Thermalhydraulic Performance of CANFLEX Fuel

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ABSTRACT

CANFLEX is a 43-element CANDU fuel bundle, which is being jointly developed by AECL and KAERI, to facilitate the use of various advanced fuel cycles in CANDU reactors through the provision of enhanced operating margins. The design uses two element diameters (13.5 and 11.5 mm) to reduce maximum element ratings by 20%, yet maintaining the same bundle power and a uranium content very close to that of the standard 37-element design. The CANFLEX design also includes the use of critical-heat-flux (CHF) enhancing appendages, to increase the minimum CHF ratio or dryout margin of the bundle. The combination of these two features makes the CANFLEX bundle of interest for both advanced fuel cycles and also for use in existing CANDU reactors where it can compensate lost operating margin that is due to rising inlet header temperature and pressure tube creep.

The major components of the thermalhydraulic testing are the evaluation of the CHF performance and the pressure drop with respect to the current 37-element bundle design. In addition, post dryout and drypatch mapping has been done to assist in the understanding of the performance of the CHF enhancing appendages, and to provide a baseline for future modifications to further improve the CHF enhancement. Both the CHF and the pressure drop measurements have been done using Refrigerant-134a, the first with an electrically heated 6-m-long simulation of a string of 12 CANFLEX fuel bundles, and the second with a string of 5 actual CANFLEX fuel bundles. The results clearly demonstrate the superior thermalhydraulic performance of the CANFLEX design compared with the current 37-element design, and based on this a demonstration irradiation of 24 bundles is planned in a CANDU 6 reactor for 1998. To allow full advantage to be taken of the improved performance, a water CHF test is planned before any full-core conversion to CANFLEX.

This paper gives the results from the R-134a program showing an expected minimum critical channel-power improvement of 4% compared with the current 37-element bundles. It also shows that there is a similar or possibly slightly less of a reduction in the CHF performance because of pressure tube creep with a CANFLEX channel, as compared to a 37-element channel. In addition, examples of the detailed CHF, pressure drop and post dryout measurements are given.

INTRODUCTION

About seven years ago, a joint study was initiated by AECL and KAERI to investigate the use of the new CANFLEX 43-element fuel bundle as a carrier for advanced fuel cycles in CANDU reactors. In addition to reducing the fuel ratings and thus allowing more flexibility in fuel material, the CANFLEX bundle design resulted in increased operating margins. These increased margins can provide significant economic benefit to our older CANDU reactors by mitigating aging and extending operating time.

A key limitation on reactor operation is the channel power at which dryout of a fuel sheath (also known as critical heat flux, CHF) first occurs. The power at which initial dryout occurs is a strong function of the fuel design, the channel flow and the coolant inlet temperature. As the flow decreases or the inlet temperature rises, the critical power decreases. Reactor operation is regulated to ensure that dryout will not occur in the reactor under all normal modes of operation.

Because the reactor channels are connected in parallel to the inlet and outlet headers, the channels operate under essentially constant pressure drop conditions. Flow is dependent on the friction and obstruction losses in the channel and also on the steam quality being produced in the channel. Because of this, as the channel power goes up the channel flow will go down, and both of these tend to precipitate dryout of the fuel sheath. In design and safety analyses the CHF as a function of flow and other variables is combined with the channel hydraulic characteristics to determine the critical channel power (CCP) for constant header to header pressure drop conditions.

During the life of a reactor the pressure tubes slowly increase in diameter (creep), which results in an increased channel flow for the same header to header pressure drop. However, because the pressure tubes are horizontal and the fuel bundles sit on the bottom of the tube, creep also results in an increased distance between the pressure tube and the top of the bundles which can allow a significant amount of the coolant to bypass the fuel. This reduces the effective flow through the bundle and reduces the CHF for a given bundle design. An integral part of CANFLEX fuel is the use of CHF enhancing appendages, which increase dryout margin of the bundle, and makes the CANFLEX bundle of interest for advanced fuel cycles and also for use in existing CANDU reactors where it can compensate for lost operating margin that is due to rising inlet header temperature and pressure tube creep.

To quantify the thermalhydraulic performance of the CANFLEX design, pressure drop measurements were made using CANFLEX bundles, and CHF and post dryout measurements were made using an electrically heated cluster that simulated a string of twelve aligned CANFLEX bundles. The measurements were performed in the MR-3 Freon Heat-Transfer-Loop facility which is capable of performing the tests on full-scale CANDU-6 fuel channels. Freon 134a is used as a modelling fluid which allows comparison tests to be done at a much lower pressure and temperature than in water. Thus, tests are done at a lower cost and in a shorter time period. This paper reports the results of these measurements.

PRESSURE DROP MEASUREMENT FACILITY

The pressure drop test section consists of five 43-element CANFLEX fuel bundles (bundles O, A, B, C and D), placed horizontally in a fibreglass flow channel (liner). The axial pressure gradient along the bundles is measured with both fixed wall pressure taps and with sliding pressure probes [1]. The probes' axial position and the bundle misalignment angle can be varied by using a semi-automatic mechanised system. Each bundle is 50 cm (nominal) long and has 3 bearing pad planes (not shown); the test section assembly is shown in Figure 1.

The test section inlet and outlet temperatures are measured by an RTD and a thermocouple respectively. The inlet and outlet pressures are measured by both pressure transducers and Heise gages. Seven differential pressure transmitters (DP-cells DP-1 through DP-7 in Figure 1) measure the axial pressure gradients. The DP-cells, DP-5 & DP-6 measure the ΔP signals from the two probes. Each probe has a sensing hole for pressure drop measurement. The remaining five DP-cells are connected to the four pressure taps drilled in the test section liner as shown in Figure 1. The presence of the probes restricts the misalignment angle to ±50°. Three angles, 0°, 12° and 24° are chosen for the probe-based profile tests at fixed misalignments. For the 0° to 360° rotation tests, the probes are withdrawn from the test section; DP-1 and DP-2 are used to measure the junction pressure drops between bundles B and C, and bundles C and D. DP-cells DP-3 and DP-7 measure the pressure drop across one bundle length each. Two upstream turbine flow meters measure the flow. The signals from each of these instruments, and from the axial and angular position detectors, are recorded by the data acquisition computer.

CHF CLUSTER and TEST FACILITY

The CHF test cluster simulates a string of twelve aligned CANFLEX bundles in a pressure tube. It has a heated length of 6 m and is divided up every 50 cm by simulated end plates, and contains all of the CHF enhancing appendages, spacers and bearing pads that exist on actual CANFLEX fuel. The cluster is electrically heated by passing a direct current through the thin walled tubes that make up the cluster, the wall thickness being chosen such that the axial heat flux profile is uniform and the radial heat flux profile simulates that expected in a reactor fuelled with natural uranium fuel. A picture of the cluster is shown in Figure 2. The cluster is mounted eccentrically in a flow tube to simulate the geometry existing in a reactor, and the flow tube/cluster assembly is mounted vertically in the MR3 test loop. The cluster is heated by a 165 Volt, 12000 Amp infinitely variable power supply, and cooled by a flow of refrigerant R-134a from the loop. The loop is capable of providing the flows, temperatures and pressures which correctly model the conditions of interest in a CANDU reactor.

The cluster is equipped with movable thermocouples inside all of the tubes in the downstream three segments for CHF detection, measurement of the post dryout wall temperatures, and delineation of the sizes and shapes of drypatches during post dryout operation.

CHF TESTS

Two series of CHF tests with the CANFLEX cluster were done, the first in an uncrept pressure tube, and the second in a tube that represented 3.1% diametral creep. In all of the tests initial CHF occurred at the end of the heated length. The data from the uncrept tests are shown in Figure 3 plotted as cluster power against inlet subcooling for various flows and pressures. The data are well behaved with a linear dependence on subcooling which increases with increasing flow. As expected, increasing the pressure decreases the CHF for a fixed inlet subcooling.

The CHF data taken at one pressure in a flow tube simulating a 3.1% crept pressure tube is compared to the uncrept data in Figure 4 again as power versus inlet subcooling. The data show the same trends as the uncrept data but CHF occurs at consistently lower powers. Although not shown, the data for the crept tube at other pressures behaved similarly. The CHF penalty due to pressure tube creep varies between 10 and 20% with the average reduction of 16.5%. This value of 16.5% can be compared to 25% given by Leung [2] for a 37 element bundle tested in water with a 3.3% crept pressure tube. Although there were significant differences between the current tests and those in [2] it does indicate that pressure tube creep has a smaller effect on CHF in CANFLEX than it does in the 37 element bundle.

The radial location of the initial dryouts for both the uncrept and the crept cases are shown in Figure 5. The locations varied slightly with different thermalhydraulic conditions but generally initial dryout in the uncrept tube occurred on one of the outer rods nearest the pressure tube but in the rod-to-rod gaps or facing the inner subchannels. This was then followed by elements in the inner 7 ring. In the crept tube this was often reversed with initial dryout in the inner ring followed shortly after by the outer ring.

PRESSURE DROP TESTS

Axial Pressure Drop Profile.

Figure 6 presents typical pressure drop profiles along a 43-element and a 37-element bundle obtained by the pressure probes in the 0^{o} or "fully aligned" bundle configuration. The profiles are obtained by sliding the probes by a distance of either 5 mm or 10 mm at a time along the bundles through the test section. On Figure 6 the perturbations in the axial profile due to the bundle junctions and mid-plane spacers for the 43- and the 37-element bundles can clearly be seen. The overall pressure drop of the 37-element bundle is somewhat higher than the 43-element bundle and, analysis of all data suggests that the pressure drop per bundle length for the 43-element bundle (fully aligned) is about 3.1% lower than that for the 37-element bundle.

Rotation Tests.

The probes are withdrawn completely from the test section to do the rotation tests. Data from the junction pressure drops (DP-cells DP-1 or DP-2) or single bundle length pressure drops (DP-3 or DP-7) are used to represent the pressure drop as a function of misalignment angle and give the junction pressure drop signature. Rotational pressure drop measurements are important to determine both the "most probable or arithmetic average pressure drop" and also the fully aligned (minimum of the junction signature). Figure 7 shows typical pressure drop signatures (based on single bundle length measurements) for the 43- and 37-element bundles. The figure confirms that pressure drop caused by a 43-element bundle is lower than that of a 37-element bundle for the same flow, temperature and pressure and for the same test rig. Analysis of all data (uncrept and 3% crept channels) shows that all three measures of pressure drop are lower for the 43-element bundle compared to the 37-element bundle as follows.

- Minimum (fully aligned) pressure drop is reduced by about 3%,
- Most Probable (randomly aligned) pressure drop is reduced by 1.8%, and
- Maximum (fully misaligned) pressure drop is reduced by 3.4%

POST DRYOUT MEASUREMENTS

During selected CHF runs the power was increased considerably beyond initial CHF to study the drypatch spreading characteristics of the bundle. Then, at a fixed overpower, the thermocouples in selected rods were moved both axially and circumferentially to delineate the extent of the drypatch around the rod, and the sheath temperatures within the drypatch. An example of the data are shown in Figure 8 where the temperature contours over 180^{o} for the downstream 30 cm of rod #20 are shown. The location of the sector within the bundle cross section is shown below the map in Figure 8. At this 20% overpower the drypatch has spread to cover a significant portion of the sheath both downstream and upstream of the mid-plane spacers. The effect of the mid-plane spacers and bearing pad in preventing dryout just downstream of them is apparent as is the strong effect of the CHF enhancing appendages in suppressing dryout.

DISCUSSION

One of the objectives of the CANFLEX program is to obtain superior thermalhydraulic performance compared to the 37-element bundle. The uncrept CANFLEX CHF data obtained here are compared to data taken with a 37-element bundle also in an uncrept tube, but in Freon-12 [3] in Figure 9. To make this comparison, the Freon-12 data were converted via fluid-to-fluid modelling to refrigerant-134a equivalent, using Katto's modelling criteria [4]. The comparison shows that on a local conditions basis and for the same mass flow rate, the CHF for the CANFLEX bundle is between 5 and 15% better than the 37 element bundle over the flow ranges of interest.

As is shown in section 5 the pressure drop across a CANFLEX fuelled channel is also lower than an equivalent 37-element fuelled channel, and thus the flow through the CANFLEX channel will be higher for a constant header-to-header pressure drop. This will further increase the CHF compared to the 37-element channel. When these two factors are combined and for a constant header to header pressure drop, the critical channel power improvement with CANFLEX fuel is around 4%.

The post dryout measurements showed that the CHF enhancing appendages are very effective in suppressing dryout. To improve the CHF performance of the CANFLEX bundle still further we have an ongoing program to study and optimize the locations of these appendages within the bundle. Also, some uncertainty exists in the 43 to 37 element comparison because of the fluid-to-fluid modelling conversions required. To eliminate this uncertainty we will be testing a 37-element cluster in refrigerant 134a to allow direct comparison.

CONCLUSIONS

Pressure drop and CHF tests have been made in refrigerant-134a to characterize the thermalhydraulic performance of CANFLEX fuel. Under constant channel flow conditions and for the same dryout quality and pressure, the CHF in the CANFLEX bundle is between 5 and 15% better than the current design 37-element bundle in an uncrept pressure tube. Indications are that this performance may be further improved in a crept pressure tube. The drypatch spreading data have shown that the CHF enhancement features in the CANFLEX bundles are very efficient at suppressing dryout.

The pressure drop measurements show that for the same channel flow the overall channel pressure drop with a string of CANFLEX bundles will be 1.8 to 3.4% lower than for a corresponding string of 37-element bundles. With a constant header-to-header pressure drop this will result in a higher channel flow for the CANFLEX bundles.

Both the improved CHF performance and the increased flow will combine to increase the critical channel power by about 4% relative to the 37-element bundles. These tests have given us confidence in the superior performance of the CANFLEX design such that we are taking the next step which is the demonstration of the irradiation performance in a CANDU-6 reactor. We have an ongoing program in Refrigerant 134a to optimize the locations of the CHF enhancing appendages and to test a 37-element cluster to reduce modelling uncertainties. In parallel with these and the demonstration irradiation, we will be conducting CHF tests with a water cooled CANFLEX string that will allow us to realize the full benefit of the increased reactor operating margins on a full core conversion to CANFLEX fuel.

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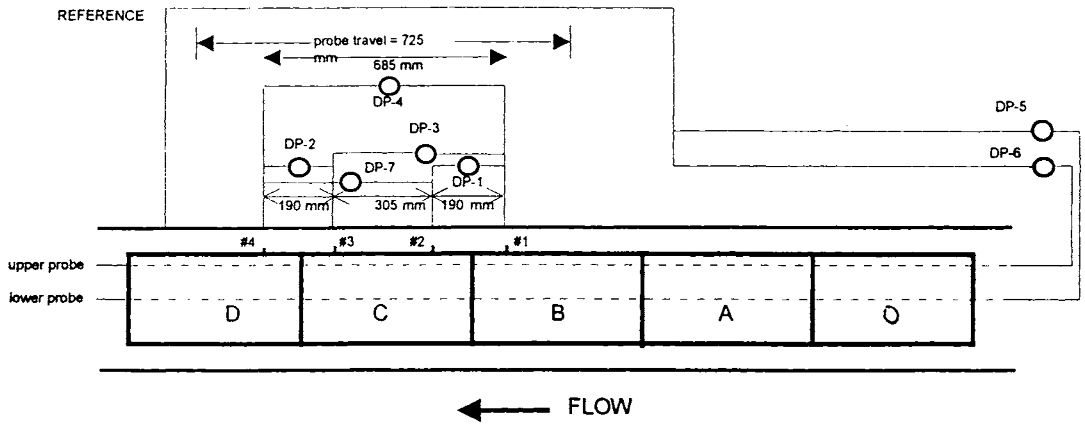


FIGURE 1: SCHEMATIC OF PRESSURE DROP MEASUREMENT TEST SECTION

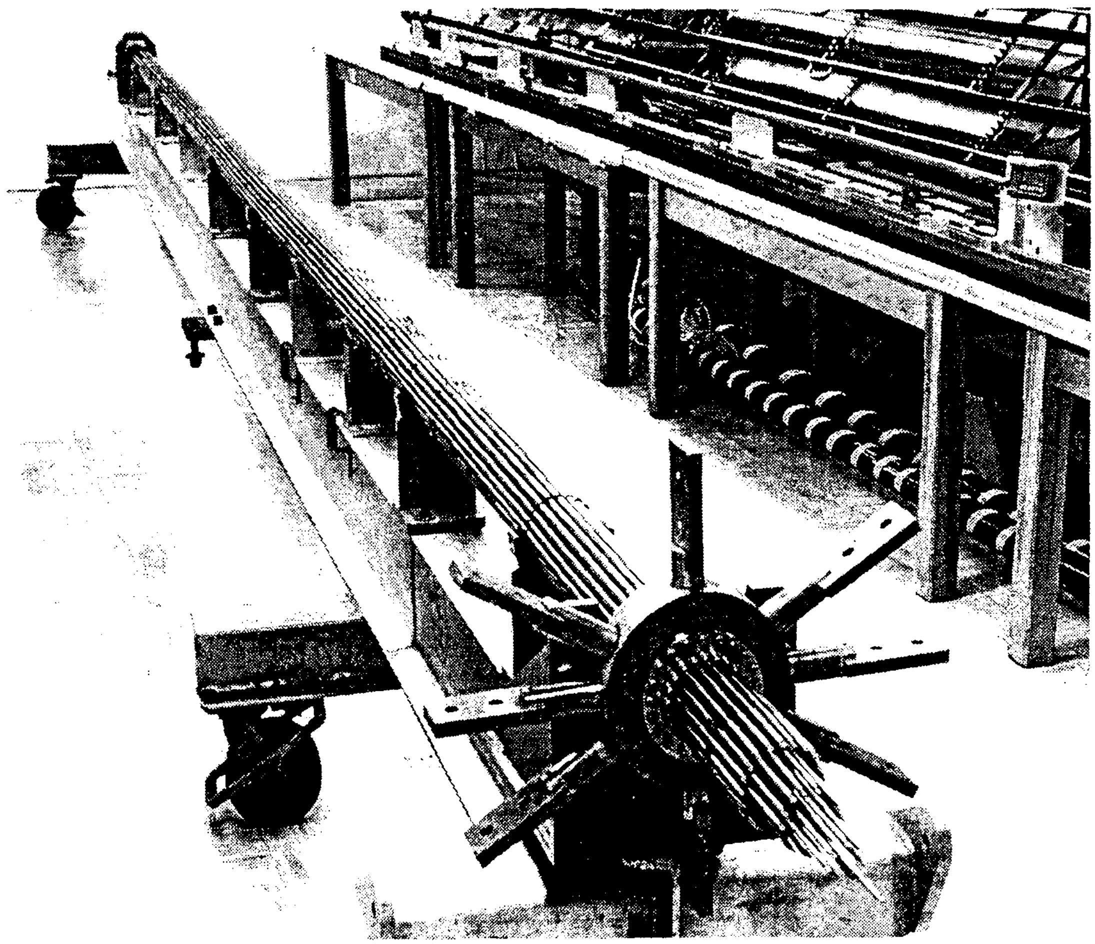


FIGURE 2: PHOTOGRAPH OF CHF TEST CLUSTER

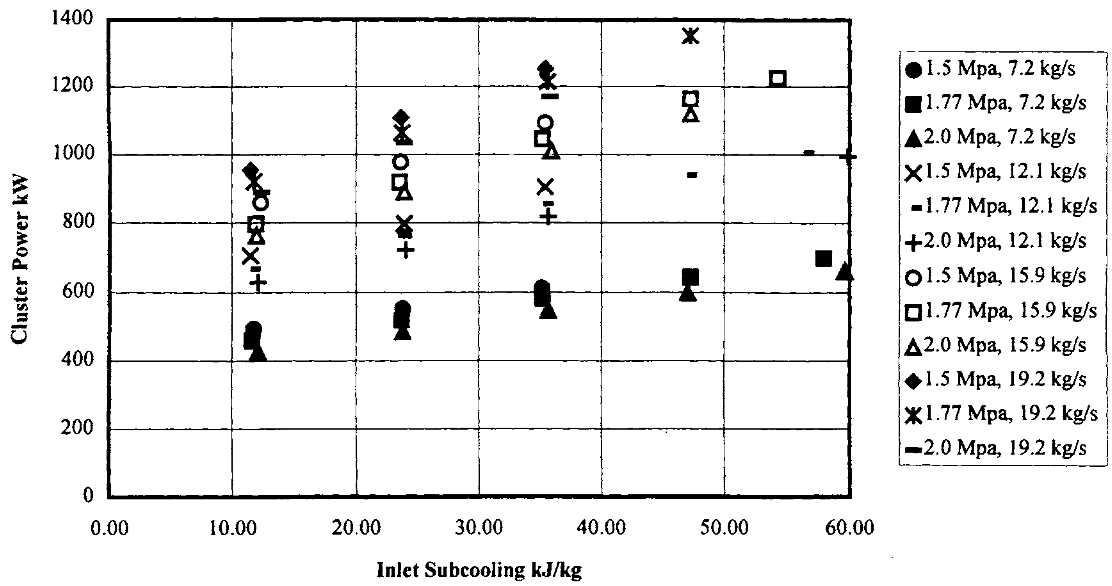


FIGURE 3: CANFLEX CHF DATA WITH AN UNCREPT PRESSURE TUBE

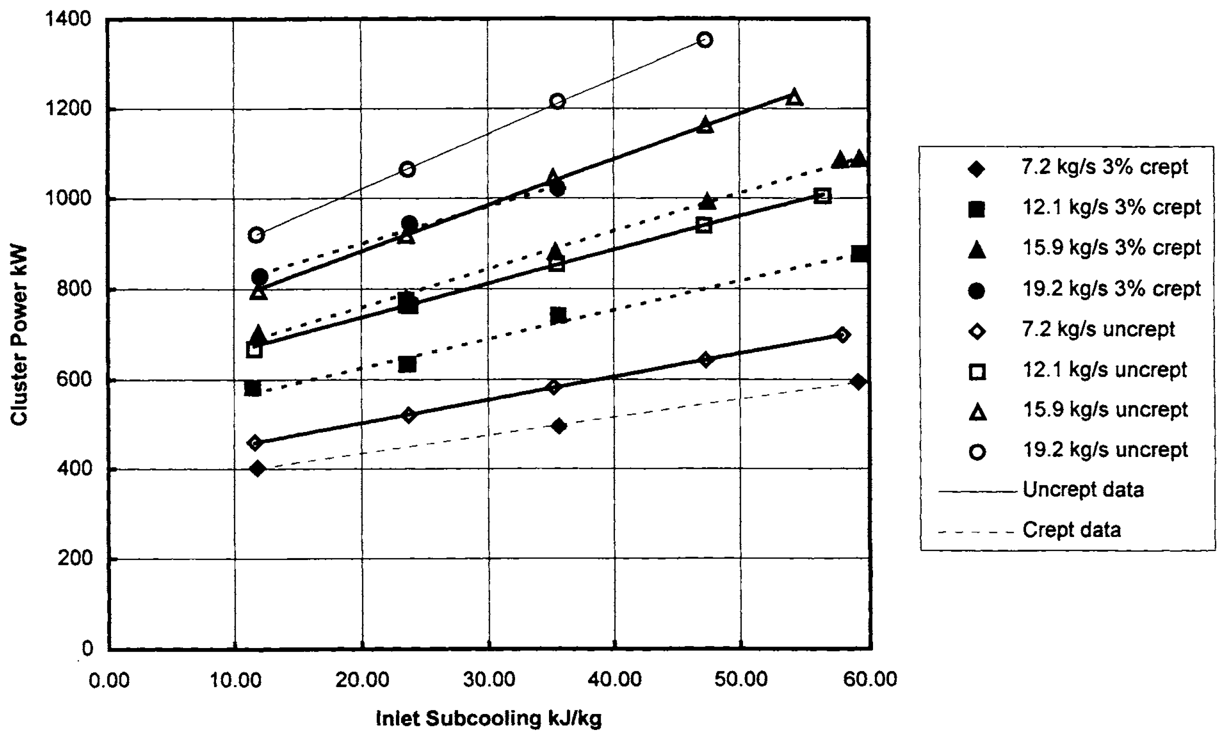
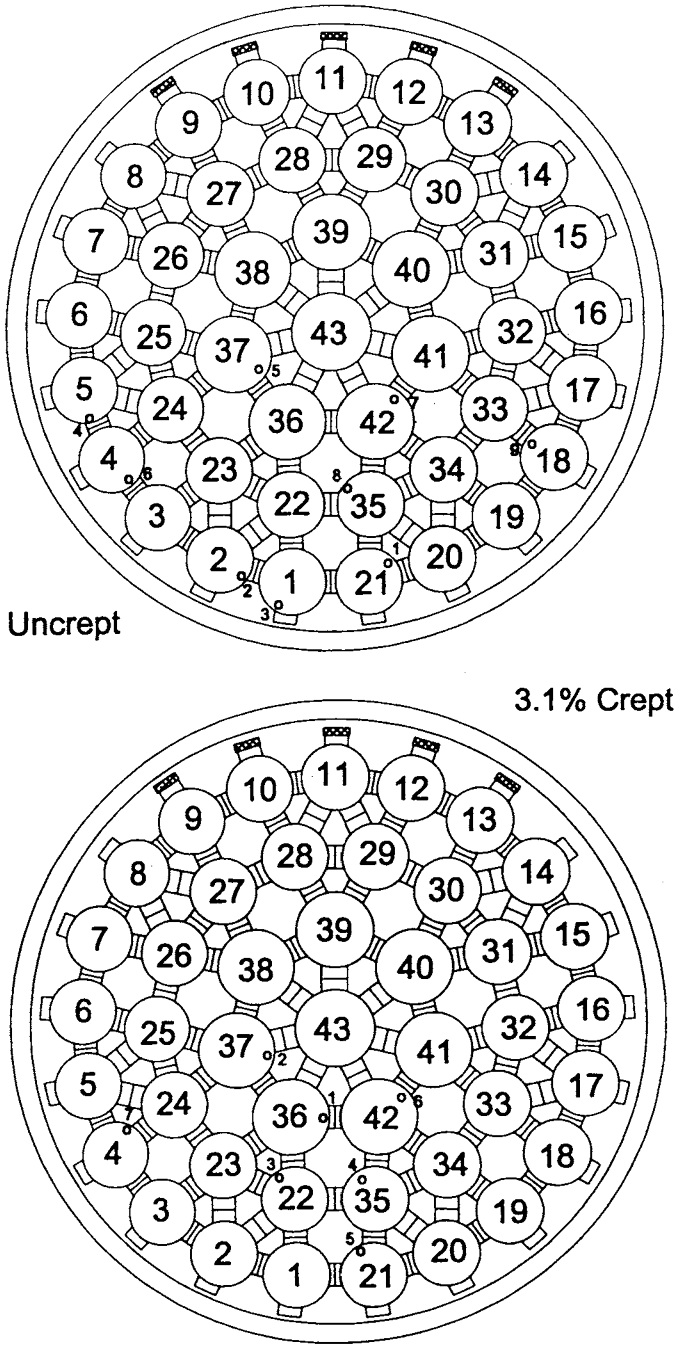


FIGURE 4: CANFLEX CHF DATA WITH CREPT AND UNCREPT PRESSURE TUBES, PRESSURE = 1.77 MPa



Flow = 12.0 kg/s
Pressure = 1.77 Mpa
Inlet subcooling = 24 kJ/kg
The numbers adjacent to the thermocouples show the sequence of dryouts

FIGURE 5: LOCATIONS OF INITIAL DRYOUT AND SEQUENCE OF SUBSEQUENT DRYOUTS

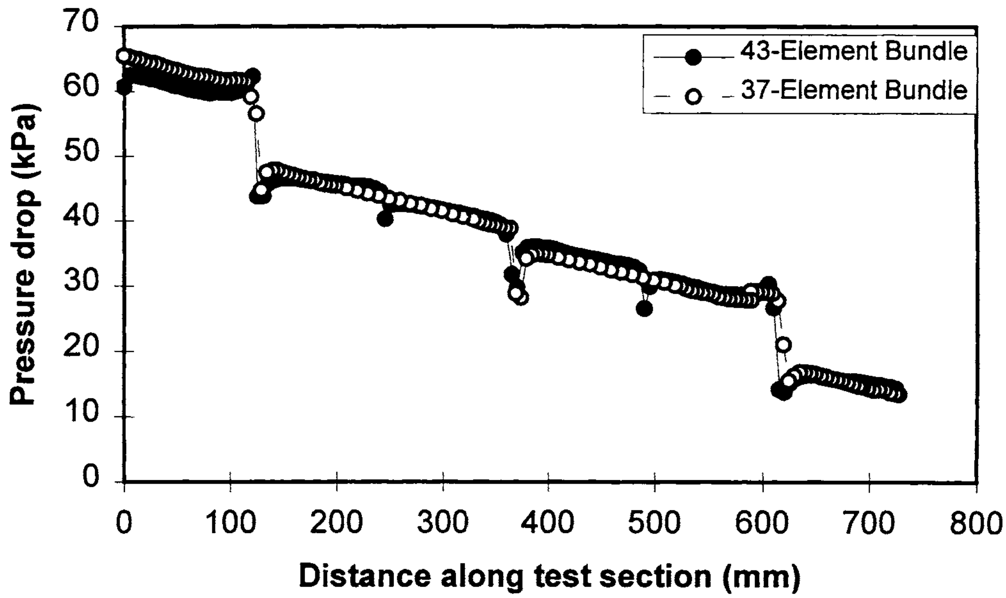


FIGURE 6: AXIAL PRESSURE DROP PROFILES OF 43- AND 37-ELEMENT BUNDLES IN 3% CREPT CHANNEL AT W = 28 kg/s; T = 57 °C; P = 1980 kPa

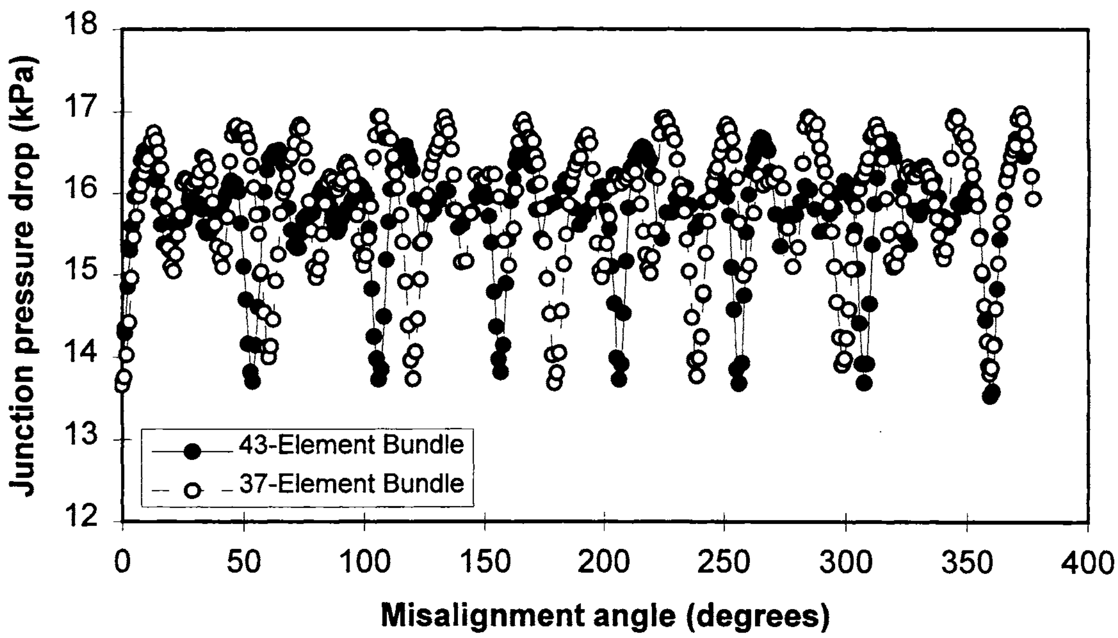


FIGURE 7: JUNCTION PRESSURE DROP (PER BUNDLE) SIGNATURES OF 43- AND 37-ELEMENT BUNDLES IN AN UNCREPT CHANNEL AT W = 15 KG/S; T = 41 °C; P = 1980 KPA

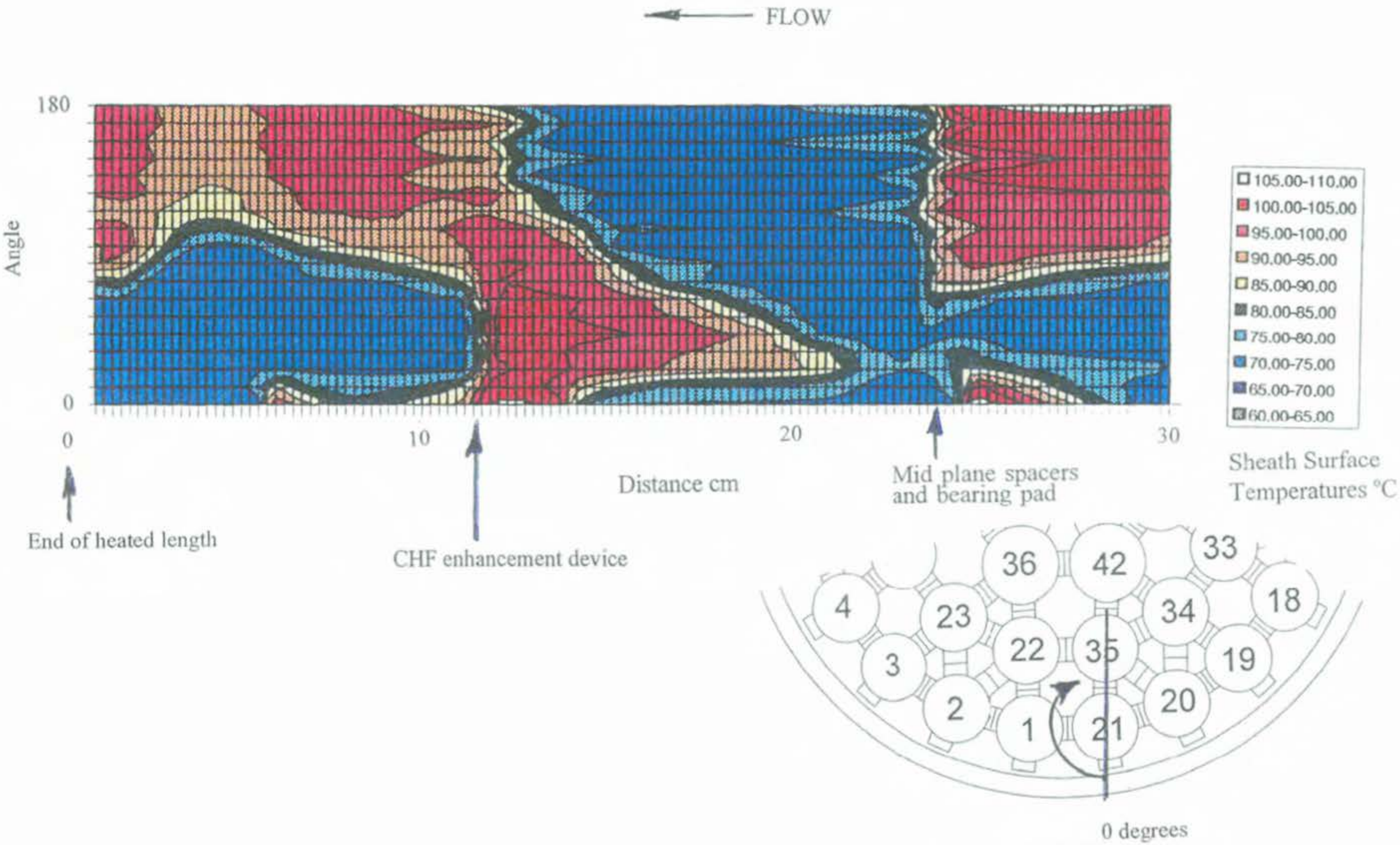


Figure 8. Post Dryout Temperatures and Drypatch Extent on Rod #21 at 20% overpower

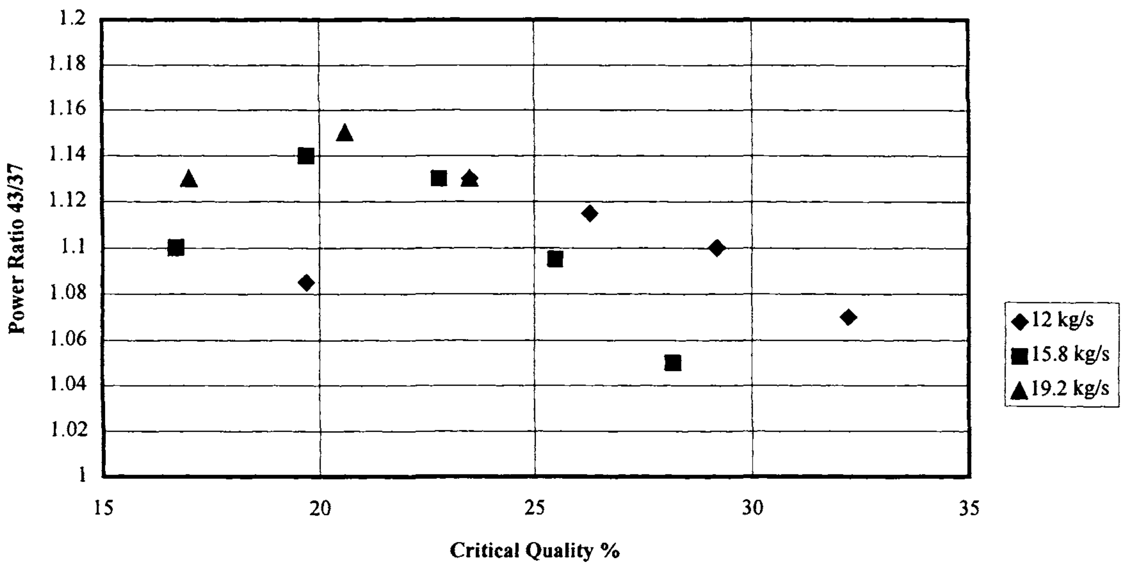


FIGURE 9: UNCREPT CANFLEX DRYOUT POWER COMPARED TO 37-ELEMENT DRYOUT POWER BASED ON THE SAME MASS FLOW CONDITIONS