FULL SCALE WATER CHF TESTING OF THE CANFLEX BUNDLE

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Abstract

CANFLEX is a 43-element CANDU fuel bundle that uses two diameters of elements, 13.5 mm for the inner eight, and 11.5 mm for the remainder. The thermalhydraulic performance of the CANFLEX bundle has been improved over the current 37-element design by both the increased fuel subdivision and by the use of patented CHF enhancing buttons attached to the elements.

To quantify the improved performance, a series of CHF and pressure drop measurements with an electrically heated assembly simulating a string of twelve aligned CANFLEX bundles in a 5.1% crept CANDU fuel channel, were undertaken at Stern Laboratories. The heated part of the string was nominally 6 m long and was equipped with spacer planes, bearing pads, button planes and simulated end plates to mimic the geometry of a string of aligned CANFLEX bundles. The axial heat flux profile was a cosine skewed towards the outlet end of the fuel string and the radial profile simulated that for natural uranium fuel. The five downstream bundles were equipped with moveable internal thermocouples to measure the surface temperature and to detect CHF. As one of the applications of CANFLEX is to alleviate the eroding operating margins due to reactor aging, the string was tested in a flow tube that simulated a 5.1% crept pressure tube.

Both single- and two-phase pressure drop, and CHF data were taken. The flow conditions covered the ranges from 6 to 11 MPa outlet pressure, 10 to 25 kg/s flow, and 200 to 290°C channel inlet temperature. For the same channel inlet conditions both the single- and two-phase pressure drops were very similar to 37-element fuel. Thus, there should be no significant effect on overall reactor operation during transition refueling. For the parameter region around the normal reactor operating conditions, the channel dryout power for CANFLEX was at least 10% higher than that for the 37-element design, based on similar channel inlet conditions. The focus of this paper is on the experimental hardware and the procedures used to obtain high quality thermalhydraulic data.

1. INTRODUCTION

The primary objective of the tests was to obtain CHF and pressure drop data for CANFLEX over the range of flow conditions of interest for reactor operation. The bundle design, experimental procedures, data acquisition, QA etc., all built on previous experimental campaigns conducted at Stern Laboratories with a 37-element bundle [1]. A key concern in this program was ensuring repeatability and demonstrating the validity of the data. Also, because this was the first testing for CHF of a CANFLEX bundle in water, the CHF behaviour e.g. preferred dryout locations, was unknown. Thus, a number of single and two phase tests were used to both understand the thermalhydraulic behaviour of the bundle, and to ensure data

validity. These consisted of heat balances, single phase rotational temperature scans, Onset of Nucleate Boiling (ONB), Onset of Significant Void (OSV), and single- and two-phase pressure drop measurements. The emphasis in this paper is on the experimental hardware and the procedures used to obtain high quality thermalhydraulic data. The details of the data themselves are reported in [2].

2. EXPERIMENTAL FACILITY

2.1 Fuel String Simulation

The fuel string simulation is an electrically heated, 43-element, segmented design with a nominal 6 metre heated length and a non-uniform, downstream skewed cosine, axial heat flux distribution, as shown in Figure 1. The fuel string external geometry was constructed in accordance with general fuel design drawings and was intended to provide an exterior surface that as close as possible simulated a fully aligned string of 12 CANFLEX fuel bundles. The design maximum operating power level is 13.5 MW at 240 volts DC with a design pressure of 13.5 MPa and a maximum local sheath surface temperature of 650°C.

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 CANFLEX design. The simulated spacers, bearing pads and buttons are a hollow design to minimize local current mal-distributions. The diameter of the inner eight heater tubes is 13.5 mm and the diameter of the remaining heater tubes is 11.5 mm.

The twelve fuel bundles are identified as "A" through "L", where "A" is located at the inlet, or upstream end, and "L" is located at the outlet, or downstream end. The bundle cross-section showing the orientation of the end plates, and the element nomenclature, as viewed looking downstream, is given in Figure 2. The radial flux distribution, expressed in terms of local linear element power ratio with respect to the average, is 1.034/ 1.081/ 0.873/ 1.056 from center to outer ring element, which simulated a natural uranium fueled CANFLEX bundle.

2.2 Test Section

The test section comprises 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.

The ceramic liners, which form the flow channel and simulate the inside surface of the reactor pressure tube, are made from high purity alumina (Al_2O_3). At the inlet and outlet of the channel the liners are "uncrept" and have a uniform inside diameter of 103.86 mm (104.11 mm hot, at 303°C). The liners for the crept portion of the flow channel have inside diameters machined to provide non-uniform axial profiles to simulate crept pressure tubes with maximum diametral creep of 5.1%. The axial creep profile is shown along with the axial flux profile in Figure 1.

Each liner segment is approximately 0.25 metres long with interconnecting steps at each end for alignment. The inner surface is very smooth (roughness less than 1.5 micron rms, new, prior to use). To minimize flow bypass in the annulus between the liners and the pressure housing, the diametral clearance between the liners and the housing is small (nominally 0.23 mm, at operating conditions) and special "piston ring" seals are installed between liners at various locations along the length of the test section.

The pressure boundary is fabricated from identical short (1 m) length spools 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.

2.3 Test Loop

The primary test loop [3], shown in Figure 3, consists of a main circulating pump, the channel inlet and outlet feeder piping, a preheater (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 7.2 and 8.0. 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 mho.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.

2.4 Power Supplies

The electrical power to the fuel string is provided by seven individually controlled rectifiers, with a total rated output capacity of 13.6 Megawatts DC (i.e. 56,666 amps @ 240 volts). 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 seven 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.

2.5 Instrumentation

The test section is fully instrumented to measure temperature, pressure and differential pressure at the locations shown in Figure 4.

The fluid temperatures at the test section inlet and outlet, and at the flow meters, are measured using Resistance Temperature Detectors (RTD). Two RTD's are located at the test section inlet and outlet tees, for redundant measurements, and one RTD is located at the flow measurement location. The primary coolant flow to the test section is measured using two calibrated orifice meters in series, each with an estimated measurement uncertainty of ±0.3% (2σ) of full scale.

Absolute pressures are measured at the fuel string inlet and outlet with two pressure transmitters at each location for redundant measurement. Differential pressures are measured along the flow channel over a 0.4953 metre length (equivalent to 1 fuel bundle). The pressure taps are located on the sides of the channel, slightly below the horizontal centerline to minimize trapped vapour in the sense lines, and upstream of the bundle centre-plane appendages to avoid flow disturbances.

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). In addition, 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 CHF detection instrumentation consists of two hundred and fifty-eight (258) thermocouples that are mounted in movable 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". The thermocouple carrier design, utilizes Macor material with grooves surrounding the thermocouple tip and slits in the sides to reduce conduction and minimize any temperature offset effects during transient and post-dryout testing. A thermocouple drive mechanism which is remotely controlled by a Programmable Logic Controller (PLC) device is used to position the bundle thermocouples. It can move all of the 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 $rev.s^{-1}$.

2.6 Data Acquisition System

The data acquisition system consists of a MicroVAX 4000-100 mini-computer (running under a VAX/VMS operating system) with four CPI scanners (120 A/D input channels each), a MicroMAC digital input/output system, various magnetic disk storage units, a 1 Gb/650 Mb R/W optical disk storage unit, various graphics terminals, text display terminals, video display monitors, and graphics printers.

The individual instrumentation signals are connected, via signal conditioning devices, to the data acquisition system. Prior to each series of testing, the instrumentation devices are connected via patch cabling and connection devices to the CPI scanners and the input signal paths are verified by exciting each instrument (as close to each instrument as possible) and observing an appropriate change in the engineering value displayed by the data acquisition system.

During testing, the data acquisition system uses in-house custom software to scan and digitize approximately 370 instrument signals at the rate of 5 or 10 samples per second per channel. A unique test point number is automatically incremented and assigned each time a data file is saved. The signals are converted into engineering units and selected data are continuously displayed on terminals and video displays for on-line monitoring by test personnel.

The data acquisition system computer also provides on-line monitoring of the fuel string thermocouples for CHF detection (dryout). The operators can select on-line, via keyboard entry, up to 10 thermocouple signals for real time display on each of two special graphics display terminals. Temperature changes of the order of 1°C are readily detectable on the screen and dryout behaviour is easily distinguished on the monitored thermocouple traces. A typical display is shown in Figure 5.

For the steady-state CHF tests, all of the thermocouples signals are continuously scanned by the data acquisition system and the standard deviation of each signal is calculated. If the standard deviation of any of the bundle thermocouples exceeds 0.5°C, the channel number and identification for that thermocouple is flashed onto the video screen to alert the test operators. It can then be selected for real-time viewing and for visual confirmation of dryout by the test engineers. This criterion, using the standard deviation, or noise, of the thermocouple signals to indicate dryout, was selected based on past experience. It gives good agreement with the visual observations and generally avoids "false" indications of dryout that can occur during changes in power or during bundle thermocouple rotation if the criterion was based on changes in absolute temperature.

In addition to the above automatic dryout detection system, each thermocouple signal (corrected for the temperature rise across the heater wall) is compared to the average of 10 upstream thermocouple signals. If the temperature for any individual thermocouple is 10 degrees or more above this average, the channel number of that thermocouple is flashed onto the video screen to alert the operators. Thus, the test operators are alerted if any of the 258 bundle thermocouples goes into a post-dryout condition, where the temperature can become relatively steady and hence may not be picked up by the previous temperature noise dryout detection system.

For steady-state tests, all of the data signals are recorded for a 30 second period, typically 300 samples per channel, at an operator selected appropriate time. For time-history recordings, the signals are recorded continuously for a selected period (typically 30 to 45 minutes). All of these data are stored and are retrievable for post-test processing, such as plotting selected data channels versus time, converting the as-measured heater temperatures to heater tube outer surface temperatures, etc. Also, via Ethernet communication links, the data are transferred to IBM compatible PC's for insertion of the steady-state data into database summary files and for further analyses, such as preparation of contour plots of the heater tube outer surface temperatures.

3. TEST PROCEEDURES

Because of electricity costs, all testing was done during weekends when off-peak power was available. A typical test weekend consisted of loop startup at zero power on Friday morning with a series of single-phase pressure drop runs being performed at up to 260°C, the loop temperature being reached using pump heat. The loop was maintained hot (with zero power on the test section) for both the Friday and Saturday night periods when CHF testing was not ongoing. Maintaining the loop hot during the weekend, put less stress on the bundle and loop components, and also allowed more efficient data production as warmup times were eliminated. With this procedure a whole testing campaign could be completed in about 5 weekends. Besides the CHF tests, a number of tests were performed to both monitor the correct operation of the loop and bundle, and also to provide a fuller understanding of the thermalhydraulics within the bundle. These other tests are detailed below.

3.1 Heat Balances

Heat balances at 2 and 8 MW were performed prior to the start of each weekends testing. Additional heat balances were also performed on the Saturday evening, Sunday morning and at the end of the weekend to

ensure that all the loop instrumentation continued to perform correctly. Typical heat losses were between 25 and 50 kW, i.e. less than 1%, and could be ascribed to a combination of heat loss through the test station insulation and loss to the cooling systems for the end seal flanges.

3.2 Temperature Rotational Scans

During all of the 2 MW heat balances, the test section thermocouples were positioned axially just upstream of the mid-plane bearing pads and fully rotated while recording the readings. This resulted in a complete temperature map of all the rods at that axial location. An example of one of these maps is given in Figure 6, where the local temperatures are depicted by various colours. It is immediately obvious that the upper part of the bundle is significantly cooler than the lower part. This confirms that the bundle was physically sitting on the bottom of the flow tube with the large bypass gap (as a result of the 5.1% creep) at the top of the bundle. An additional observation is that line of symmetry is not completely vertical but passes through approximately rods 2 and 13. This slight tilt was caused by the large magnetic forces attracting the bundle to a slightly off center steel floor beam. The tilt will have no significant effect on the CHF results and was monitored throughout the tests to ensure that it did not change.

3.3 Onset of Nucleate Boiling (ONB)

Measurement of the ONB in individual subchannels provides a method of estimating the enthalpy distribution throughout the bundle. In these tests the thermocouples were oriented towards the subchannels and starting from single-phase conditions and with constant flow, inlet temperature and pressure, the power was increased in small steps while recording the thermocouple temperatures. An example of these data is shown in Figure 7. Initially, before boiling occurs, the temperatures are below saturation and rise relatively steeply with power. When the ONB point for each thermocouple is reached, the thermocouple traces flatten out and the temperature is close to saturation and relatively independent of power. In Figure 7 only a few of the bundle thermocouples are plotted but they show that the rods on the upper half of the bundle require about twice the power to reach nucleate boiling compared to rods on the bottom of the bundle. This dramatically illustrates the large bypass flow that exists with a 5.1% crept liner.

3.4 Onset of Significant Void (OSV)

Measurement of the pressure drops along the bundle during the ONB tests gives information on the OSV. The data for the last six pressure taps in the bundle for the test in Figure 7 are given in Figure 8. The flat portion of the curve is the single-phase pressure drop and the knee in the DP curves is where significant void first occurs in the bundle at that location. The single-phase pressure drop for DP8 to DP11 are very similar as these are in the region of maximum creep. At the DP12 and DP13 locations the pressure tube diameter is changing rapidly back to the uncrept value which accounts for the higher single-phase pressure drop. The progressive movement of the OSV point up the bundle with increasing power is evident.

3.5 Single- and Two-Phase Pressure Drop

A series of single-phase pressure drop measurements were made prior to starting CHF testing each weekend. These were used to monitor the condition of the bundle for buildup of crud deposits on the heater surfaces. An example of the pressure profile along the heater string in single phase is shown in Figure 9. The profile deviates from a straight line due to the varying axial creep profile which affects the bundle flow area and hence pressure gradient along the bundle length. Generally it was found that the single phase pressure drop would rise by about 1 to 2% as a result of the crud deposited during one weekends CHF testing. In addition to the specific single phase pressure drop runs, the pressure transducer signals were automatically recorded whenever a computer scan was taken, e.g. during OSV or CHF tests and this resulted in a large number of two-phase pressure drop data. A typical axial pressure gradient in two-phase is

also shown in Figure 9. Comparison with a single phase pressure gradient measurement at the same loop flow shows that the two-phase started at about bundle H. From these data the two-phase multipliers can be extracted.

3.6 CHF Tests

Approximately 90 CHF points were taken during the campaign of testing with the 5.1% crept pressure tube. The procedure used was to fix the inlet temperature, flow and outlet pressure at the desired conditions, and then slowly increase the bundle power until CHF was detected. It was, of course, essential to be sure that the first indication of dryout anywhere on the bundle for each CHF test had been found. Thus, after the initial indication of dryout, the power would be increased by typically 100 kW and the thermocouples axially slid and rotated to ensure that there was not an earlier CHF at any other location. If an earlier CHF was found, the thermocouples were moved to that location, the power reduced and the CHF value for the new location determined. This procedure was repeated until it was certain that the first indication of dryout anywhere on the bundle had been found and this then became the CHF point. Following recording of the CHF data, the test-section power was increased gradually to up to 5% overpower until additional thermocouples indicate the CHF condition. Typically one or more additional thermocouples would come into dryout with less than a 1% power increase. A number of CHF points taken, usually on a prior weekend, were repeated. The repeatability was excellent, CHF generally being detected within 100 kW (~1%) of the previous value.

An example of the CHF data taken at 11 MPa is shown in Figure 10 plotted as power against inlet temperature. The data follow the normal trends of the dryout power increasing with increasing flow and decreasing inlet temperature. The data are very well behaved and follow conventional trends by being approximately linear when cross plotted as power versus flow, as shown in Figure 11. At 17 kg/s and above, the data are essentially linear, with some deviation occurring at 13.5 kg/s and 10 kg/s due to flow stratification effects.

The initial dryouts were generally in bundles J or K (sometimes both simultaneously) on the outer rods in the lower part of the bundle. The radial position on the rod varied depending on the axial location. If the dryout was just upstream of the mid-plane spacers, it generally occurred facing an inner subchannel, e.g. on rod #3 facing the subchannel formed by rods 3, 23 and 2. If it was just upstream of the downstream button plane, the dryout tended to be in the subchannel formed by two outer rods and the pressure tube, i.e. immediately upstream of the button. These dryout locations show that the button planes provide significant protection against CHF immediately downstream. At the lowest flow, 10 kg/s, initial dryout occasionally occurred at the downstream end of bundle J on rod 37, i.e. in the inner part of the bundle.

3.7 Onset of Dry Sheath (ODS)

In a number of CHF tests the power was incremented in small steps beyond the initial CHF point to obtain the post-dryout temperature versus power profile. These measurements allowed the determination of the ODS power, i.e. the power at which the sheath temperature exceeds the critical point of water, 374°C. The data for one test is shown in Figure 12. Initial dryout was at 6050 kW and the ODS point is at about 6160 kW, a power increase of 1.8%.

4. SUMMARY

A full scale electrically heated simulation of a CANFLEX fuel string has been constructed and tested in a high pressure water loop at representative reactor thermalhydraulic conditions. The primary objective of the experiments was to obtain CHF and single- and two-phase pressure drop for CANFLEX fuel. In addition a

number of secondary data were obtained which both provided an understanding of the thermalhydraulic behaviour within the bundle, and also provided confidence in the quality of the CHF data. The data exhibited the conventional trends of CHF increasing with increasing flow and decreasing inlet temperature. Repeat CHF points taken at random during the testing program showed that the repeatability of the data was excellent.

5. REFERENCES

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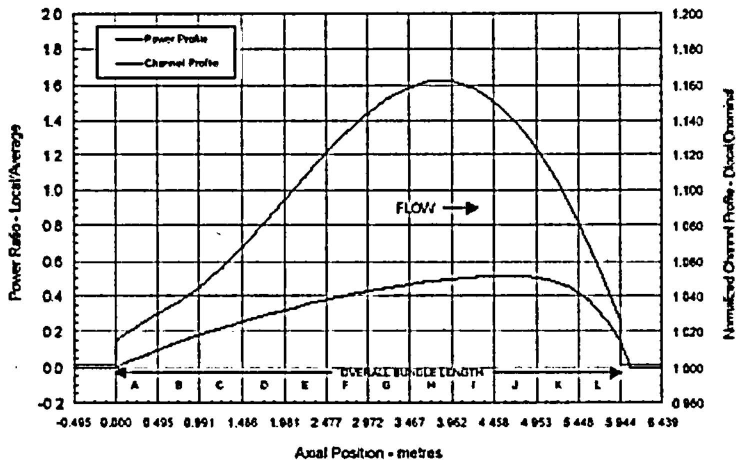
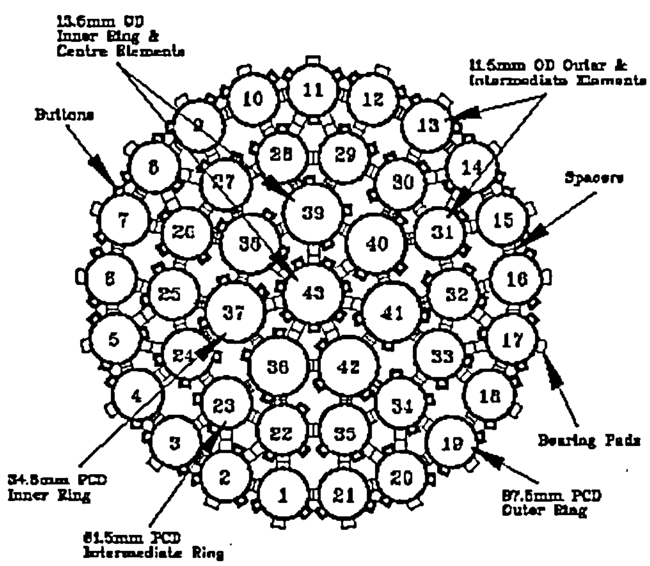
2 Leung, L.K.H. et al., "Critical Heat Flux and Pressure Drop for a CANFLEX Bundle String Inside an Axially non-uniform Flow Channel", 6th Int. Conf on CANDU Fuel, Niagara Falls, Canada, 1999 September 26-30.

3 Fortman, R.A. et al., "A New Facility for the Determination of Critical Heat Flux in Nuclear Fuel Assemblies", INC93, Toronto, Canada, 1993 October 3-6.



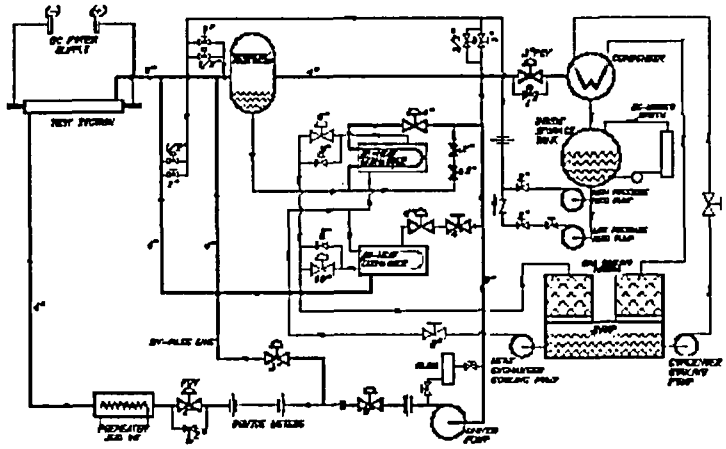
Axial Power and Flow Channel Profiles

Figure 1



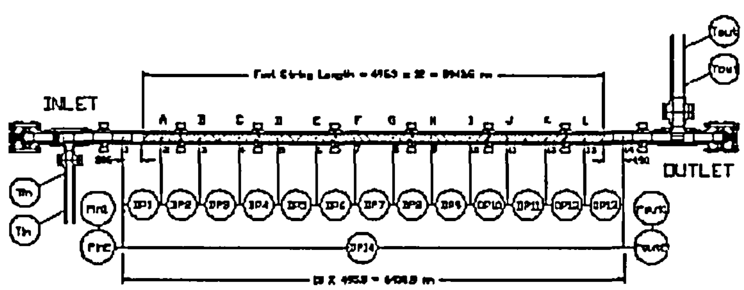
CANFLEX Bundle Cross Section
(Looking Downstream)

Figure 2



CHF Test Loop

Figure 3



CANFLEX Test Section

Figure 4

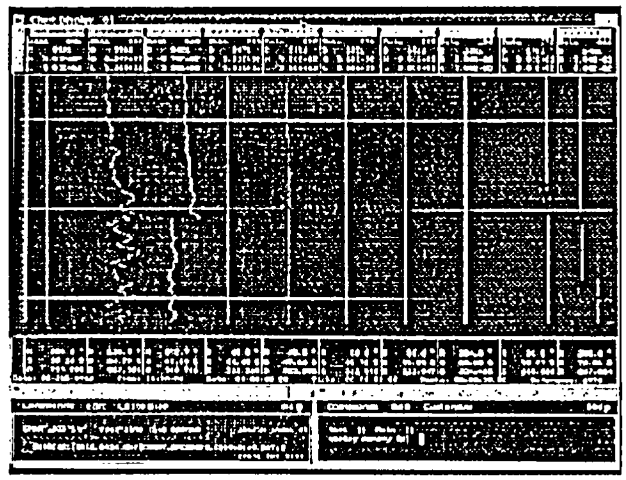
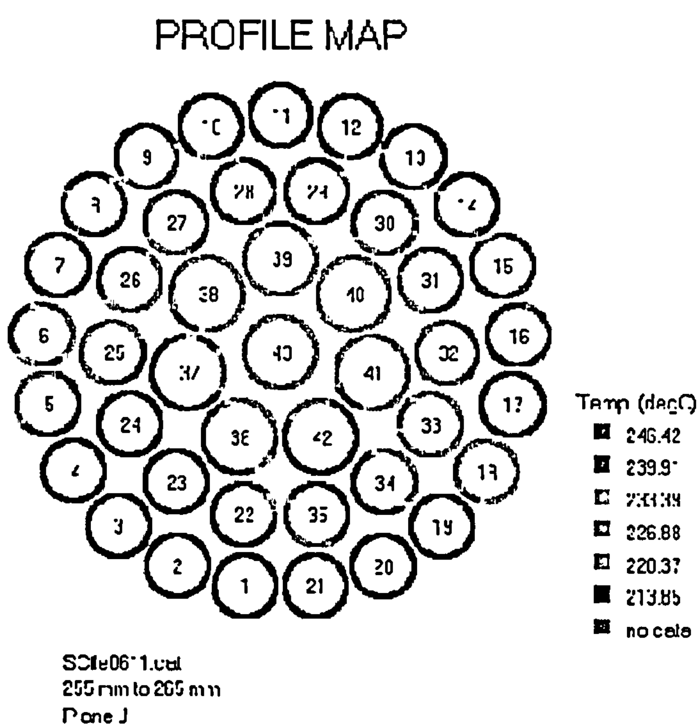


Chart Display for Dryout Detection

Figure 5



Temperature Map from Profile Scan (#611J)

Figure 6

Figure 7 Onset of Nucleate Boiling

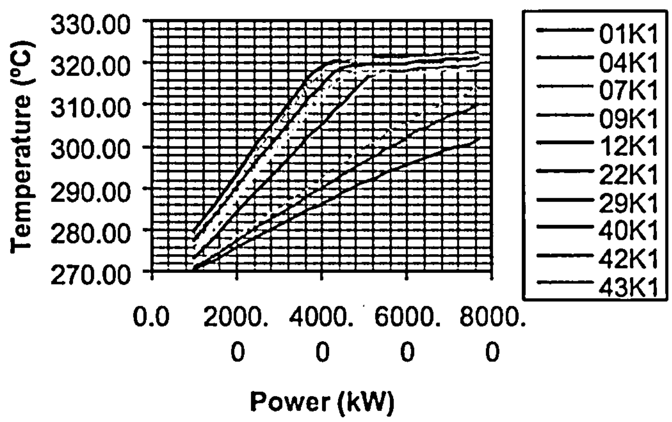
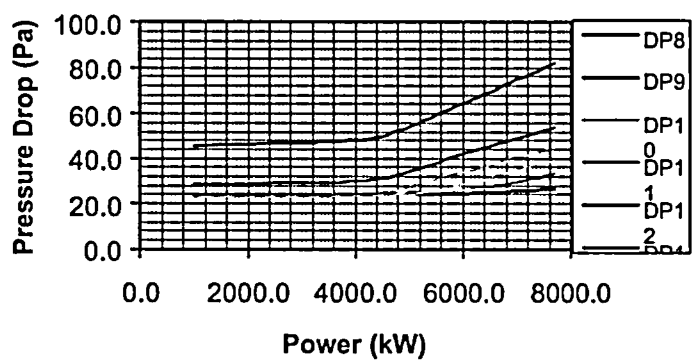
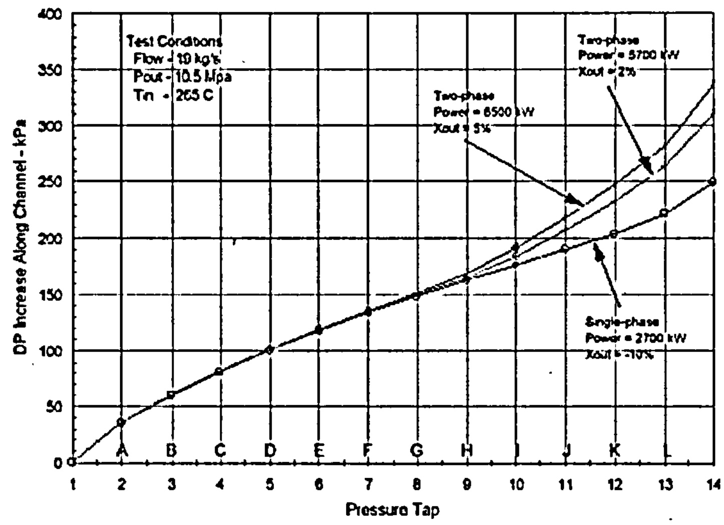


Figure 8 Onset of Significant Void





Pressure Gradient Along Flow Channel

Figure 9

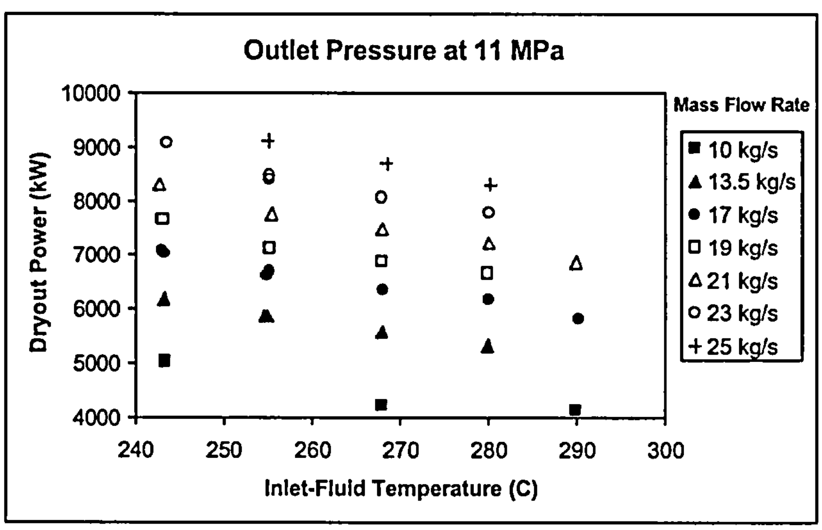


Figure 10 CANFLEX CHF Data

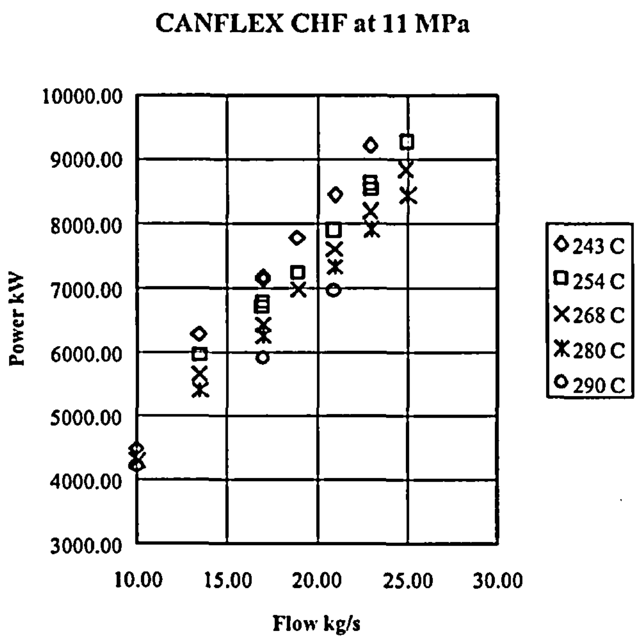

CANFLEX CHF at 11 MPa
Power kW
10000.00
9000.00
8000.00
7000.00
6000.00
5000.00
4000.00
3000.00
10.00
15.00
20.00
25.00
30.00
Flow kg/s
243 C
254 C
268 C
280 C
290 C

Figure 11

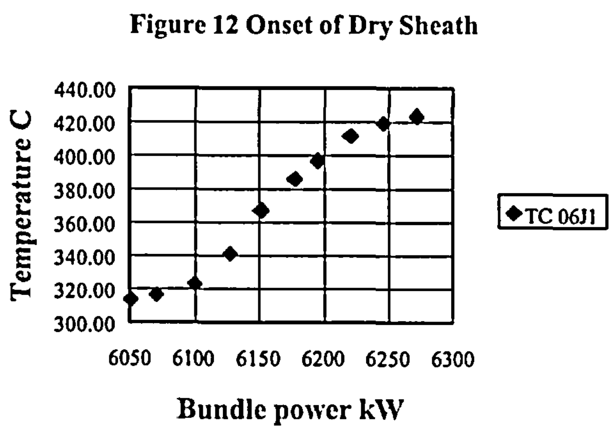


Figure 12 Onset of Dry Sheath
Temperature C
440.00
420.00
400.00
380.00
360.00
340.00
320.00
300.00
6050
6100
6150
6200
6250
6300
Bundle power kW
TC 06J1