STERN LABS HIGH-TEMPERATURE BUNDLE DEFORMATION EXPERIMENTS UNDER CONDITIONS APPLICABLE TO LBLOCA WITH ECI AVAILABLE

F. Abbasian, G. I. Hadaller, R. A. Fortman and R. C. Hayes
Stern Laboratories Inc.,
(Hamilton, Ontario, Canada L8H 3L3, (905) 548-5328, fabbasian@sternlab.com)

ABSTRACT- A high temperature bundle deformation experiment was performed in Stern Laboratories to investigate the bundle behavior under conditions applicable to LBLOCA with ECI available. A bundle comprised of seven CANDU fuel elements was used in the experiment. A self-contained test loop was constructed to perform the simulations under pressures up to 2 MPa in saturated steam environment. The bundle was heated by directly passing electrical current through it and real-time planar element deflections were measured using two Linear Variable Displacement Transducers at each point of interest.

Four different tests were performed, each one using a unique power profile. The peak power values were gradually increasing to account for conditions applicable to AOO, and eventually LBLOCA. At the LBLOCA nominal condition, a maximum power value of 64 kW was applied, which caused maximum and local heat-up rates around 64 and 56 °C/s, respectively, a local sheath peak temperature of 950 °C, and a high-temperature (>800 °C) duration above 30 seconds. The transient displacement profiles indicate a sag-type deformation with a magnitude of ~1 mm at midspan between the bearing pad planes. The post-test inspection revealed that the bundle remained intact and that the elements exhibited a sag-type deformation consistent with the transient deflection data. The temperature-deflection correlations and analyses were obtained from the test data.

Introduction

A COG sponsored program to investigate high temperature fuel bundle deformation was completed at Stern Laboratories. The objective of the experiment was to investigate the deformation patterns of a CANDU fuel bundle under simulated Large Break Loss of Coolant Accident (LBLOCA) conditions. The test consists of three main stages: pre-heat, in which the fuel bundle is heated up slowly and the sheath temperature is raised to about 300 °C; slow transient, when low to intermediate levels of power are applied to the bundle at different steps to raise the sheath temperature to 400-700 °C; and the fast transient, when high power is applied to raise the sheath temperature to above 1000 °C at a heat-up rate of 50-100 °C/s. The experiment was performed in a steam environment. A 7-element bundle was used for this experiment since a 37-element bundle would produce stronger magnetic forces which could affect bundle deformation [1]. The bundle power was provided by passing electrical current, supplied by a 150 kW (30 DCV, 5000 DCA) rectifier, directly through the bundle. The bundle was instrumented with thermocouples and Linear Variable Differential Transformers (LVDT) at various points for temperature and deflection measurements. The proposed test conditions were obtained from the documents given in [2-4] and are shown in Table 1.

1. Experimental Set Up

1.1 Test rig

The test rig, shown in Figure 1, consists of a pressurizer, preheater, test section, coolers, storage tank, piping and instrumentation. The test loop schematic is shown in Figure 2. The steam flow is provided to the test section by boiling water using a heater installed at the bottom of the pressurizer. The steam flow passes through the bundle inside the test section and is then cooled with the condensate released to the storage tank.

The pressurizer is made from an 8 inch Schedule 80 S.S pipe. A 20 kW immersion-type heater is installed at the bottom of the pressurizer to boil the water. The pressurizer is equipped with a Pressure Relief Valve (PRV) and instrumentation to measure temperature, pressure and water level.

The test rig is instrumented with thermocouples, absolute and differential pressure transducers, and an orifice installed upstream of the test section to measure the steam flow rate as it enters the test section. A PRV is installed downstream of the test section and is vented to a water tank. The steam flow at the exit of test section is cooled in two stages: first by a cooling coil wrapped around the pipe, and then by three coaxial heat exchangers with an overall heat removal capacity of 75 kW. The test section is installed in an isolated area with all operations remotely controlled, as shown in Figure 3.

1.2 Test section

Test section is made from 6 inch Schedule 80 S.S pipe, as shown in Figure 4. The test section consists of three layers: Zirconia liner tubes as the inner layer, firebrick thermal insulation as the intermediate layer, and S.S pressure housing as the outer layer. The bundle assembly is electrically live at the inlet end and grounded at the outlet end. At the inlet end, the test section is electrically isolated from the blind flange using a reinforced phenolic gasket.

The bundle assembly is fixed at the outlet end and free to slide at the inlet end. The fixed constraint is provided by a stop block fitted over the Nickel electrode and screwed to the blind flange. The test section is pressure sealed by high-temperature O-Rings placed inside the blind flanges. In order to more efficiently cool the super-heated steam at the exit of the test section, a cooling flange was placed in contact with the outlet blind flange, as shown in Figure 5, to cool the O-Rings to the allowable operating temperature range, normally below 200 °C. City water constantly passes through paths inside the cooling flange to provide the cooling. A similar configuration with no cooling flange was used at the inlet end (Figure 6), plus a compression spring used to apply a force equivalent to the friction force of eight 7-element bundles (~340 N). The use of eight bundles for the compression force calculations was based on the channel critical location being at bundles I and J.

In order to mount LVDT's for deflection measurements, four Swagelok couplings were welded to the test section. The test section and the LVDT assemblies were fully covered by cooling coils, as shown in Figure 7.

1.3 Bundle assembly

The 7-element bundle, shown in Figure 8, was cut from a standard Bruce/ Darlington 37-element fuel bundle. Bearing pads, made from Zircaloy material with a height of 2.04 mm, were spot welded on the elements to provide contact with the liner tubes. Bearing pads were used at five axial locations, similar to the Bruce/Darlington design (Figure 9).

1.4 LVDT assembly

As shown in Figure 10, the element deflection was measured using LVDT's installed on the bottom elements at the midpoint between the middle and side bearing pads, where the maximum deflection was expected. Each of the two bottom elements was instrumented with LVDT's. Two LVDT's were used at each point to provide planar deflection data. The LVDT's, as shown in Figure 11, were installed in thermowells, which were screwed to the couplings welded to the test section. A lightly spring-energized assembly was used to ensure a continuous contact between the probe and element. The probe was made of Zirconia to electrically isolate it from the bundle.

1.5 Thermocouple assembly

The bundle temperatures were measured using eight Type K ungrounded thermocouples (TC's) attached to the sheath at various locations, as shown in Figure 12. For each of the bottom elements, one TC was used at the vicinity of LVDT's to provide local temperature data required for deflection-temperature correlations. At the same axial location, another TC was attached to the same element at a diametrically opposite position to provide circumferential temperature measurements. Other thermocouples were used on the other elements at the inlet and outlet ends.

As shown in Figure 13, the TC's were placed inside Alumina ceramic tubes for electrical isolation. The junctions were spot welded on the sheath, and TC wires were passed through Conax fittings installed at the outlet flange.

2. Uncertainty

The uncertainties of the measurements represent the total error, including errors associated with the instrument, its calibration (where applicable), the signal conditioning and the data acquisition system. The estimated 2σ value uncertainties are given in Table 2.

3. Results and Discussion

3.1 Test Series

A low-level power was applied to the bundle to provide a uniform steam flow into the test section. Once a steady state condition with a bundle temperature around 300 to 400 °C was obtained, a high-level power was applied to increase the bundle temperature as required. Four transient tests TS1 to TS4 were performed with different power profiles used. The deflection data are based on plane B (see Figure 10) measurements as some erroneous readings were observed for the other location. The maximum power levels applied to the bundle for TS1 to TS4 were 7.9, 15.8, 63.9 and 79.5 kW, respectively. The maximum sheath temperatures detected were 550, 747, 995 and 1066°C, respectively. The maximum heat-up rates achieved were, 5.0, 13.8, 63.9 and 74.7 °C/s, respectively. Finally, the maximum deflection values measured were 0.03, 0.47, 0.96 and 1.07 mm, respectively. All the measured deflections were in the form of sag in the downward direction.

3.2 Temperature & deflection plots

The deflection and temperature plots for all test series are shown in Figure 14. The data labels used in the plots are described in Table 3. In each test series, the transient power was applied in the form of combined stepped and ramped power profiles. At the end of each transient, the power level was lowered and test section was cooled to prepare for the next transient. Deflection was considered to be positive for outward element motion, opposite the direction of magnetic forces (inward).

From the plots shown in Figure 14, it is evident that there is a correlation between the deflection and temperature with no measurable effects of magnetic forces. The power peaks generally occurred at the intermediate rather than maximum temperatures, hence higher strengths were available against magnetic forces during the transients. The only case where magnetic forces appeared to have an effect was observed during TS4 at the peak power level of 80 kW, and was outweighed by the temperature effects at the end of power application. The plots in Figure 14 indicate that unlike in TS1 & TS2, the bundle exhibited a dominantly plastic deformation pattern in TS3 & TS4. The deformations were generally of sag type with downward direction. The instabilities that occasionally occurred for the bottom element temperature (TEXCTR) were due to the movement of the TC junction during the assembly and do not reflect real sheath temperature fluctuations.

Figure 15 shows the bottom element temperatures in TS3. It is evident that there is a circumferential temperature gradient with the lower temperature at the pressure tube side. The gradient was ~53 °C at the beginning of the transient and ~105 °C at the peak.

Figure 16 shows the correlations between the deflection and temperature for test series TS1 to TS3. As the element had significant permanent sag after TS3, TS4 was not chosen for this set of plots.

As shown in Figure 16, there is a clear correlation between deflections and heat-up rates for the three tests. For TS3, the high-temperature phase of the test (>600°C) exhibits trends affected by secondary factors such as creep, varying sheath material properties, sheath-to-pellet heat transfer, etc.

The element position at the end of the transient tests is shown in Figure 17. The maximum measured deflection corresponds to 1.07 mm at an angle of ~20° from the downward axis.

3.3 Post-Test Bundle Inspection

After the transient tests, the test section was cooled and a thorough examination for contamination was performed. Once zero contamination status was verified, the bundle was removed and a post-test inspection was performed.

As shown in Figure 18, at the end of the tests the bundle was intact with no sign of sheath rupture. Post-test resistance measurement showed the same value as the pre-test measurement. A view of the bottom element (element # 6) is shown in Figure 19. The gap between the element and ruler is coloured to show the point of maximum deflection that coincides with the point of LVDT measurement at the bearing pad- spacer mid-span location.

4. Conclusions

A high temperature bundle deformation test was performed to investigate fuel bundle behaviour under conditions applicable to LOCA with ECI available. A 7-element bundle was used with bundle heating provided by directly passing electrical current through the element sheaths. The test was performed in a steam environment at pressures up to ~ 0.2 MPa. Four test series, TS1 to TS4, were performed applying different levels of power, during which sheath temperatures and element deformations were recorded by the data acquisition system. The sheath temperatures were measured by a thermocouple (TC) attached to each of the 6 ring elements of the 7-element fuel bundle. For the two bottom elements an extra TC was attached to opposite side of the first TC to measure circumferential temperatures. The deformations were measured using two perpendicular LVDT's at two axial locations where the highest deflections were expected to occur at the bottom elements.

At the end of the test, the findings are as follows: the maximum power levels applied to the bundle for TS1 to TS4 were 7.9, 15.8, 63.9 and 79.5 kW, respectively. The maximum sheath temperatures detected were 550, 747, 995 and 1066°C, respectively. The maximum heat-up rates achieved were, 5.0, 13.8, 63.9 and 74.7 °C/s, respectively. Finally, the maximum net deflection values measured were 0.03, 0.47, 0.96 and 1.07 mm, respectively. All the measured deflections were in the form of sag with a downward direction. In TS3 the maximum circumferential temperature gradient measured at a sheath peak temperature of 947 °C was about 105 °C. In the high-temperature TS3 & TS4 series the bundle exhibited plastic deformation with permanent sag close to the maximum measured deflection. The post-test inspection revealed no sign of sheath rupture or endplate cracking.

5. References

[1] F. Abbasian, "Analysis Report for the High Temperature Bundle Deformation Tests at Temperatures and Durations Applicable to LBLOCA with ECI Available" COG OP-11-2107, 153-37100-COG-003, 2012.

[2] R.S. Dickson, "Test Plan for Fuel Bundle Behaviour Apparatus Single-Element Commissioning Test ", AECL Report 153-124700-COG-008 (TN-09-2075), February 2010.

[3] R.S. Dickson, "Assessment of Experimental Information on High-Temperature Fuel Bundle Behaviour", AECL Report 153-124700-COG-003 (COG-07-2070), August 2008.

[4] COG R&D Proposal "CANDU Fuel Bundle Sag Tests at Temperatures and Durations Applicable to LBLOCA with ECI Available", COG-10-FFC12.

Table 1: Proposed Test Conditions

Bundle preheating temperature (°C)	Sheath peak temperature, (°C)	High temperature duration (s)	Steam pressure (MPa)	Test environment	Heat up rate (°C/s)	Steam flow (g/s)
300-400	up to 1500	30-50	up to 2	Saturated steam	up to 100	9-10

Table 2: Measurement Uncertainties

Flow	Pressure	Temperature	Deflection	Bundle Voltage	Bundle Current	Calculated Bundle Power
±3%	±0.5%	2.2°C	0.03 mm	0.3%	±0.1%	±0.4%

Table 3: Data Labels (see Figures 10 & 12 for the instrument positions)

Data Label	Description
TINBOT	Section A-A element#1 (bottom) temperature (°C)
TINCTR	Section A-A element#1 (top) temperature (°C)
TINTOP	Section A-A element#4 temperature (°C)
TEXRT	Section B-B element#2 temperature (°C)
TEXLT	Section B-B element#5 temperature (°C)
TEXBOT	Section B-B element#6 (bottom) temperature (°C)
TEXCTR	Section B-B element#6 (top) temperature (°C)
TEXTOP	Section B-B element#3 temperature (°C)
LDASID	Section A-A element #1 side LVDT measurement (mm)
LDABOT	Section A-A element #1 bottom LVDT measurement (mm)
LDBSID	Section B-B element #6 side LVDT measurement (mm)
LDBBOT	Section B-B element #6 bottom LVDT measurement (mm)
DEFLA	Section A-A element #1 total deflection (mm)
DEFLB	Section B-B element #6 total deflection (mm)
ANGLA	Section A-A element #1 angle of deflection (°)
ANGLB	Section B-B element #6 angle of deflection (°)
PWRED	Bundle power (kW)
TIME	Time (s)

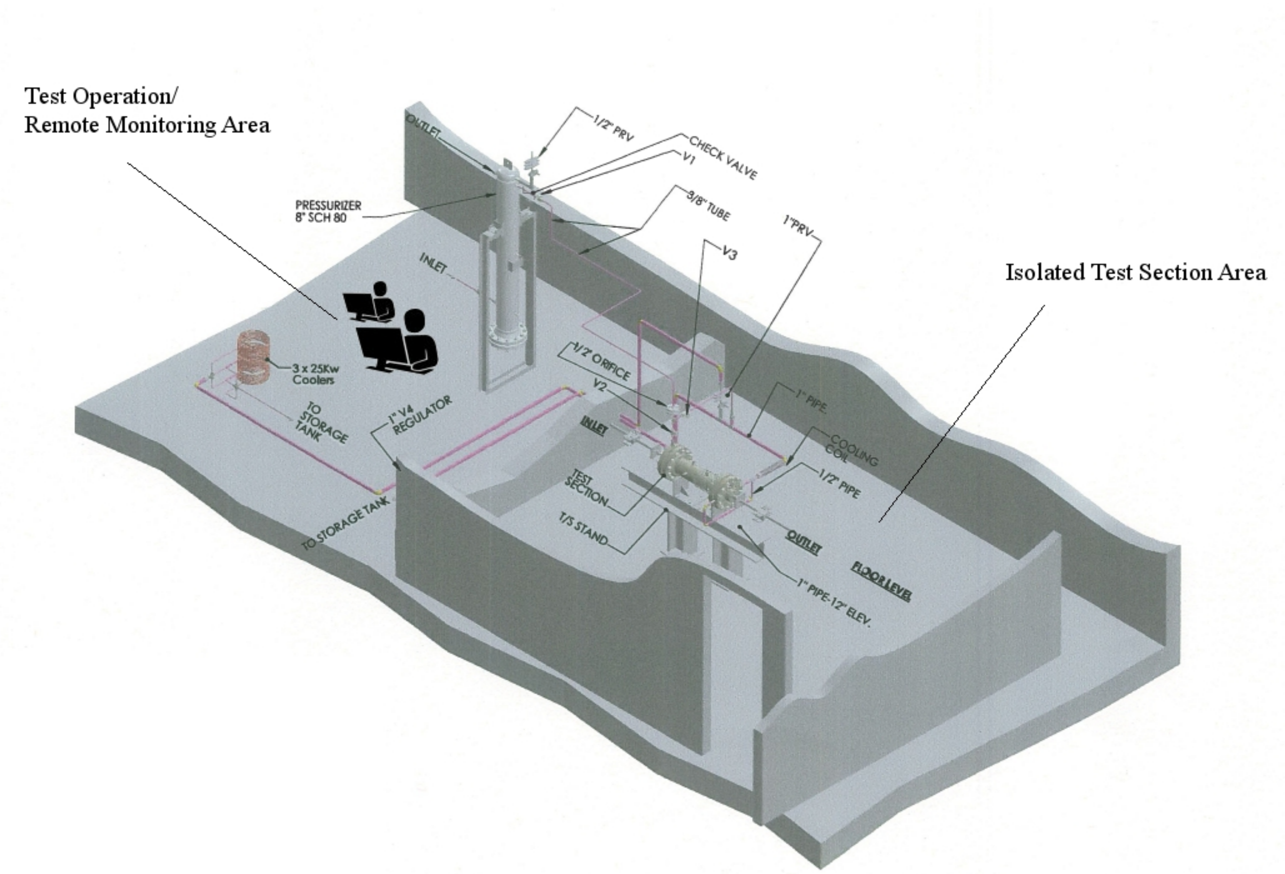

Figure 1: Test Apparatus

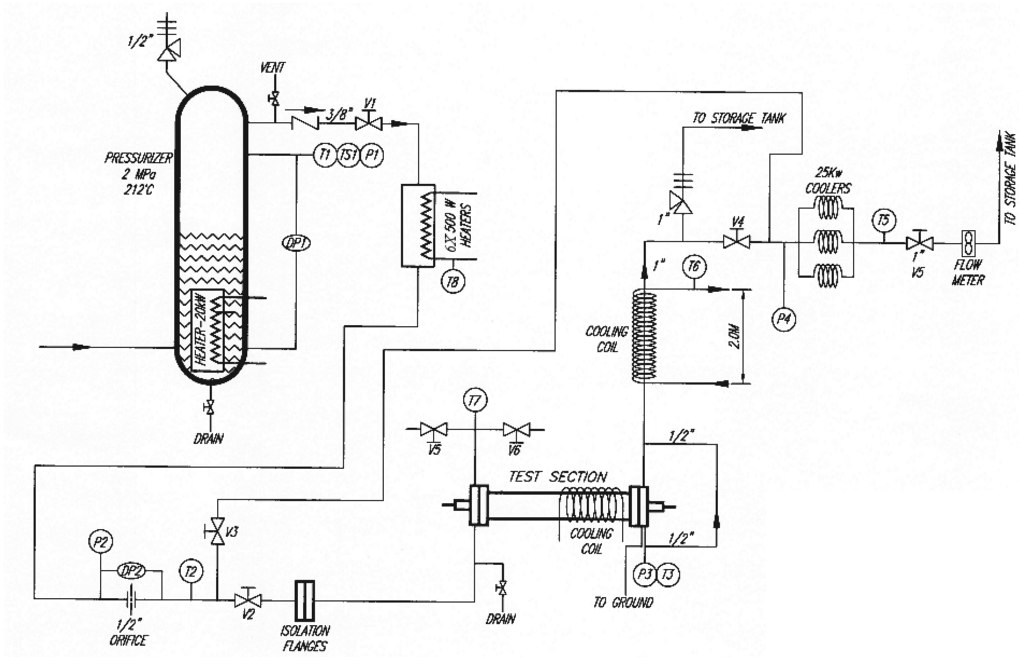

Figure 2: Test Loop Schematic

Figure 3: Test Operation, Remote Monitoring

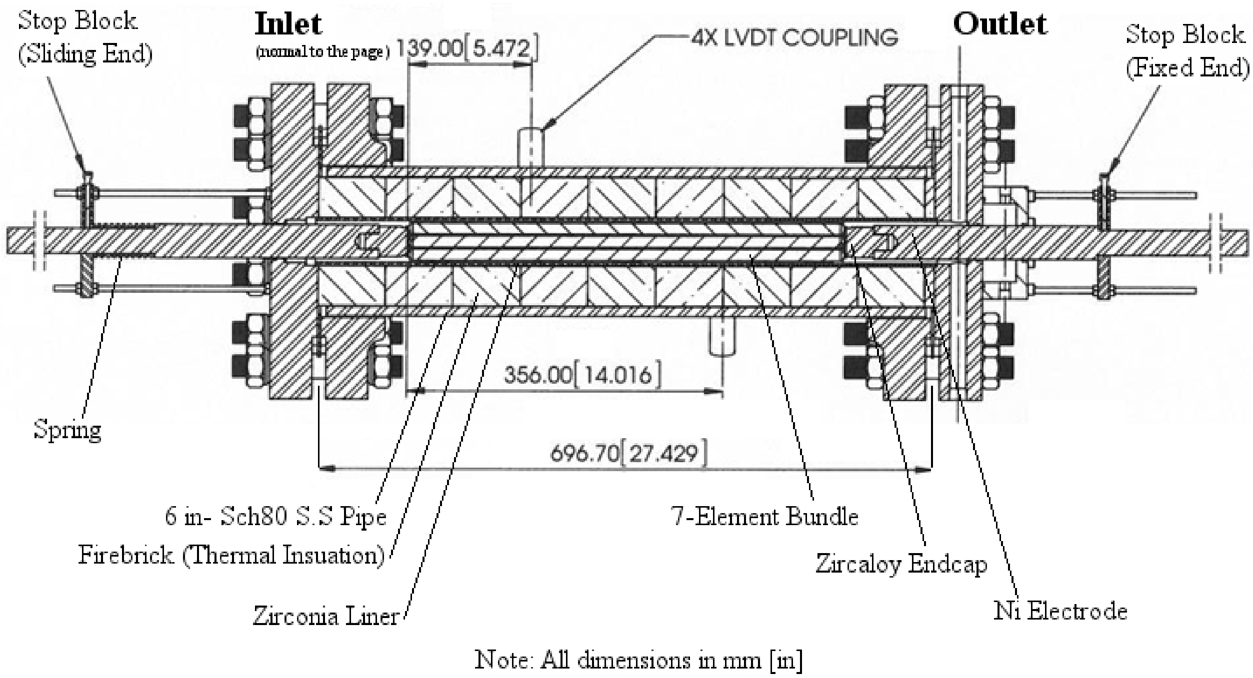

Figure 4: Test Section

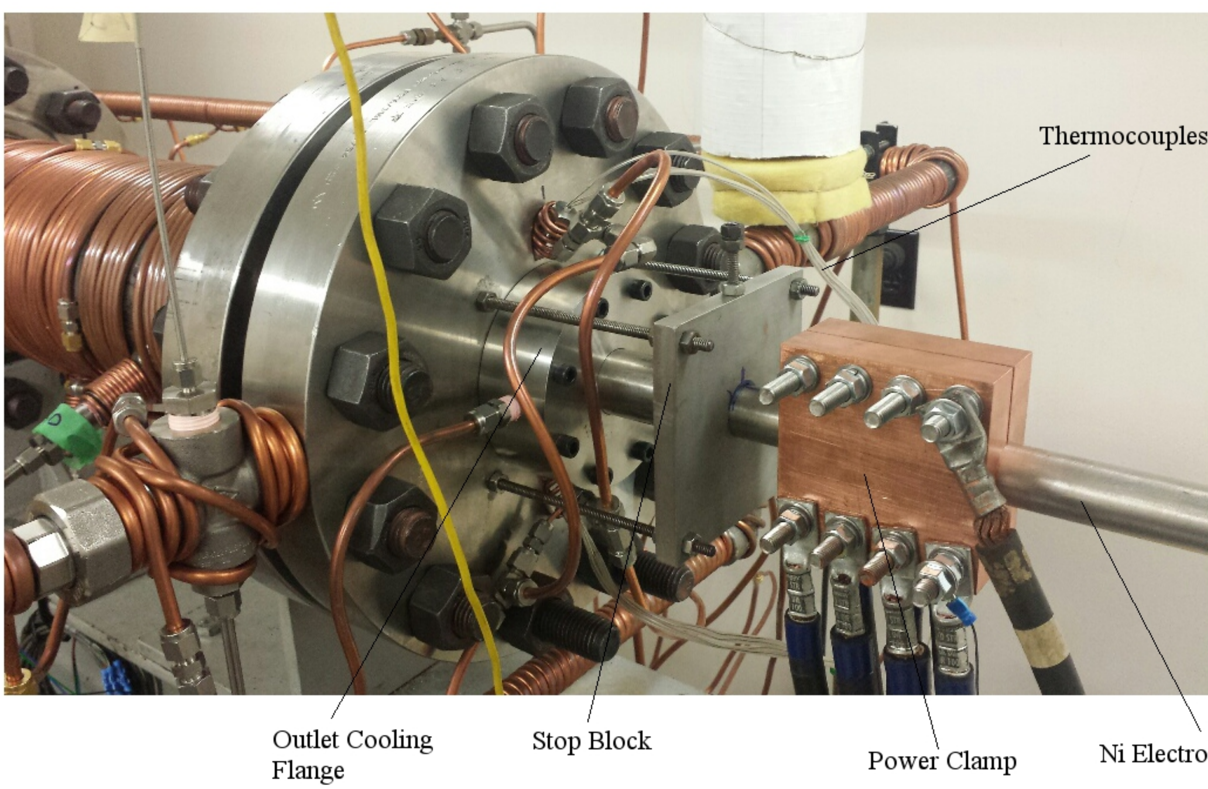

Figure 5: Outlet Flange

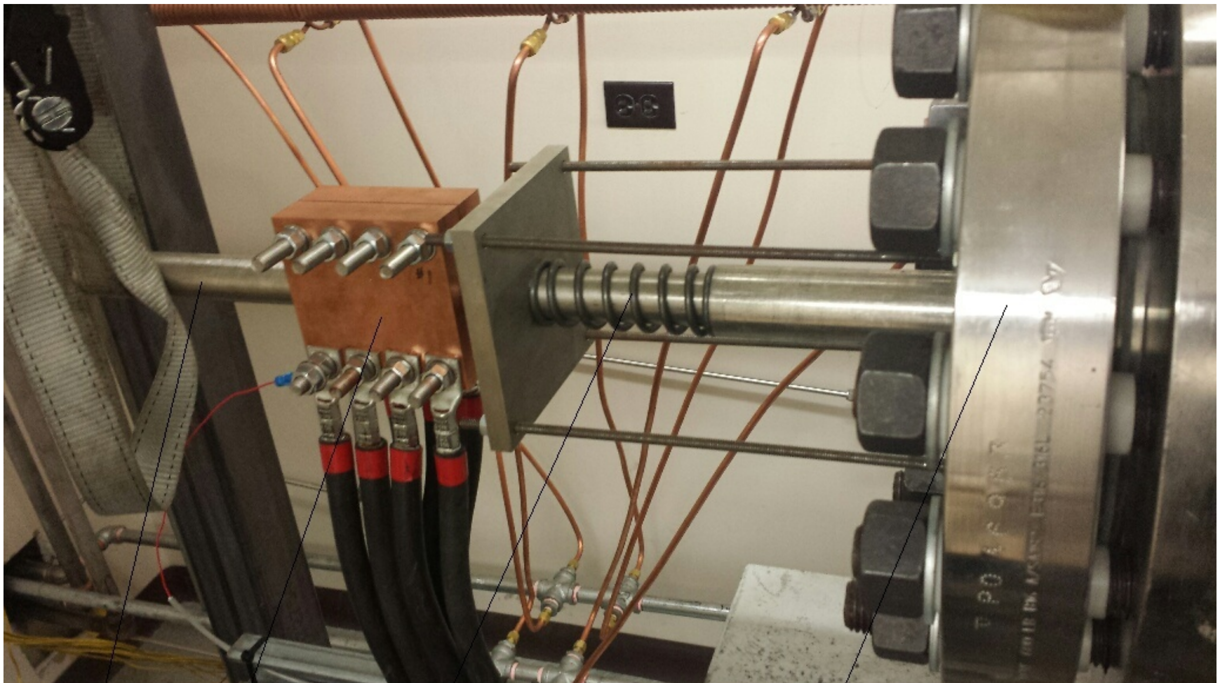

Figure 6: Inlet Flange

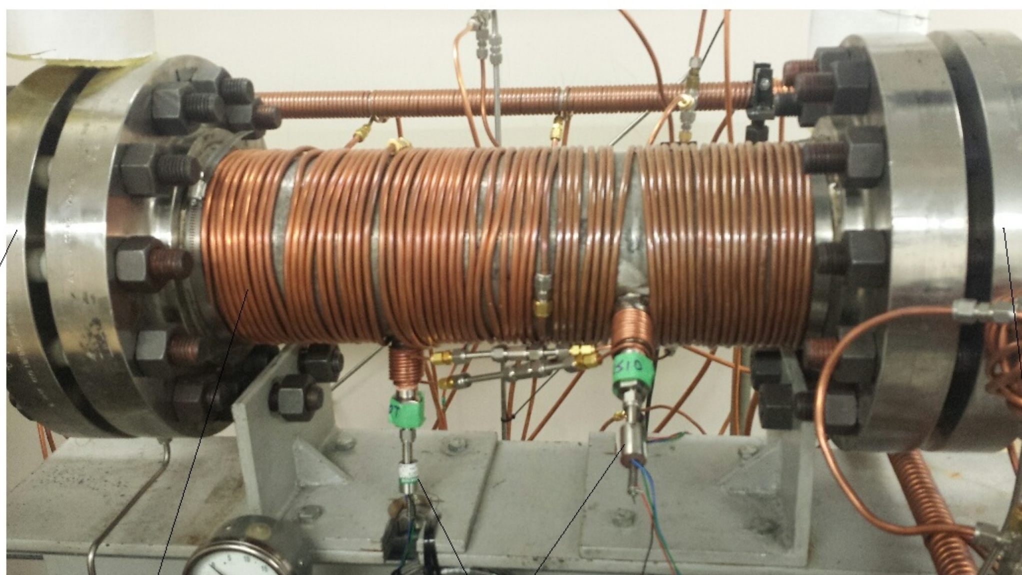

Figure 7: Test Section Assembly

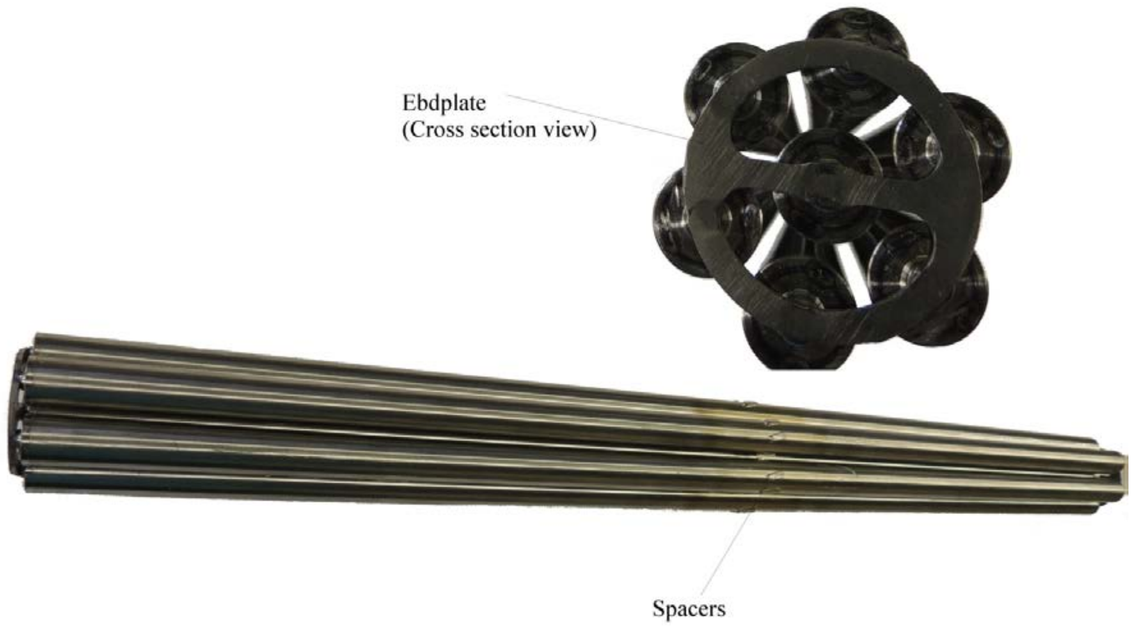

Figure 8: 7-Element Bundle

Note: All dimensions in mm [in]

Parts List			
Qty.	Item	Description	Material
1	1	7-Element Bundle (Make Form Bruce 37-Element Assembly)	
2	2	Endcap	Zircaloy
2	3	Electrode (Extension Bar)	Nickel 200
12	4	Bearing Pad	Zircaloy
6	5	Bearing Pad (Modified For Spacer Pad)	Zircaloy

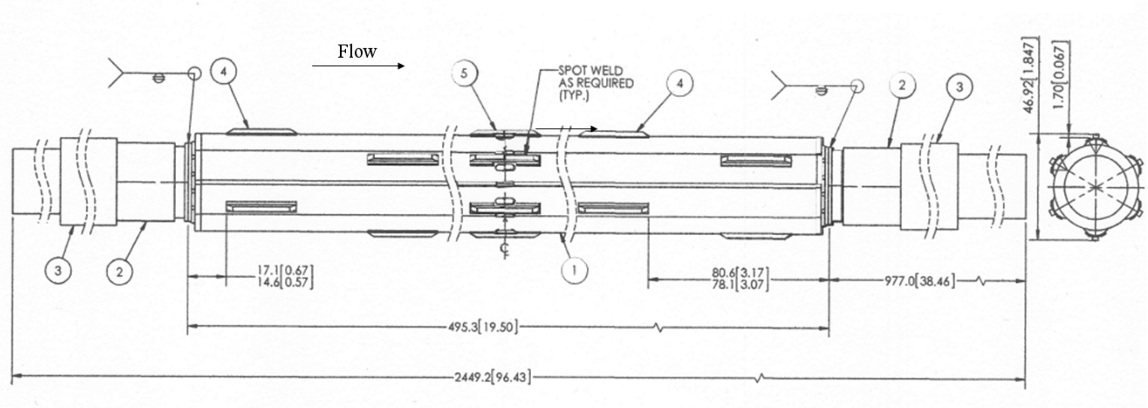

Figure 9: Bundle Assembly

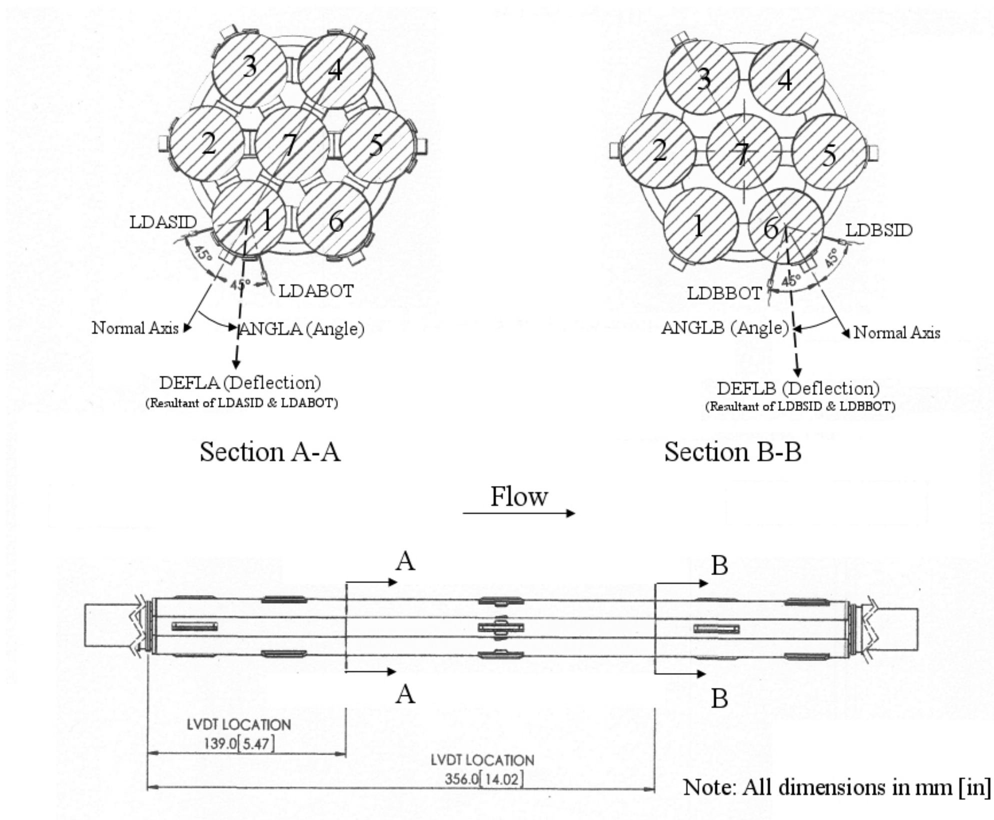

Figure 10: LVDT Positions

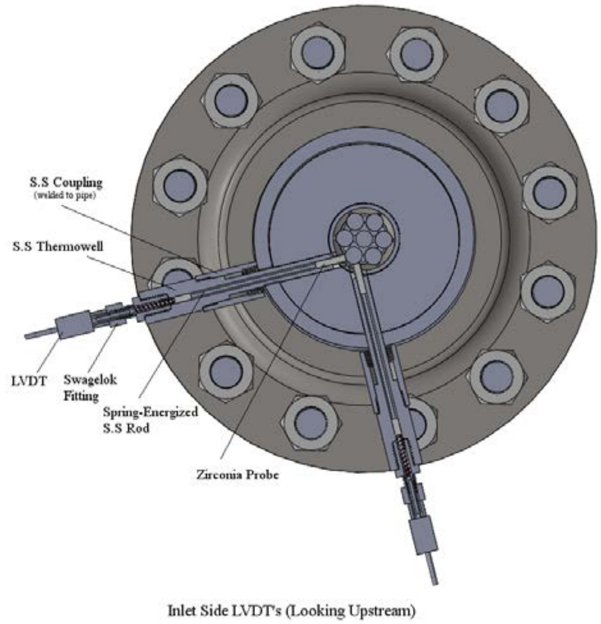

Figure 11: LVDT Assembly

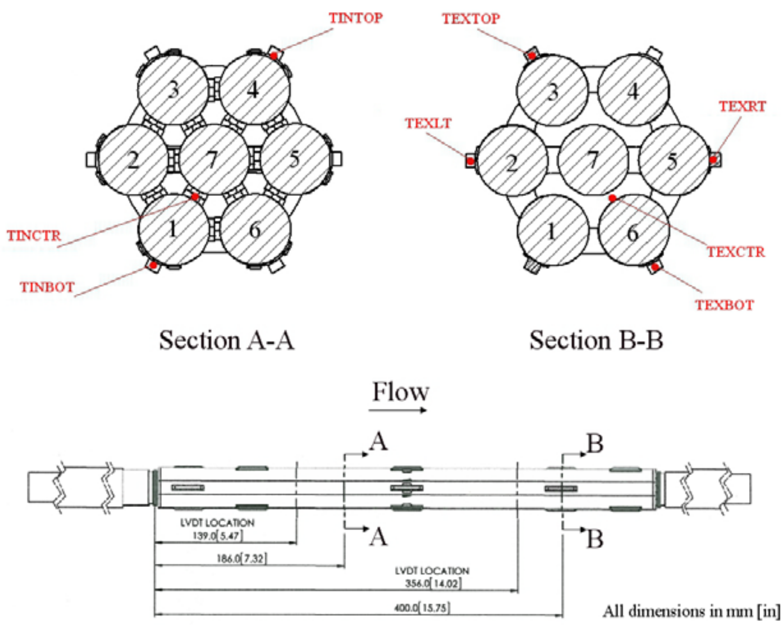

Figure 12: Thermocouple Positions

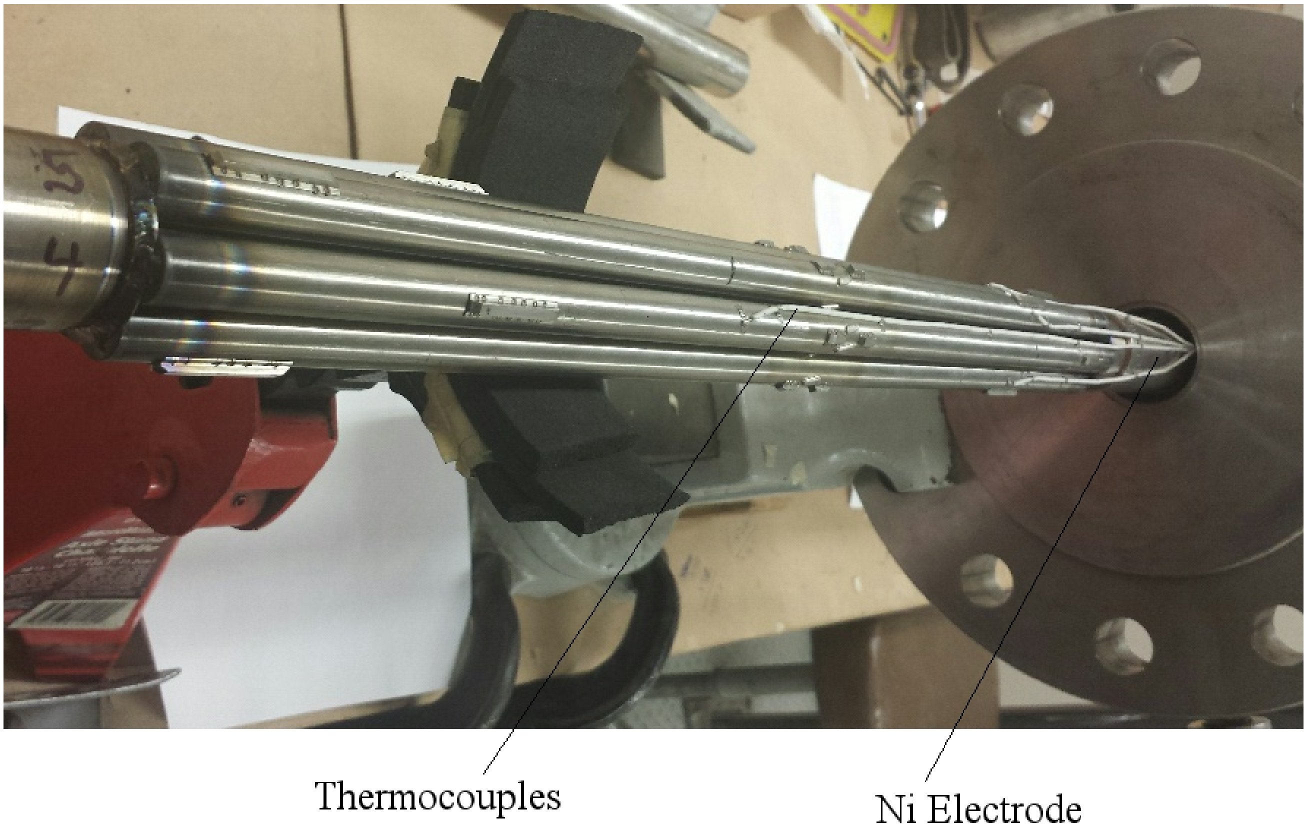

Figure 13: Thermocouple Assembly

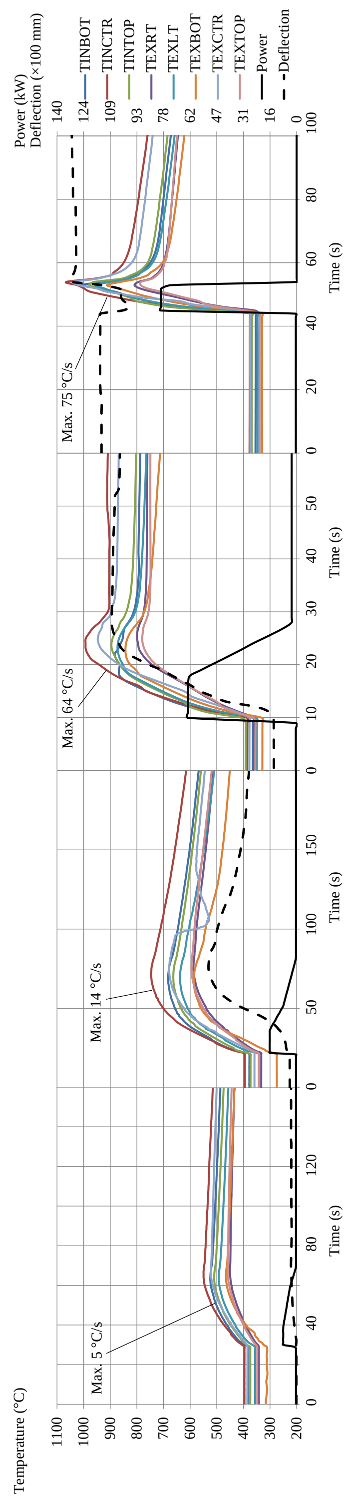

Figure 14: Temperature & Deflection Plots, All Test Series

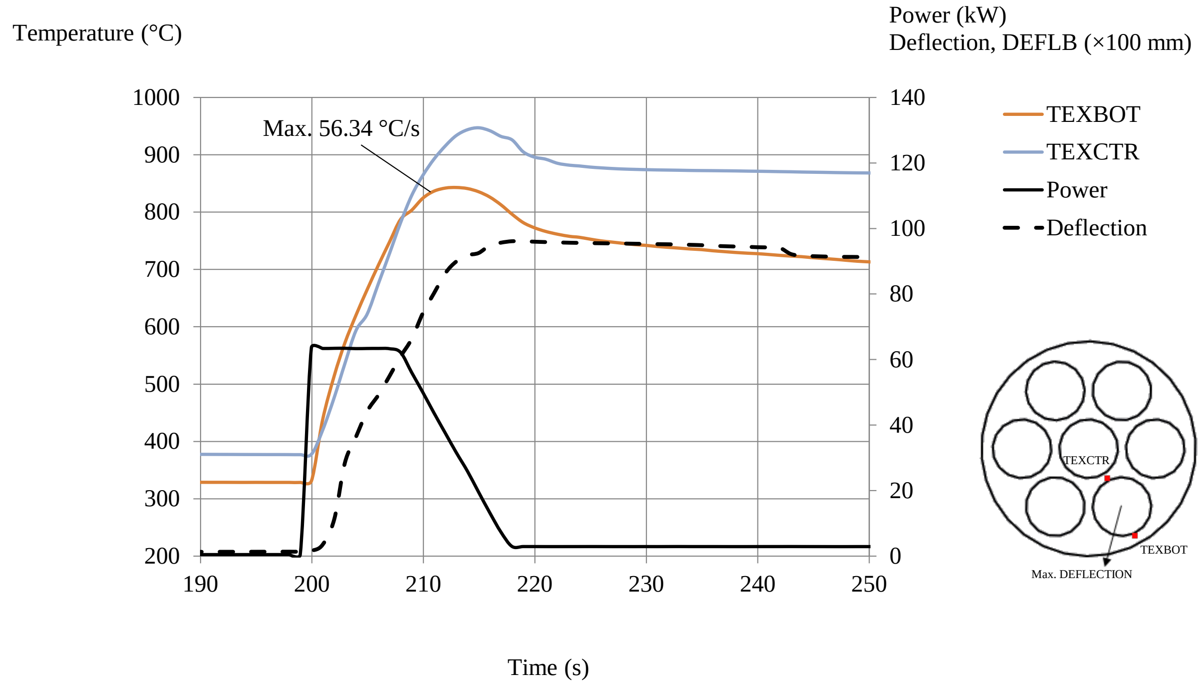

Figure 15: Temperature & Deflection Plots, TS3

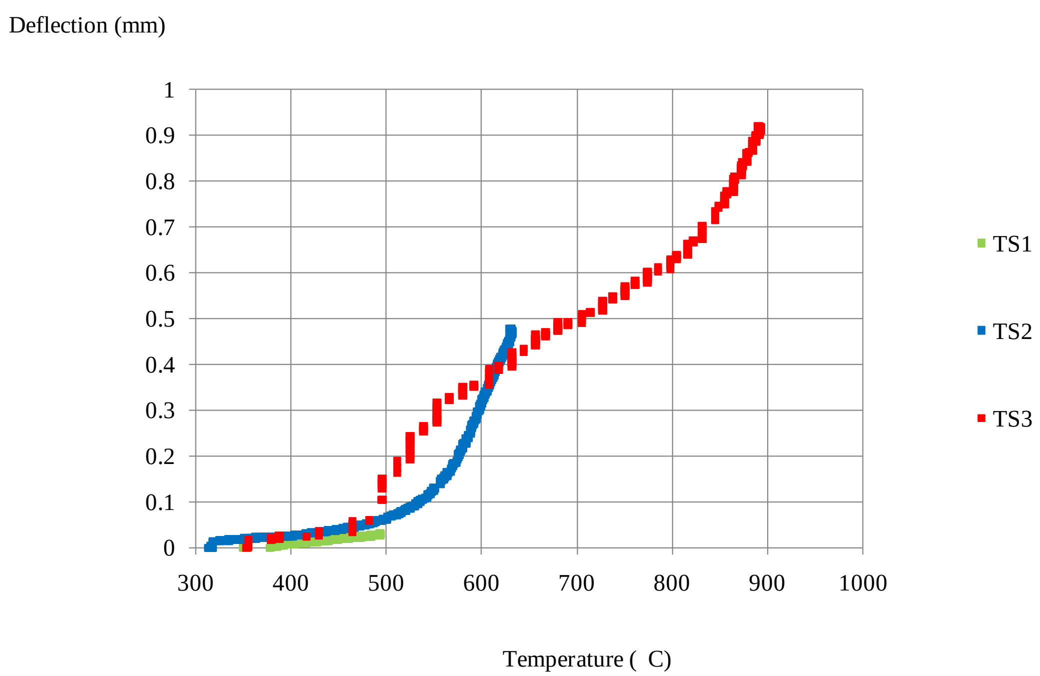

Figure 16: Deflection vs. Temperature Plots

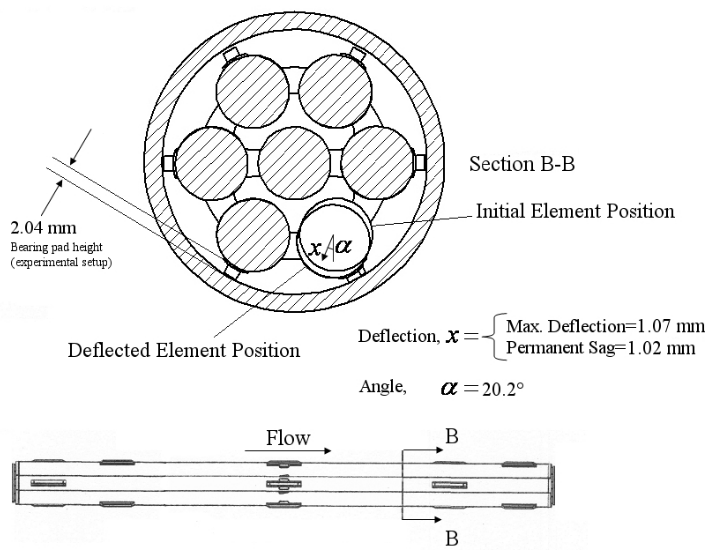

Figure 17: Element Deformation at the End of TS4

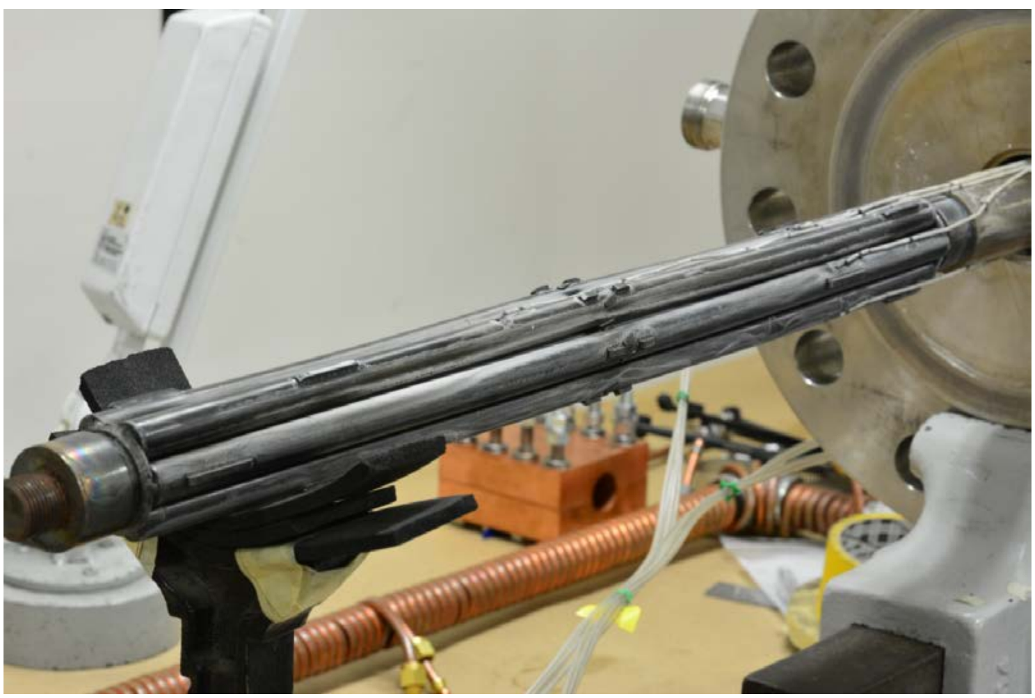

Figure 18: Post-Test Inspection, Bundle Isometric View

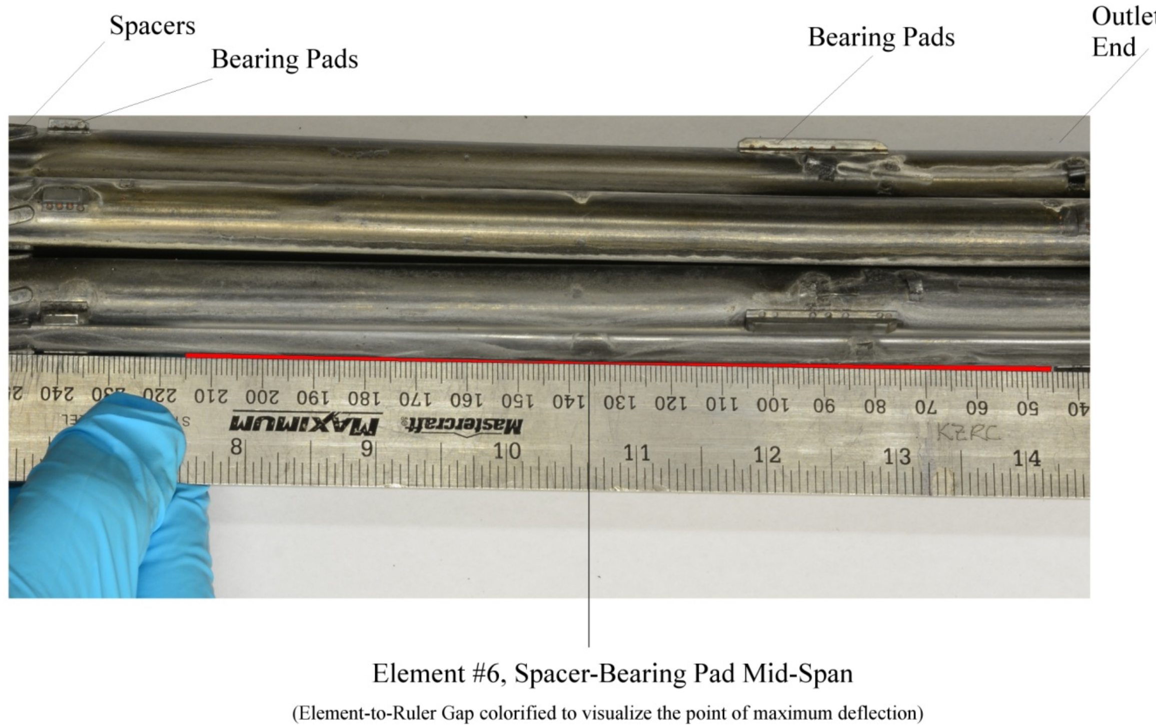

Figure 19: Bundle Side View; Maximum Deflection at the Point of Measurement (Mid-Span between the Bearing Pad and Spacer Planes)