UNDERSTANDING CANDU FUEL BOWING IN DRYOUT: AN INDUSTRY APPROACH

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ABSTRACT

Fuel element bow induced by dryout could potentially perturb the coolant flow distribution and heat transfer from the fuel element to the coolant. Some accident scenarios leading to dryout of the fuel element are: loss of power regulation, pump trip, pump seizure, small and large break loss of coolant accidents. In these accidents, it is desirable to show with confidence that the fuel remains sufficiently cooled to maintain its geometry, even if it is in dryout. This can be demonstrated if fuel elements are separated from each other and from the pressure tube, with a sufficient (and stable) gap. Therefore, the prediction of the amount of bow, and its effect on heat transfer conditions is required for the assessments.

The utilities have joined force in launching an experimental investigation at Stern Laboratories to characterize the bowing phenomena.

This program will investigate the amount of deflection, transient and permanent, that results from accident conditions which cause a dry patch on one side of the sheath. This is expected to

bound the consequences of fuel bowing due to dryout. Since the accident transients begin at full power and high coolant pressure (about 10 MPa) they generate sharp thermal gradients (dry patch) and it is necessary to develop a simulation with representative dry fuel sheath conditions initiated from a normal full power and coolant state.

The amount of bow is driven by thermal gradients in both the fuel pellets and the sheath, therefore, the thermal gradients should be representative. This program is structured in a series of tests progressing from simple representation to complex simulation. It is divided into 3 experimental phases:

Phase 1 Thermalhydraulic simulation of fuel element bow by a heated tube.

Phase 2 Thermal and mechanical bow with a simulator which accounts for pellet / fuel sheath interaction with internal pellet temperature distributions,

Phase 3 Fuel element bow with a simulator using Zircaloy-4 fuel sheath and internal heater with UO_2 fuel pellets.

This paper describes the strategy of the program and presents some of the test results from Phase 1.

1. INTRODUCTION

This paper describes some of the background understanding of fuel element bow, the concerns that it causes in safety analysis, and the experimental program developed by the Canadian utilities to quantify the degree of bow under dryout conditions which might occur in safety analysis.

The amount of fuel element bow is important to both safety and plant operation. The concern in safety assessments is that the phenomena of fuel element bowing introduces an uncertainty in the predictions of fuel temperatures in licensing based accident scenarios. The purpose of the experimental program is to characterize the bowing phenomena with sufficient confidence such that statements can be made and used in assessing the safety and operational impact of fuel element bowing under dryout conditions. These statements are expected to be sufficiently well supported by the experimental evidence that they can be generally applied to all CANDU designs.

Fuel element bow is induced by dryout conditions. In a CANDU fuel bundle, the bow causes a change in the sub-channel coolant flow areas and could potentially perturb the coolant flow distribution and heat transfer from the fuel element to the coolant. If this perturbation is large, it could lead to over-heating of the fuel and increases the potential for fuel deformation and melting. If fuel elements are separated from each other and from the pressure tube, with a sufficient (and stable) gap, the heat will be removed and the fuel integrity is maintained. Therefore, the prediction of the amount of bow, and its effect on heat transfer conditions is required for the assessments. For plant operation, it is also necessary to show that the plant is 'fit for service' after process upsets that are within the design capability of the plant, such as in the case of a loss of class IV power. In many of these types of events, before the second shutdown system trip is initiated, the fuel could be in dryout for a brief period of time. Therefore, it is important to show that no permanent damage has been done to the fuel and that the fuel can be considered to be fit for continued use.

The overall objective of the program is to ensure the consequences of fuel element bowing is clearly defined. A prerequisite in safety analysis, is to demonstrate that fuel element bowing will not result in fuel to pressure tube contact (a sufficient, but not a necessary condition). The utilities have undertaken to support COG programs (in working parties #7, 8 and 9) which should validate our understanding of the fuel element lateral deflection caused by realistic fuel dryout conditions, assess the changes in thermal hydraulic conditions that may result, and determine the degree of bow-thermal-hydraulic feedback that may exist.

2. BOW MECHANISMS AND CHF TESTS

2.1 Fuel Element Bow Mechanisms.

Fuel element bow is the result of a change in the axial strain around the circumference of the element. If one side of the element becomes longer because of thermal expansion, then bowing occurs towards that side. If the thermal gradient is linear across the section, then there are no internal stresses built up within the material. However, if a non-linear thermal gradient exists, stresses will result. The magnitude and non-linearity of the thermal gradients may result in stresses beyond the yield stress of the material. If the material is at high temperature and creep occurs (this may occur in a period of days at normal sheath temperatures of about 330°C, or seconds at a temperature of about 700 °C), the stresses may cause permanent creep strains and permanent bow.

Normal fuel operation may cause thermal gradients within the UO_2 fuel pellet and the sheath, (power gradients across the fuel from neutron flux gradients) hence the fuel element bows. If the sheath is stressed and creeps or deforms as a consequence, the permanent strain results in a "set" of the bow. These bows are small and of little concern.

In accident situations resulting in dryout at full power, thermal gradients could become large around the circumference of the fuel element. In the sheath portion where dryout occurs and heat transfer to the coolant is degraded, the predicted fuel sheath temperatures are much higher than the sheath portion that remains wetted by the coolant. Therefore, the amount of bow is larger than for normal operating conditions. There is also a strong potential for a permanent bow because of the higher temperatures, increased plasticity of the sheath and the more severe fuel to clad interactions. However, the duration of the transients may be short enough that the permanent bow is negligible.

Under degraded cooling conditions at decay power, heat transfer is mainly to the moderator heat sink through the pressure tube boundary resulting in radial temperature gradients across the fuel bundle and its elements. These cases result in a nearly linear thermal gradient across the element because of heat conduction through the element (rather than the strong heat generation and convective heat transfer at the element surfaces in post dryout under full power conditions). Consequently, the thermal stresses induced within the sheath material are small.

The potential for permanent deflection is thus dependent on the stress developed in the sheath and the duration of the transient. The mechanical stress in the sheath is a result of stresses imposed from either the UO_2 fuel, the constraints of the geometry, or the thermal gradients within the material. Bow and fuel element deflections are restricted within the bundle and channel by the constraints imposed on them by spacers, bearing pads, adjacent fuel elements, and / or pressure tube boundary. These constraints will translate some of the thermal bow into sheath stress. As discussed previously, UO_2 and non-linear sheath thermal gradients can impose stresses on the sheath . Hence, permanent bow can result from creep and plastic deformation of the sheath.

The permanent direction of bow may be in the opposite direction of the hot dryout bow after it returns to normal cooled conditions. This depends on the stress magnitude, thermal conditions, and stress relaxation at high temperature. Bow reversal can occur because the transient bow is set at temperature and on re-cooling, a greater contraction of the previously hot side occurs, reversing the bow direction.

Past programs at AECL-WL(1) have focussed on the bowing deflections of fuel elements caused by heating methods which resulted in linear temperature gradients across the element. That program demonstrated that a simple tube deflection model would give good agreement with the experiments if the UO_2 fuel pellet to sheath clearance was large, i.e. there was little interaction between them. However if there was significant UO_2 fuel pellet-to-sheath mechanical interaction, the amount of bow was significantly increased, and it also resulted in permanent creep deflections. For example, at a differential temperature of 300°C across the fuel element simulator, the amount of deflection was 0.7 mm with loose pellets (similar to a calculated tube deflection), and 1.6 mm with tight-fitting pellets and high eccentric heating (on the 0.25 m measurement length). Thus the fuel pellets are responsible for a significant amount of bow, and stress on the fuel sheath. Therefore, the thermal conditions of the pellet are critical to assessments, as well as the fuel pellet-to-sheath contact pressures.

The effect of the thermal gradient in causing bow is complicated because the fuel element is not a single solid. The UO_2 fuel pellets form a fuel stack which has some axial and circumferential clearance from manufacture. During operation, the fuel pellets expand and coolant pressure causes the sheath and pellet to be in tight contact. The thermal coefficient of expansion of the UO_2 is greater than the Zircaloy-4. Thermal gradients within the UO_2 fuel pellet and the sheath, as a result of the dryout conditions, form the driving forces for the deflections. Therefore, axial and circumferential heat transfer, expansions, and interactions between the pellet and sheath, the element and bundle, and the bundle and pressure tube should all be considered.

2.2 CHF Test Results.

The full scale CHF tests conducted at Stern Laboratories Inc.(2) have shown the extent of dry patches as the bundles were overpowered beyond the onset of dryout. The fuel element dryout occurred first just upstream of an end plate or a spacer plane. The dry patch tended to spread axially, and around the circumference. Even at overpowers of 14.5% at a flow of 17 kg/s, the dry patch of an element extended only to about 120 mm, less than half way toward the mid spacer plane of the bundle from the downstream end. There are up to two sets of dry-patches on each element, one extending from the endplate, one extending from the mid-plane; the two patches may counteract the deflections. Up to half of the circumference of an element was in dryout and the maximum observed temperature was below 600°C. The limited axial extent of dryout could be expected to result in only a small amount of element bow. Thus the extent and temperatures of dryout should be carefully considered in the evaluation of the bow of the element in fuel bundles in transients.

3. EXPERIMENTAL PROGRAM PLANS

This program will provide the tools to estimate the amount of transient and permanent deflections that results from accident conditions which cause a dry patch on one side of the sheath. Those conditions generate non-linear thermal gradients while the coolant pressure is high (up to about 10 MPa) due to a transient beginning at full power. Thus, it is necessary to develop a simulation representative of fuel sheath dryout conditions; where realistic coolant forces are applied to the element, which results in non-linear thermal gradients around and along the length of the element.

The program is divided into 3 phases:

Phase 1 Tubular element hydraulic simulation and thermal conditions in dryout. It will determine the bow of a tube based on the sheath temperature gradients. These tests quantify the sheath surface temperature field in the assembly using direct resistance heated elements so that this field can be used in the subsequent phases of the program. This will provide the input conditions which will then be used to infer the thermal conditions of the sheath in subsequent tests with fuel simulators. The resistance heated tubular fuel element allows a full thermal map to be developed using thermocouple assemblies which move axially and circumferentially, inside the heated elements.

Phase 2 Fuel element bowing in realistic dryout conditions. This test will account for pellet / fuel sheath interaction with internal pellet simulation. A ceramic pellet (probably ZrO_2) with a central heater will be used to develop the required power to simulate the fuel expansion behaviour. A Zircaloy-4 fuel sheath with CANLUB will be used, and this sheath may be resistance heated to generate the total power necessary to cause dryout. The thermal distribution of the sheath will be inferred from phase 1 and calibrated to a small number of fixed position thermocouples in these simulators. The bow is expected to be similar such that additional corrections will not be required (The difference between the thermal feedback between the two types of simulators, Phase 1 and Phase 2, is expected to be small since the difference in the magnitude of bow is expected to be similar).

Phase 3 Evaluation of Zircaloy-4 element bowing. This will account for the thermal properties of UO_2 and internal gas pressure. This utilizes a fuel simulator using Zircaloy-4 fuel sheath and internal heater as above, but with UO_2 fuel pellets. UO_2 is required for simulating "real" fuel, but it is experimentally much more difficult (low UO_2 thermal conductivity may result in high inner heater temperatures, possible element failure and loop contamination).The situation will be re-evaluated after the second phase of the program is completed. This will provide a simulator which has the mechanical interface of as manufactured fuel (including CANLUB). Several experiments may be required to explore a range of differential pressures across the fuel sheath (i.e. to simulate fuel of high burnup and gas release, and fresh fuel with little internal gas pressure).

The Phase 2 and 3 tests will provide a reasonable simulation of the effects of coolant pressure on fuel sheath and fuel pellet interactions. The intent is to conduct the tests over a wide range of experimental conditions of coolant flow and pressure, so that they are applicable to the safety analysis. However, as the program proceeds into Phases 2 and 3, the power limitations may necessitate the experiments to be conducted with lower flows and "aggressively" achieve dryout at lower heater powers. Nevertheless, the small but significant database can be used to validate models and analysis methodology.

The following table shows how out- and in-reactor tests compare in their ability to simulate the CANDU fuel element dryout. Some judgments are made in the table on the available experimental techniques to do the tests.

	OUT-REACTOR TESTS	IN-REACTOR TESTS
Conditions for dryout	yes	yes
Measurements of thermal distribution	yes, by correlating spot measurements to previously calibrated tube distributions.	inference from spot measurement
Measurements of deflection	yes	no
Thermal hydraulic feedback	yes	yes
Fuel performance feedback	simulation	real

The out-reactor tests provide a more complete measurement of the thermal distribution from well calibrated tubular test assembly. The use of bow measuring devices will provide deflections caused by the measured thermal distribution. However, since fuel element simulators are used, the properties of a real fuel element has to be inferred by relating the simulated material properties to UO_2 fuelled elements. There are no phenomena associated with in-reactor testing which are not incorporated in the out-reactor tests.

It is well understood that simultaneous measurements of the thermal distribution and bow can not be provided with current state of the art instrumentation in-reactor tests. Achieving high reliability of instrumentation in fuel experiments in-reactor is extremely difficult and expensive. Moreover, direct measurements of fuel temperatures on the sheath surface and bow measuring devices will perturb the flow and change the dryout characteristics, thus making the amount of bow attributable to the thermal distribution of dubious value.

4. PRELIMINARY PROGRAM TEST RESULTS

Two series of tests have been completed as part of Phase 1 of the program at Stern Laboratories Inc. These tests were designed to qualify the apparatus for dryout experiments. Secondly, they explore the range of conditions that could be used in Phases 2 and 3 simulator experiments.

4.1 Test Conditions.

The Phase 1 experiments were designed to investigate the CANDU element bow under similar conditions to those in full scale CANDU fuel. The test geometry consisted of a 1.5 m long directly heated tre-foil fuel element simulator string. Each simulator consisted of three 0.5 m long simulators of Inconel 718 tube with internal sliding thermocouples in the downstream section. These tests quantify the sheath surface temperature field in the assembly using direct resistance heated elements so that this field can be utilized in the subsequent phases of the program.

The tre-foil is installed in a pressure housing with internal ceramic liners (insulators) which were designed to simulate the internal geometry of a CANDU 37 element fuel bundle. The hydraulic and heated equivalent diameters were 4.5 mm and 8 mm, respectively. The average of these is nearly the same as that of CANDU 37 element fuel, 6.3 mm. A cross section of the assembly is shown in Figure 1.

One downstream element is instrumented at two axial planes with LVDT probes, one at the mid plane, and one at the 1/4 plane to measure the lateral deflection and resolve into tangential and radial components. This element operates at 10% higher power than the other elements to ensure that dryout occurs.

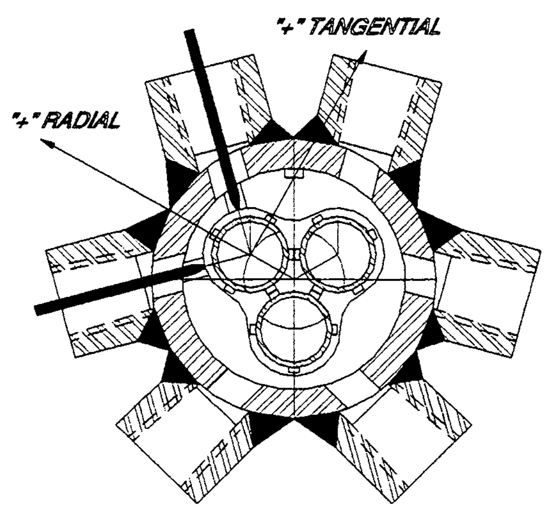

Figure 1: CROSS SECTION (looking downstream)

The test loop provides a simulation of full reactor pressure, temperature and mass flux conditions. The 2.5 MW direct power supply was sufficient of inducing the dryout conditions over a wide range of selected mass fluxes. Two test conditions were chosen:

Table 1: TEST MATRIX

Test	Inlet Sub-Cooling (temperature) °C	Mass Flux ($kg.m^{-2}.s^{-1}$) (equivalent CANDU channel Flow $kg.s^{-1}$)	Predicted CHF[1] $kW.m^{-2}$ (Linear Power $kW.m^{-1}$)	Exit Pressure MPa
1	5 (298)	2000 (7.7)	1350 (55)	9
2	5 (298)	1000 (3.84)	1040 (43)	9

notes: 1) CHF power levels predicted using the Groeneveld look up table (3).

The test conditions were maintained constant and dryout was approached from lower power with the thermocouples placed at the expected dryout locations. When dryout occurred, the temperatures were scanned to confirm the location of the maximum temperature. The string power was then incrementally increased in steps of 2% until about 10% overpower was reached. At each step the temperatures were scanned to map the temperature distribution. While this was taking place, the element displacements were also recorded.

4.2 Test Results and Discussion.

As expected, the preferential location of dryout patches were just upstream of the endplate plane in both series of tests. Figures 2 and 3 show maps of the dryout patch for the two tests. The figures show that the lower mass flux test has a dry patch approximately 10 mm longer for nearly the same over power condition beyond the initial dryout power. Note that the actual element power for Test 1 is nearly 30% higher.

Figures 4 and 5 show the radial and tangential bow deflections versus the peak temperatures recorded. These figures show that the element bowed in the direction of the dry-patch that occurred facing the inner subchannels in Test 1. The maximum displacement, resolved from both the radial and tangential components of displacements, in Test 1, is -0.64 mm with a maximum dry-patch temperature of ≈640°C. Similarly in Test 2, a maximum displacement of -0.61 mm was measured at ≈600°C. In Test 2, the figures show that the element bowed downward in the direction of the dry-patch which had formed adjacent to the sub-channel between element 3 and the ceramic liner wall. The different locations of initial dryout may be correlated to the flow regime condition in each test for horizontal channels; Test 1 is in homogeneous annular flow, whereas Test 2 is in stratified annular flow(3). A small residual bow of 0.11 mm was measured at the downstream end of the element after the maximum temperature condition had been removed, for Test 1. Post test examination confirmed the degree of permanent deflection, although on dis-assembly, the constraint condition of the channel was removed and the measured element bow was not the same as the in-situ bow.

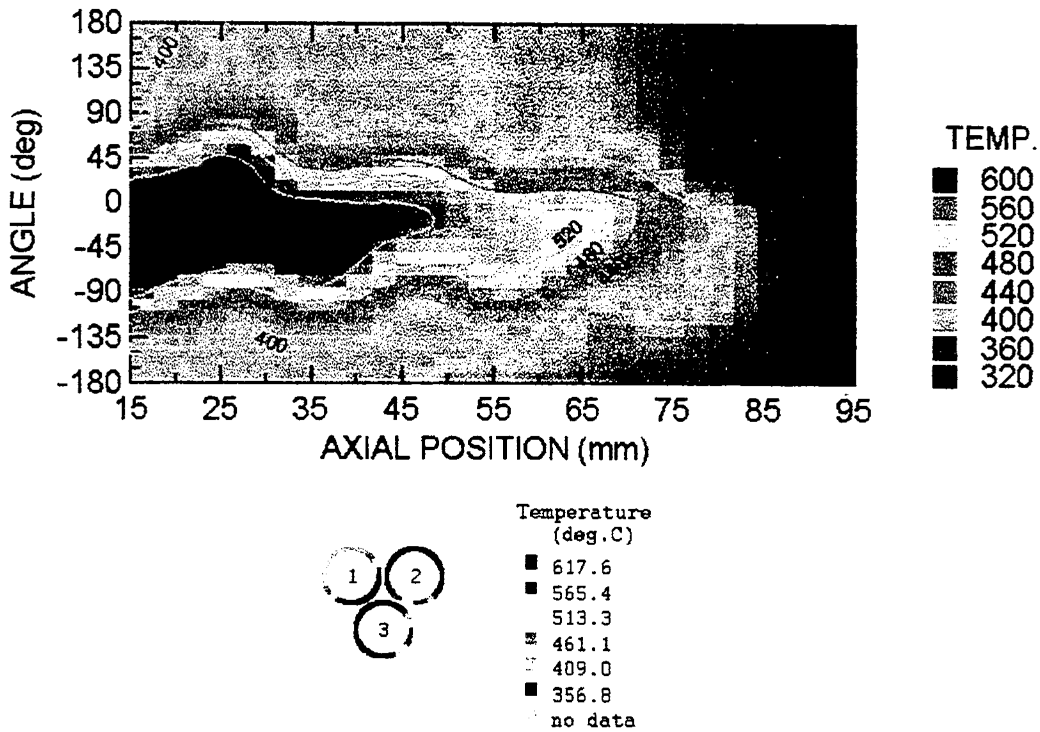

Figure 2: TEST 1 DRYOUT PATCH AND CROSS-SECTION

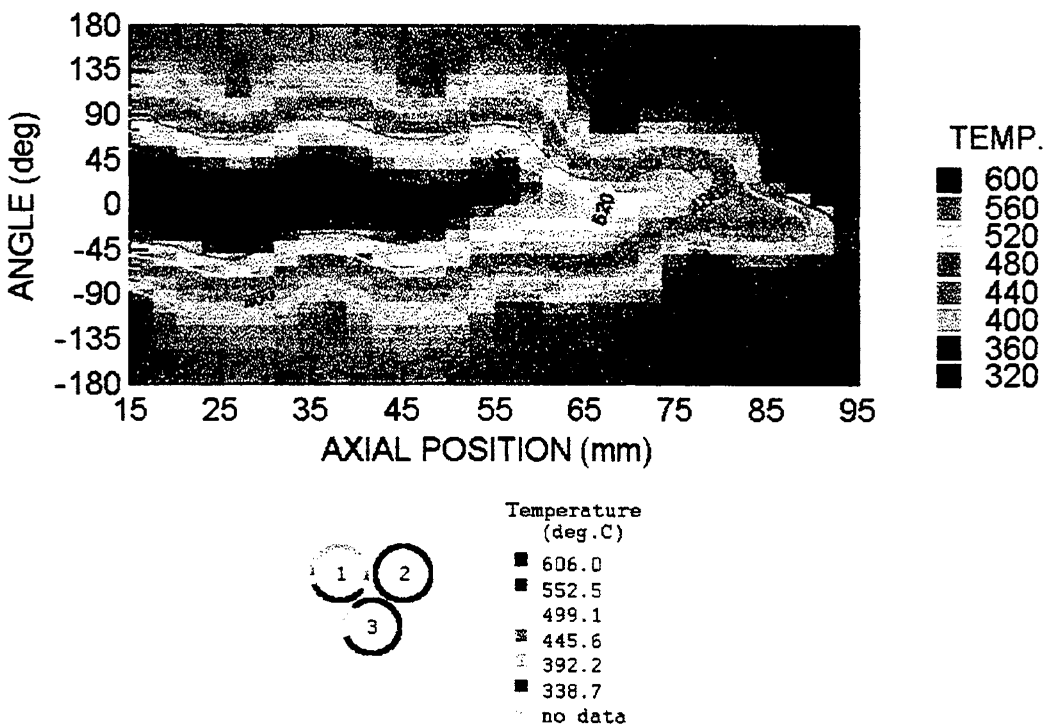

Figure 3: TEST 2 DRYOUT PATCH AND CROSS-SECTION

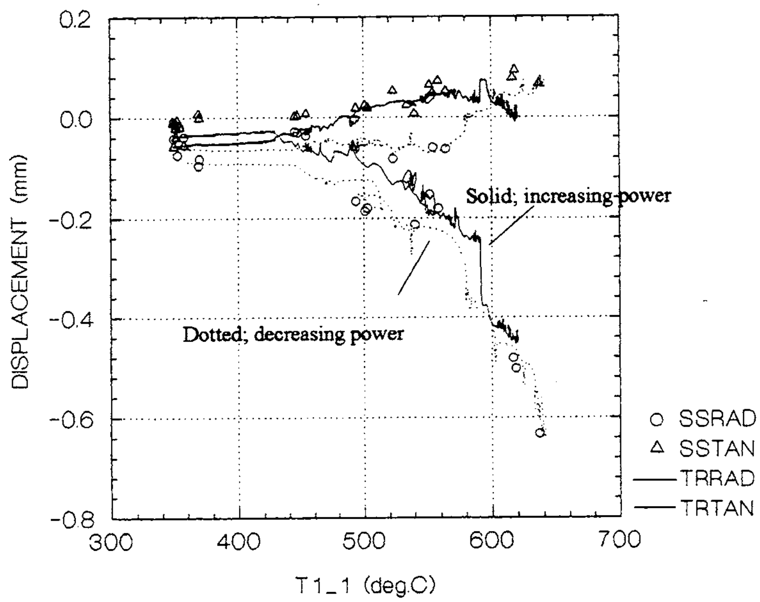

Figure 4: TEST 1 BOW VS. PEAK TEMPERATURE

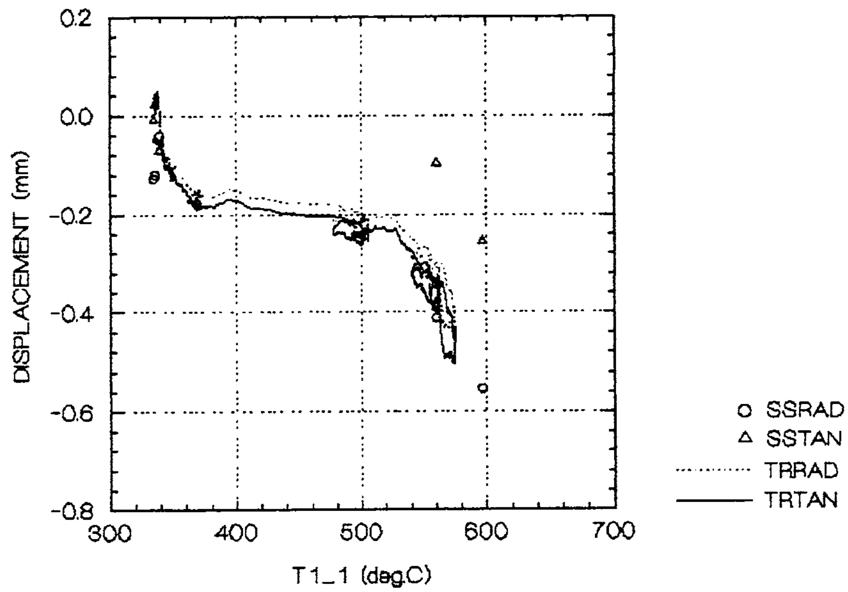

Figure 5: TEST 2 BOW VS. PEAK TEMPERATURE

5. SUMMARY

The utilities, through jointly supported COG programs (in working parties #7, 8 and 9) are in the process of validating our understanding of the fuel element lateral deflection caused by realistic fuel dryout conditions. This program has started to quantify the effects of dryout induced bow. For dryout temperatures of 600°C, the bow was about 0.6 mm, for the test conditions chosen and with inconel tubular heaters. This is an indication of the transient bow an element could experience under severe temperature gradients. No significant feedback on CHF characteristics was noted at this magnitude of bow.

6. REFERENCES

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