-element bundles that may result in an increase in dryout powers for the uncrept and crept pressure tube. The purpose of this program is to develop a modified 37-element bundle that has enhanced critical heat flux capability in a pressure tube that has significant diametral creep due to ageing. For accident conditions, where CHF is a concern, the ideal design is one where all fuel elements reach dryout at the same time. The location of the first dryout in the bundle depends on the accident. For example, during a loss of regulation accident, reactor trip occurs at relatively high flow and the first dryout occurs near the bundle centre subchannels [2]; whereas for a small break, the flow when dryout occurs is lower and dryout occurs first at the outer fuel ring of the bundle [2]. Since the operating margin is tight for Neutron Over Power (NOP) trip coverage and this margin is being reduced as a result of pressure tube diametral creep, optimization of the design for high flow events is considered to provide the greatest benefit.

Other Canadian utilities joined OPG and the program continued under the umbrella of CANDU Owners Group (COG).

2.1 ASSERT Simulation

The ASSERT subchannel code [1] was used to explore potential modifications to the 37-element bundle that may result in increased dryout powers in an uncrept and crept pressure tube. The intent of a subchannel code is to compute the distribution of the flow and enthalpy through the passages in a fuel bundle. For analysis, the rod bundle is divided into subchannels separated from each other by hypothetical lines drawn between neighbouring rod centres as shown in Figure 4. The flow conditions in the subchannels are used as input for a CHF prediction method.

Although ASSERT was not directly validated for such applications, ASSERT is considered to be a useful tool to explore the impact of minor changes on dryout powers.

The ASSERT simulations considered the following three options:

(a) Reduce the diameter of the centre fuel element to increase the cross-sectional area of the inner ring subchannels,
(b) Increase the diameter of the inner-ring pitch circle to increase the cross-sectional area of the inner ring subchannels, and
(c) Increase the height of bearing pads to offset the impact of pressure tube creep and move the bundle upward towards the centre of the channel and thus reduce the area of the flow bypass at the top of the bundle.

The ASSERT analysis results can be summarised as follows:

(1) Significant increase in dryout power for option (a),
(2) Significant increase in dryout power for option (b), and
(3) Small increase in dryout power for option (c).

Option (b) was rejected because it entails noticeable changes to the bundle design. Option (a) was pursued because it results in a significant change in CHF and requires minimum changes to the bundle design.

2.2 Confirmation of ASSERT Predictions

The CHF tests at Stern Laboratories investigated fuel element dryout with uncrept pressure tubes and with crept pressure tubes with 3.3% creep and 5.1% creep [2]. Post-dryout tests were performed for uncrept pressure tubes and 3.3% crept pressure tube. Post-dryout tests showed that it requires a significant increase in power before the dryout moves from the inner ring to the outer ring of the fuel bundle. The post dryout tests show that dryout moves from the inner ring for overpower ratio that could be as high as 1.12. Over power is the ratio of power to onset of dryout power. This is a promising conclusion that warranted further investigation. An experimental program at Stern Labs was initiated for the modified design.

3.0 Description of Stern Labs Test Facility

3.1 Fuel String Simulation

The fuel string is an electrically heated, 37-element bundle, segmented design with a nominal 5.94 meter heated length and a non-uniform, downstream skewed cosine, axial heat flux distribution as shown in Figure 5.

The radial flux distribution, expressed in terms of local heat flux ratio with respect to the outer ring element, is 1.000/ 0.845/ 0.779/ 0.749 (or 1.102/ 0.932/ 0.859/ 0.826 if expressed as the ratio of ring to average heat flux).

Based on heater tube wall thickness and outside diameter measurements obtained from the inspection processes, the calculated deviation in axial heat flux from the specified axial heat flux distribution is within 1.2% (2 sigma standard deviation; i.e. 2σ) and the calculated ratio of ring to average heat flux distribution is 1.101/ 0.932/ 0.860/ 0.828. The fuel string consists of twelve simulated fuel bundles, each 495.3 mm long cold (480.1 mm actual heated length), with fully aligned elements and end plates, representative of the Bruce/Darlington design. The simulated spacers and bearing pads are a hollow design to minimize local current mal-distributions. The heater tube diameter is 13.06 mm (13.11 mm hot) and the actual heated length is 5761.4 mm (5943.6 mm overall length). The overall bundle OD, including bearing pads, is 102.28 mm (102.69 mm hot). The twelve fuel bundles are identified as "A" through "L", as shown in Figure 6, where "A" is located at the inlet, or upstream end, and "L" is located at the outlet, or downstream end.

3.2 Test Section

The test section is comprised of the pressure housing, ceramic liners which form the flow channel and provide electrical isolation of the fuel string, "tee sections" at each end with electrical isolating flanges, sealing flanges at each end for the electrode extensions which provide for relative motion due to differential thermal expansion, pressure tap instrumentation, thermal insulation and structural supports. Suitable leads are included at each end to connect the heater electrode extensions to the power supplies.

Ceramic liners, which serve to electrically isolate the fuel string from the pressure boundary, form the flow channel and simulate the inside surface of the reactor pressure tube. The ceramic liners for the uniform “uncrept” flow channel geometry are made from high purity alumina (Al_2O_3) with a uniform inside diameter of 103.86 mm (104.11 mm hot, at 303°C). The liners for the 3.3% crept flow channel geometry are made from the same alumina material with the inside diameters machined to provide a non-uniform axial profile to simulate crept pressure tubes which have a maximum of 3.3% diametral creep. The liners for the 5.1% crept geometry are made from zirconia material. The axial profiles of the ceramic liner inside diameters are shown in Figure 5.

The pressure boundary is fabricated from identical short length spools (1 meter) made from 410 stainless steel forgings with integral flanges. The clamped connections are sealed with metal "O rings" and have interconnecting steps at each end to ensure alignment. The tee sections at each end incorporate calming regions with re-entrant geometries to minimize flow mal-distribution. The test section is mounted on pipe rollers to allow for thermal expansion, with the downstream flange fixed.

3.3 Test Loop

The primary test loop consists of a main circulating pump, the channel inlet and outlet feeder piping, a pre-heater (normally used for pressure drop tests), two heat exchangers, a steam/water separator, a condenser, a filter, and various valves and controllers to control flow, pressure and temperature.

Heat rejection from the primary loop is accomplished by passing flow through the heat exchangers and by feed and bleed using the separator and condenser. The secondary water for the heat exchangers and condenser is recirculated by pumps through two cooling towers.

The flow through the test section is controlled by pneumatically operated globe valves in the inlet feeder piping. Some flow is normally maintained through the loop bypass line to condense steam in the outlet line before entering the separator. The system pressure is maintained by controlling the rate of bleed from the separator and the temperature is adjusted by controlling the rate of feed of the cold makeup water in conjunction with control of the primary flows through the heat exchangers.

A high pressure chemical feed pump is used to inject hydrazine into the primary loop water at the circulating pump inlet to control the pH level of the water between 7.8 and 8.5. This serves to maintain the dissolved oxygen content below 5 ppb to minimize corrosion of the test loop components which are mainly carbon steel. The electrical conductivity of the loop water is also monitored and generally held below 5 μmho.cm^{-1} to prevent appreciable electrolytic corrosion in the test section. A low pressure (for initial startup) loop bypass cartridge filter and a high pressure (for continuous use) loop bypass cartridge filter are installed across the main circulating pump to remove any particulate matter in the loop water during operation.

3.4 Power Supplies

Direct Current (DC) electrical power to the fuel string is provided by eight (8) individually controlled rectifiers, with a total rated output capacity of 15 Megawatts DC (i.e. 60,000 amps @ 250 volts). At the design voltage of the fuel string (220 volts) and the rated maximum current, a total power of 13.2 Megawatts DC is available. The power supplies are connected to the fuel string with the positive terminals grounded at the downstream end and the negative terminals floating at the upstream end. The specified maximum allowable output ripple of the power supplies is 3% of output power, over the range of 25% to 100% output power. The ripple frequency is 720 Hz.

The eight power supplies are remotely controlled using the data acquisition system computer. Using custom, keyboard driven software, the computer outputs a control setpoint, handles the current sharing among the power supplies, and provides incremental control, ramping, etc. of each power supply. Incremental steps of 25 kilowatts (total of all supplies) are typically used for power increases and decreases. Steps of 5 kilowatts may be used for small increases as the onset of CHF is approached.

3.5 Instrumentation

The test section is fully instrumented to measure temperature, pressure and differential pressure at the locations shown in Figure 6.

The fluid temperature at the test section inlet and outlet, and at the flow meters, is measured using Resistance Temperature Detectors (Rosemount RTD Model 68 and Transmitter Model 3044C). Two RTDs, for redundant measurements, are located in the piping near the test section inlet and outlet tees and one RTD is located at the flow orifice meter. The RTDs are installed in thermal wells inserted into the flow stream and welded in the pipe wall. The RTDs are connected through RTD transmitters for signal conditioning to the data acquisition system. The uncertainty in temperature measurement for the RTDs is estimated to be ±0.4°C (2σ). Absolute pressures are measured with capacitance type transmitters (Rosemount Model 1151GP).

Figure 6 shows the location of the pressure taps at the test section inlet and outlet. Two absolute pressure transmitters, for redundant measurement, are used to measure the pressure at both the inlet and outlet.

The uncertainty of the absolute pressure measurement is estimated to be ±0.25% (2σ) of full scale. The differential pressures along the flow channel are measured with capacitance type transmitters (Rosemount Models 1151DP and 3051CD).

The overall power provided to the fuel string is calculated from the measured total current (using a Hall effect transducer installed around the test section) and the voltage potential between the inlet and outlet closure flanges (direct measurement). The electrical power from individual supplies is calculated from the measured current (shunt meter) of each supply and the voltage potential measured between the inlet and outlet flanges. The sum of these individual power measurements provides a redundant check of the total power. The estimated uncertainty in the overall power measurement is ±45 kW (2σ).

Two hundred and twenty-two (222) CHF detection thermocouples (ANSI Type K, with 0.89 mm diameter Inconel X-750 sheaths and ungrounded junctions) are mounted in movable ceramic carriers inside most of the heater elements in the downstream half of the fuel string. The thermocouple tips are spring loaded to contact the inner surface of the heaters. The carriers can be rotated and moved axially, by a remotely controlled drive mechanism, to measure the inside wall temperature over most of the surface of the downstream heater elements. CHF detection thermocouples are installed in Bundles "H" through "L" and have an estimated uncertainty of ±1.1°C, or ±0.4% (2σ) of the reading for the temperature range 293 - 800°C. The initial thermocouple carriers, used to the end of the C2 series, were made from alumina (Al_2O_3) material. The experimental uncertainties of the different parameters are summarized in Table 1.

The fuel string thermocouples are identified by a four digit alphanumeric code. The first two digits of the code represent the element position in the bundle for that instrument string (01 to 37). The third digit is a letter which represents the bundle (H to L) and the fourth digit is the number 1 or 2. The number "1" indicates the main thermocouple in the carrier, and therefore, its angular position is used for the instrument string angular position. The number "2" indicates a backup thermocouple, which is installed in bundles "J" and "K" only, and therefore its angular position is ±180° from the “1" thermocouple.

3.6 Thermocouple Drive Mechanism

The thermocouple drive mechanism is remotely controlled by a Personal Computer (PC) based system and can move the entire instrument strings together axially and rotate each instrument string independently. The axial speed of the drive is adjustable from 0.03 to 1.1 $cm.s^{-1}$ and the rotational speed is adjustable from approximately 0.01 to 0.07 $rev.s^{-1}$.

4.0 Test Results

The Stern Labs test results can be summarized as follows:

- As seen in Figure 8 and Figure 9, mosaics developed from the fuel string temperature measurements taken under single phase test conditions well below dryout conditions, the subchannel temperature distribution is more uniform for the modified bundle under the same conditions.
- CHF tests have confirmed that the dryout powers of the modified bundle are higher than the reference bundle.

5.0 Conclusion

The 37-element bundle was modified by reducing the center element diameter. The modification resulted in higher dryout power.

6.0 References

1. V.F. Rao and N. Hammouda, "Recent Developments in ASSERT-PV Code for Subchannel Thermalhydraulics", CNS 8th International Conference on CANDU Fuel, Honey Harbour, Ontario, Sep 21-24, 2003.

2. R.A. Fortman, R.C. Hayes, and G.I. Hadaller, "37-Element CHF Program, Steady State CHF, Transient CHF and Post-Dryout Tests with Uniform and Diametral Crept Flow Tubes", Stern Laboratories, COG Protected Information.

3. R.A. Fortman, “"Critical Heat Flux and Post-Dryout Tests Using the Modified 37-Element Fuel Simulation in Water", COG Protected Information.

Table 1: Measurement Uncertainty

Measurement	2 Sigma Uncertainty
Flow	±0.125% at Full Scale
Power	±45 kW
Element Temperature	±1.1 °C
Loop Temperature	±0.14 °C
Absolute Pressure	±0.25% Span

Figure 1: CANDU 37-Element Bundle

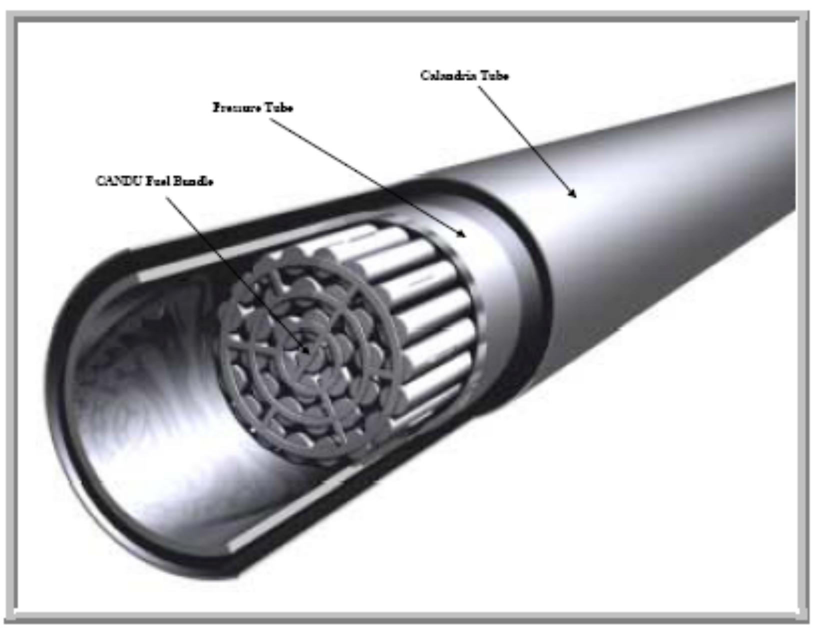

Figure 2: CANDU Channel Assembly Showing the Bundles, Pressure Tube and the Calandria Tube

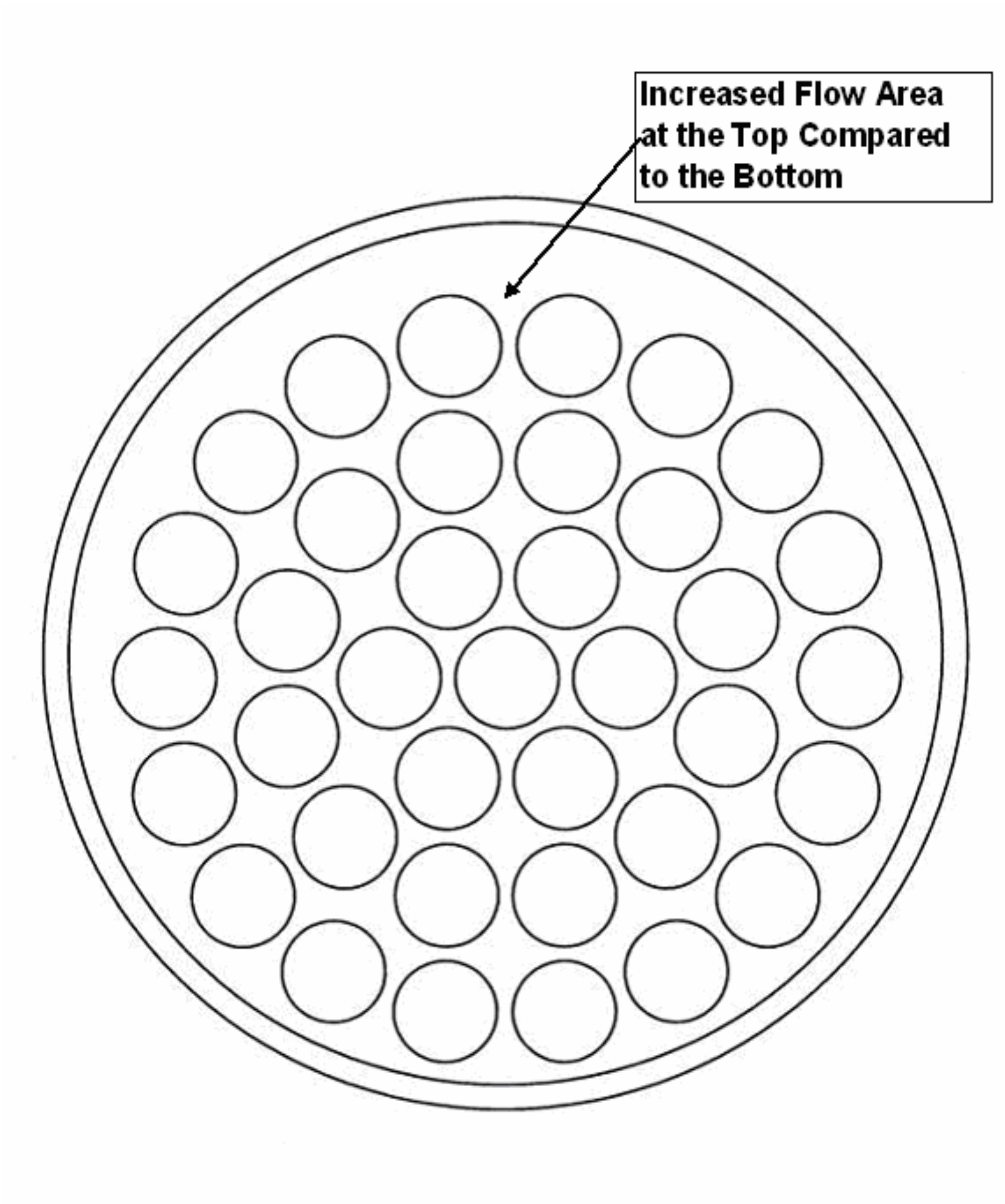

Figure 3: Cross-Section of the Reference 37-Element Bundle in a Crept Pressure Tube

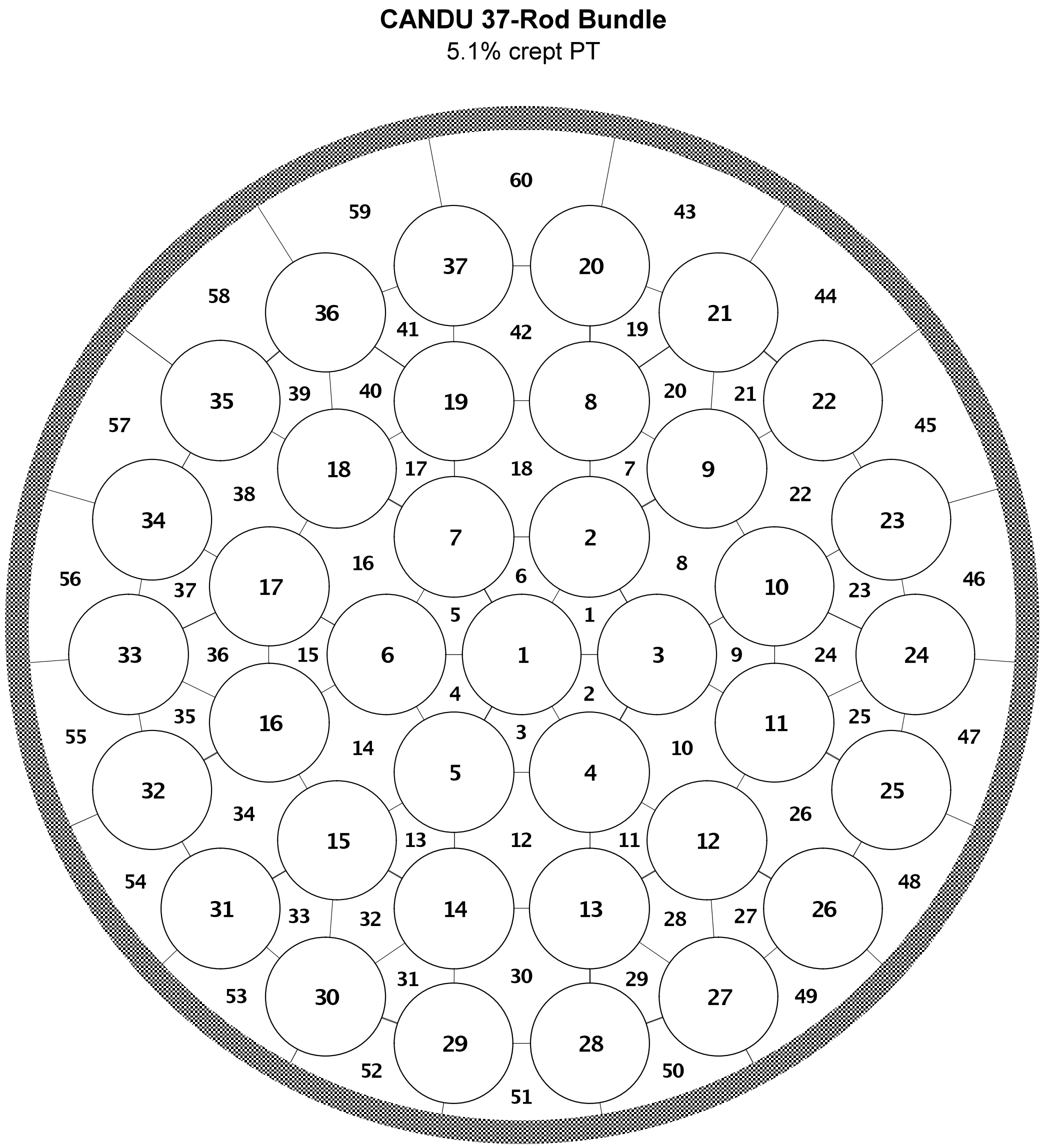

Figure 4: Typical ASSERT Subchannel and Rod Layout

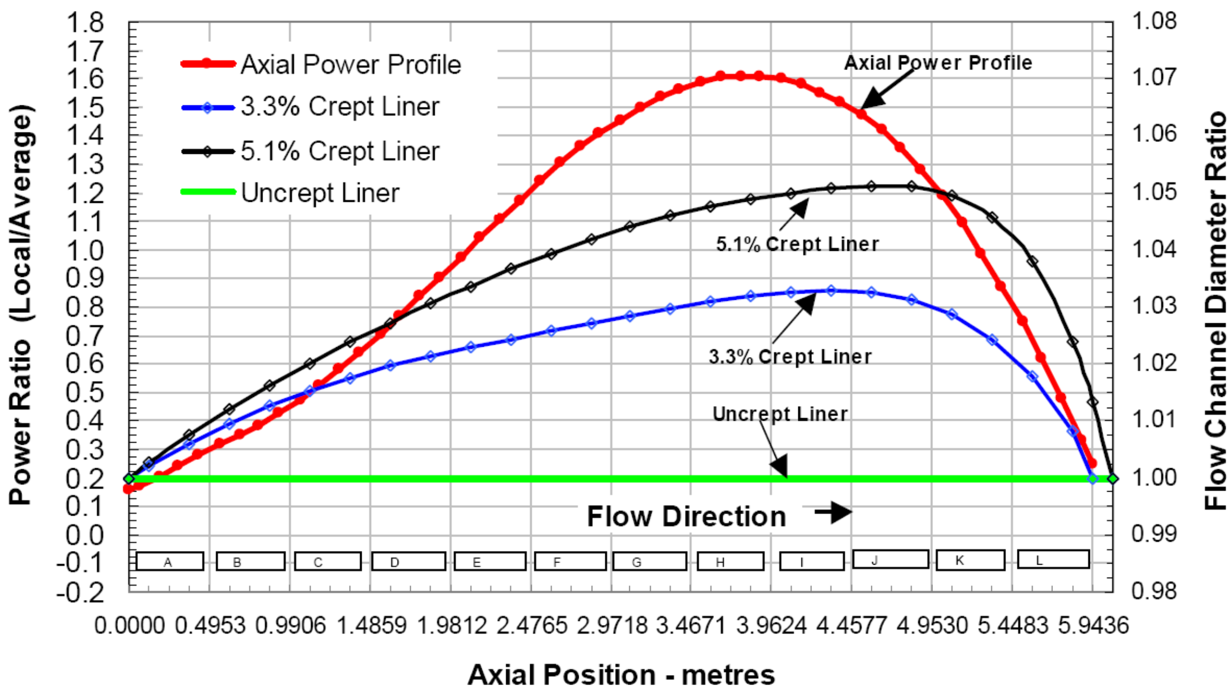

Figure 5: Axial Creep Profiles and Power Profile Used for Both Reference and Modified Bundles

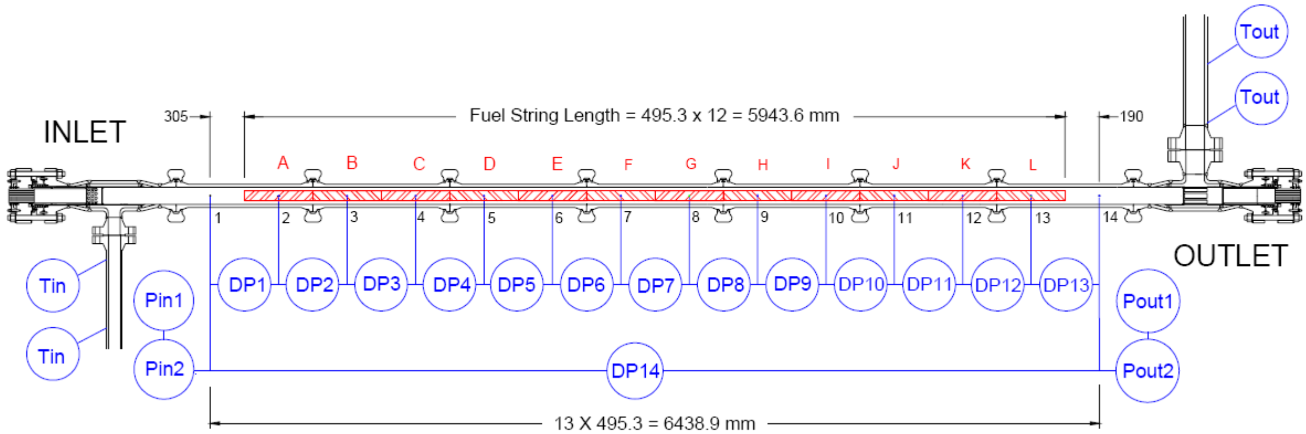

Figure 6: Test Section and Measurement Locations for Pressure Drop

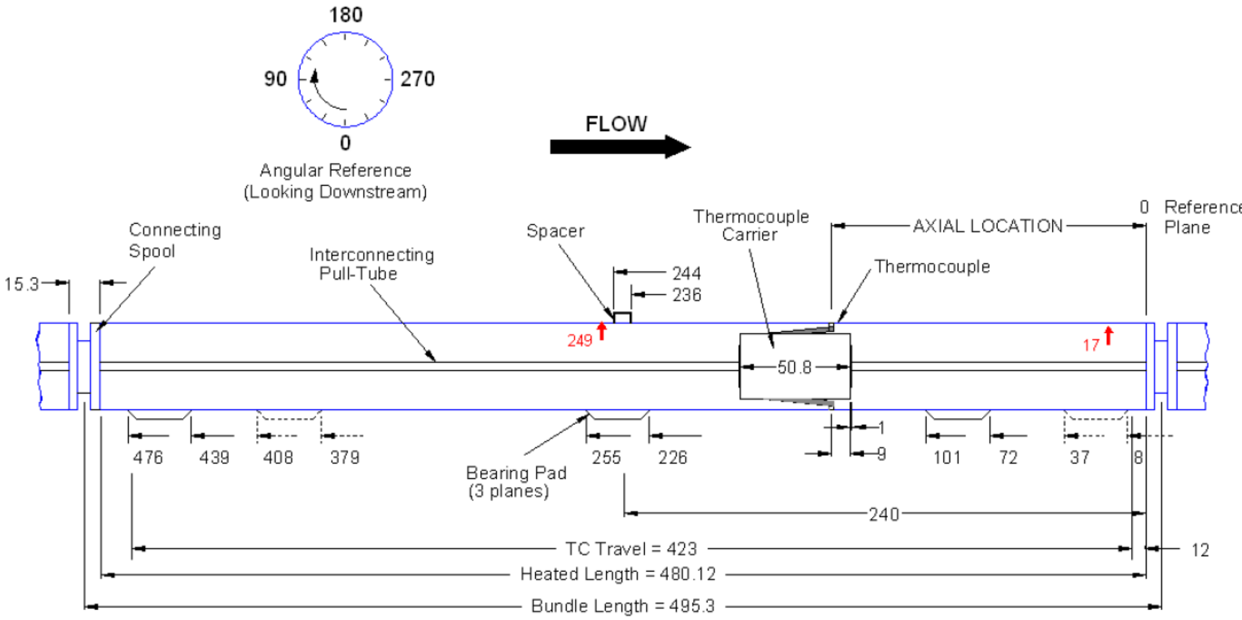

Figure 7: Thermocouple Position Reference

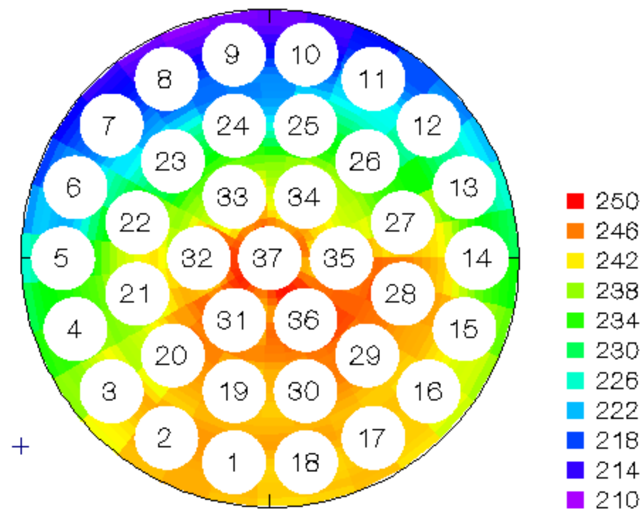

Figure 8: Temperature Profile in the Channels of the Reference Bundle

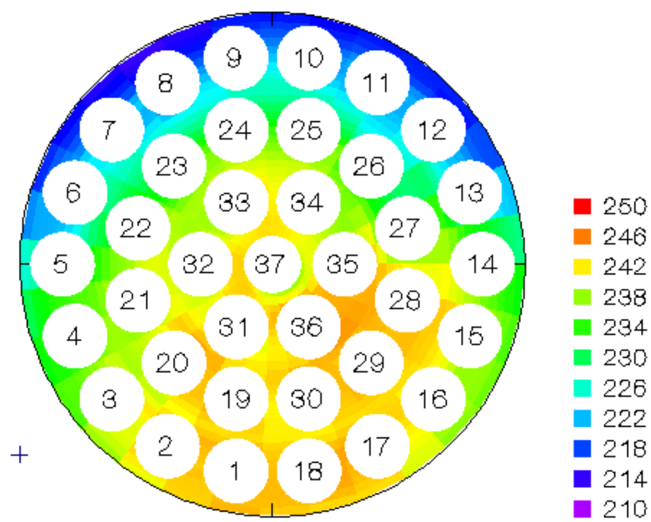

Figure 9: Temperature Profile in the Channels of the Modified Bundle