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WSRC-TR-92-45

FOUR FOOT SEPTIFOIL COOLING EXPERIMENT
UNRESTRICTED INLET/OUTLET CASE
(U)

FEBRUARY 1992

Westinghouse Savannah River Company
SAVANNAH RIVER LABORATORY
AIKEN, SC 29808

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1.0 Introduction

The ability to predict the behavior of reactor components to varying coolant flow scenarios constitutes a necessary skill for assessing reactor safety. One tool for performing these calculations is the Transient Reactor Analysis Code (TRAC). In order to benchmark the code, the Safety Analysis Group of SRL requested the Equipment Engineering Section (EES) of SRL to conduct a series of experiments to provide measurements of cooling parameters in a well defined physical system utilizing SRS reactor components. The configuration selected consisted of a short length of septifoil with both top and bottom fittings containing five simulated control rods in an "unseated" configuration. Varying power levels were to be supplied to the rods with 3.5 kilowatts per foot the value targeted for modelling during the computer runs. The septifoil segment was to be operated with no forced flow in order to evaluate thermal-hydraulic cooling. Parameters to be measured for comparison with code predictions were basic cooling phenomena, incidence of film boiling, water flow rate, pressure rise, and ratio of heat transfer through the wall of the assembly vs. heat transfer to axial water flow through the assembly. This report will document testing done with unimpeded flow into and out of the septifoil in order to assess basic cooling phenomena, incidence of film boiling and pressure rise. Previous tests (WSRC-TR-91-0557) have evaluated water flow rate and the ratio of axial to azimuthal heat transfer.

2.0 Summary

An experimental apparatus was designed and assembled incorporating five simulated control rods four feet long, joule heated inside a five foot length of a type "Q" septifoil. The septifoil segment had normal top and bottom fittings. The septifoil was positioned inside a steel tank which simulated the reactor vessel. Water in the tank was circulated through a heat exchanger which was used to maintain tank temperature at 70°C. The apparatus was arranged to allow the septifoil to draw water in from both the bottom and top inlets. External restrictions were minimized by the design. Electrical power of 10 Kw to 67 Kw was fed to the simulated rods from a DC power supply. Computer data acquisition was accomplished using "LabView" software programmed to match the configuration of the experiment along with scanning digital voltmeters and requisite signal sensors. Two video camcorders were used to provide video records of the experiment. All data acquisition sensors and data logging were done with M&TE Category 1 requirements.

At power levels below 66.2 Kw, the septifoil may be cooled by thermal-hydraulic pumping in a cyclic process, natural convection, or natural boiling. Periods of cycling varied from 6 seconds to 24 seconds during which relatively low velocity water flow would be followed by rapid ejection of water and steam through the septifoil holes, "chugging". At power levels above 66.2 Kw, (3.3 Kw/ft) film boiling was evident from an increase in rod electrical resistance of the simulated control rods. When the rods were withdrawn from the septifoil assembly, brown to blue discoloration was visible on the top quarter of the rods that had indicated film boiling. One rod bowed due to the overheating.

3.0 DESCRIPTION OF EXPERIMENTAL APPARATUS:

3.1 Control Rods

Design of the simulated control rods was constrained by availability of electrical power supplies for heating and materials of suitable melting point available for construction. The power supply available had a maximum of 50 volts at 1800 amperes, thus to achieve reasonable power to the simulated rods the total resistance of the rods connected either in parallel or in series needed to be close to 0.025 ohms. Review of materials on hand indicated that satisfactory rods could be made by machining 3/4 inch schedule 80 stainless steel pipe to an outside diameter of 0.94 inches, which is the diameter of the reactor control rods. Rods were constructed with a heated length of 48 inches. By connecting five such rods in series, the total resistance would be slightly less than 0.025 ohms. Since the experiment required the presence of the bottom end fitting, it was not possible to attach electrical leads to the bottom of the rods so copper conductors were obtained to carry current down the inside of the stainless steel pipes. Final configuration of the heater rods and their electrical characteristics are shown in Figure 1. The rods were machined in the EES machine shop in Building 723-A and fabricated in the final assemblies and tested in Building 305-A.

Performance of the rods throughout the experiment was excellent. Rods are identified by alpha characters A thru G. Rod F overheated to the point of bowing in the 10/15/91 test run. As a point of interest, this rod was destructively examined with an oxide buildup found by study of optical interference patterns. The patterns indicated approximately of 20,000 Angstroms (Å) of oxide present in two layers. Measurement of the oxide gave a thickness on the order of 10,000 Å per layer.

3.2 Septifoil Assembly

Testing utilized a modified "Q" type septifoil. The septifoil assembly was cut 52 inches below the top. The bottom end fitting was cut from the septifoil and attached to this 52 inch segment. In order to simulate the oxide present during normal reactor operation, the septifoil was anodized to obtain a 0.002 inch film of oxide. It was hoped that the oxide would also be durable enough to provide electrical insulation to prevent the simulated control rods from shorting against the aluminum septifoil. Such was not the case. To prevent contact between the heaters and the outer septifoil housing, insulating standoff loops of 0.060 inch diameter nylon were made and installed on the inside of the septifoil web. Nylon screws were installed through the housing wall to anchor the rods in place. A rubber diaphragm was attached across the top of the septifoil to prevent water flow through the top. Consequently, the guide tube assembly present in the reactor was not modelled in this test. The septifoil housing, simulated rods, and other components were assembled and supported by a stainless steel frame. Locations of data sensors on the septifoil are shown in Figure 2 and the septifoil rod identifications are shown in Figure 3.

3.3 Assembly Support

The septifoil, rods, and other equipment were held in place by a support assembly constructed of stainless steel pipe braced in a triangular configuration with stainless steel rings. Support fixtures held the septifoil rods, thermocouples, and pressure transducers in place. Pressure transducers were mounted in dry wells fabricated from PVC pipe.

3.4 Power Supply

Power to the simulated rods was provided by a DC power supply located in Building 305-A. The power supply was originally installed to provide power for a plasma arc system. The radio frequency arc initiation portion of the power supply was removed and a 0-30,000 ampere current shunt was installed on the output leads to measure current to the experiment. Electrical leads carrying current to the experiment were 500 MCM copper conductor. Interconnecting cable tying the simulated rods in series configuration were size 0000 bare copper. These were cooled by water mist spray from two misting nozzles at the top of the experiment. The current shunt was calibrated to provide M&TE Category 1 qualifications. Voltage into the simulated rods was measured by a Hewlett-Packard digital voltmeter. Both were calibrated in the Standards Laboratory. A safety computer was installed on the experiment to monitor the resistance of each of the rods. Set point limits were established such that a significant increase in the resistance of any rod would trigger an interlock on the power supply to remove power from the experiment. This was to prevent formation of an arc in the event that one of the simulated rods melted and separated. Special operating and safety procedures were written for the power supply to ensure personnel safety.

3.5 Experimental Tank

A tank was fabricated from a schedule 40, 16 inch diameter stainless steel pipe to contain water at 70°C to simulate the reactor tank and to provide safety containment for the experiment. The tank was filled with deionized water having a resistivity greater than 2 megohm-centimeters.

3.6 Deionizer

Deionized water for filling the experimental tank was obtained from a deionizing unit filled with mixed bed resin. Resistivity of the water from the resin bed remained above 2 megohm-centimeters throughout all of the experiments.

3.7 Heat exchangers

A heat exchanger was fabricated using two copper coils which were immersed in a stainless steel tank of cold water. Water from the experimental tank upper region was pumped through the coils and returned to the bottom of the tank. Water temperatures were controlled by raising and lowering the coils into the water bath. One coil was used during the 10/9/91 tests. The second coil was added for the 10/15/91 tests to enable more efficient control of tank temperatures. Pre-test measurements showed the flow through the loops to be approximately 6.6 gpm.

3.8 Data Acquisition System

Data from the 21 thermocouples, 1 pressure transducer, current and voltage signals was logged and visually indicated by a data acquisition system incorporating a Macintosh computer operating "LabView (version 2.1.1)" software. The software generated data files in "Excel" spreadsheet form and presented a color coded graphic display, shown in Figure 4. A second computer, also operating "LabView" software, monitored the six voltages and current needed to compute resistance value for each rod. Performance of both data acquisition systems was outstanding throughout the experimental effort. Permanent data records in spreadsheet form were generated and have been used to analyze results of the experiment.

3.9 Thermocouples

Thermocouples used to measure temperatures at various points in the system were type "E" thermocouples calibrated before and after the experiment. Small diameter, 0.020 inch, thermocouples were used to provide fast response and a minimum amount of disturbance to flow in the system.

3.10 Camcorders

Video recording of the flow processes at various points in the system was done by Sony type TR7 video camcorders. The camcorders performed extremely well throughout the test series and provided valuable data for post experiment analysis.

3.11 Conductivity Measurements

Conductivity of water for the experiment was monitored by flow through conductivity cells fabricated by EES for use in reactor flow studies. These conductivity cells consist of a conductivity cell with a cell constant of 0.1 connected to an inductance, capacitance, resistivity (LCR) meter measuring resistance by an alternating current measurement.

3.12 Personnel

Seven people were required to monitor and control each of the experiments. Task responsibilities were:

- Power Supply Controller
- Safety Observer
- Data Acquisition System Operator
- Heat Exchanger Operator
- Video and Log Book Recorder
- Intercom Operator
- Test Conductor

4.0 RESULTS:

4.1 Test 10/9/91

All necessary pretest calibrations and data records were made on equipment and sensors for the experiment. Type E thermocouples were mounted inside the top holes and at the midpoint of each channel between the rod and outer wall, at the septifoil inlet, on the surface of rod F (3 locations), in the bulk water at the top (2 locations), and at the bottom. A differential pressure transducer was mounted in one of the top slots. The reference side of the transducer was connected to bulk water at the same level. Power from the DC power supply was connected to the experiment through a 30,000 ampere current shunt. Voltage leads were attached at the top of each rod and connected to Hewlett-Packard voltmeters for overall voltage measurement and for safety computer computations of rod resistance.

The assembled apparatus was inserted into the tank. After filling the tank, power to the control rods was turned on and brought up to 20 Kw (1Kw/ft) to heat the water and assembly to initial temperature of 70°C. The test power profile is shown in Figure 5. Once the initial conditions were achieved, power was increased to 36.7 Kw (1.8 Kw/ft). Cooling was accomplished by energetic boiling and steam production. Thermal-hydraulic pumping of water through the septifoil became periodic at about 3180 seconds and cooling was continued by a "chugging" type of flow. Chugging is a cyclic process in which a period of low flow and boiling is followed by a period of rapid steam and water ejection from the top slots/holes and bottom inlet of the septifoil. The septifoil entered the chugging mode with water ejection from the bottom following a 10-20 second period as evidenced by the septifoil inlet thermocouple readings which recorded temperature fluctuating approximately 10°C on the period (Figure 6). Channel temperatures were nominally 100°C at the top (Figure 7) and between 76°C and 99°C at the midpoint (Figure 8). Rod temperatures rose to 100°C at this power (Figure 9). Pressure in the upper region of the septifoil followed the 10-20 second cycle noted by the septifoil inlet temperatures. Pressures stayed below 0.1 psig (Figure 10). The tank temperature increased during the test to approximately 95-100°C at the top and 92°C at the bottom. Septifoil inlet temperatures varied between 75°C and 90°C (Figure 11). Note: the bottom thermocouple was located above the septifoil inlet thermocouple. It appears that the tank water heated up during the test with the elevated water interface extending down to a point below the tank bottom thermocouple (TC 21) but above the septifoil inlet thermocouple (TC 11).

Power was adjusted to 25.1 Kw (1.3 Kw/ft), 40.7 Kw (2.0 Kw/ft), and 20.7 Kw (1.0 Kw/ft) with similar results (Figure 5). Peak pressures rose to 0.15 and 0.25 psig at the 40.7 Kw power level (Figure 12). Power was then increased to 66.2 Kw (3.3 Kw/ft) and the channel temperatures remained at their previous levels (Figure 13). The chugging period stayed within previous parameters. Peak pressures increased to between 0.2 and 0.4 psig (Figure 14). After about three minutes at this power level, at approximately 3900 seconds into the test, the resistance of the rods rose rapidly with automatic shutdown of the power system at 3920 seconds (Figure 15). Rapid rod resistance rise is a signature of film boiling as the rod is uncooled resulting in increased resistance of the rod material. Channel temperatures did not show a marked increase during this transient. This is probably due to the formation of the steam void in the channels remote from the thermocouples.

Data from two thermocouples, the B and C channel mid length thermocouples, registered high temperatures (greater than 300°C) during 36.7 Kw power level and early during the 66.2 Kw power level. These temperature measurements were not supported by an increase in rod resistance therefore a determination was made that film boiling was not presented these times. Examination of the thermocouples after the test revealed a discoloration which may have been caused by overheat due to shorting to the electrically charged control rod. Current from the rod through the thermocouple sheath would heat the thermocouple and cause a false high temperature reading.

The temperature control using a single loop heat exchanger was determined to be inadequate. A second loop was added in the hope of more stable temperature maintenance.

4.2 Test 10/15/91

Data acquisition for the 10/15/91 test was the same as in the 10/9/91 test. All necessary pretest calibrations and data records were made on equipment and sensors for the experiment. The sequence of power control for the power supply throughout the experiment is shown in Figure 16. Power was first set at 38.6 Kw (1.9 Kw/ft) to preheat the components and check for proper resistance of the rods. After components reached 70°C, power was maintained at 38.6 Kw to determine cooling at this power. Cooling was accomplished by steam production with no discernable chugging. Channel temperatures were nominally 95°C - 100°C at the top (Figure 17) and between 75°C and 100°C at the midpoint (Figure 18). The center unrodded channel recorded the lower temperature at the midpoint. Rod temperatures varied from 74-86°C at the midpoint to 100°C at the top (Figure 19). Pressure in the upper region of the septifoil followed a nominal 10 second cycle. Pressures stayed below 0.12 psig (Figure 20). The tank temperature increased during the test to approximately 98°C at the top and 71°C at the bottom (Figure 21). Septifoil inlet temperatures were approximately 71°C (Figure 22).

Power was increased to 66.5 Kw (3.3 Kw/ft) whereupon chugging operations started. Channel temperatures varied from 97°C to 101°C (Figure 23). Cooling became dominated by chugging flow at a 6-24 second period with 12 seconds the most prevalent. Septifoil inlet temperature and pressure pulses defined the chugging. Pressures increased to 0.2 psig (Figure 24). Septifoil inlet temperatures varied from 70°C to 95°C during the chugging cycle (Figure 25). The tank temperature increased to 99°C at the top and 97°C at the bottom (Figure 26).

After approximately six minutes, due to high temperatures at the tank bottom, the validity of additional data became uncertain. The test was terminated. Neither channel temperature (Figure 23) nor rod resistance (Figure 27) indicated film boiling.

5.0 Conclusions:

At the conclusion of the 10/15/91 test, the apparatus was dismantled and the rods examined. The film boiling during the 10/9/91 test was confirmed as the rods had become discolored by high temperature at their surfaces resulting from chemical reaction of the very hot surface with steam. Rod F bowed approximately 1/2 inch due to the excessive temperatures.

Test results demonstrate that the septifoil geometry forms a complex thermal-hydraulic system which behaves within certain parameters dependent on heat input. With increasing levels of heat input the cooling mechanism(s) appear to progress through the following stages:

- + very low heat input: natural convection driven by buoyancy effects (the chimney effect)
- + low to moderate heat input: buoyancy driven flow with boiling
- + moderate to high heat input: energetic boiling accompanied by chugging and reflooding
- + high heat input: film boiling leading to heater failure.

While rod temperatures can become quite high, the fluid temperatures in this series of tests remained in the neighborhood of the liquid saturation temperature (100°C). This result, combined with the observation that pressures within the septifoil remained rather low (<0.4 psig), suggests that the holes and slots in the upper fitting and the bottom end fitting passage did not choke the flow leading to high pressures and superheated fluids. Undoubtedly, the top and bottom passages impact the extent of reflooding and thus contribute to the heat input level at which film boiling was evidenced.

Modelling techniques depend on an accurate depiction of the transport phenomena. In particular, accurate modelling requires an understanding of flow patterns at the top of the assembly as flow exits and enters the vertically adjacent holes and slots. Data developed to date has not fully characterized this mechanism.

The ejection of heated water from the bottom inlet results in a zone of coolant at elevated temperatures. This fluid, when aspirated into the septifoil, is nearer its boiling point, therefore requiring less energy to initiate the phase change.

6.0 Recommendations:

Based on information obtained in the four foot septifoil experiment, the following recommendations are made for continued work:

1. Testing should be conducted using a transparent septifoil, four feet long, in order to confirm flow patterns within the assembly. Modelling techniques require a more complete understanding of the aspiration/reflood phenomena to correctly predict septifoil performance.
2. Full scale tests should be done matching as closely as possible the reactor septifoil characteristics.
3. Thermal conductivity and heat capacity of simulated control rods used in full scale septifoil experiments should be close to the values for the lithium-aluminum control rods in the reactor. These parameters will affect cyclic heat transfer.
4. The guide tube assemblies and water head above the septifoil should closely approximate the configuration in the reactor. There is a direct relationship between pressure rise and steam and water ejection from the septifoil that will be sensitive to the restricted annular spaces in the guide tubes. The momentum of the water column will affect cyclic behavior and downward flow of water through the septifoil.
5. Data from the four foot septifoil experiment may be used as a benchmark for code computations but should not be used as a model for reactor component cooling. The absence of blanket gas pressure, guide tubes, matched thermal characteristics of the rods, and comparable length to reactor rods render response too non-prototypic for extrapolation.

FIGURE 1
SCHEMATIC OF ROD USED FOR SEPTIFOIL COOLING TESTS

FIGURE 2
SEPTIFOIL COOLING TEST
 (FIVE ROD CASE WITH NO JACKET)

Experimental Setup
 on 10/9/91
 and 10/15/91

FIGURE 3
SEPTIFOIL CHANNEL IDENTIFICATIONS
(LOOKING DOWN ON TOP)

FIGURE 4
10/9, 15/91

FIGURE 5
POWER PROFILE
10/9/91

FIGURE 6
SEPTIFOIL INLET TEMPERATURE
36.7 KW 10/9/91

FIGURE 7
CHANNEL TEMPERATURE (TOP)
36.7 KW **10/9/91**

FIGURE 8
CHANNEL TEMPERATURE (MID)
36.7 KW **10/9/91**

FIGURE 9
ROD TEMPERATURE
36.7 KW 10/9/91

FIGURE 10
SEPTIFOIL PRESSURE
36.7KW 10/9/91

FIGURE 11
TANK-SEPTIFOIL INLET TEMPS
36.7 KW 10/9/91

FIGURE 12
SEPTIFOIL PRESSURE
40.7 KW 10/9/91

FIGURE 13
CHANNEL TEMPERATURE (TOP)
66.2 KW **10/9/91**

FIGURE 14
SEPTIFPOIL PRESSURE
66.2 KW 10/9/91

**FIGURE 15
RESISTANCE**

66.2 KW 10/9/91

FIGURE 16
POWER PROFILE
10/15/91

FIGURE 17
CHANNEL TEMPERATURE (TOP)
38.6 KW 10/15/91

FIGURE 18
CHANNEL TEMPERATURES (MID)
38.6 KW 10/15/91

FIGURE 19
ROD TEMPERATURE
38.6 KW 10/15/91

FIGURE 20
SEOTIFOIL PRESSURE
38.6 KW 10/15/91

FIGURE 21
TANK TEMPERATURE
38.6 KW 10/15/91

FIGURE 22
SEPTIFOIL INLET TEMP
38.6 KW 10/15/91

FIGURE 23
CHANNEL TEMPERATURES (TOP)
66.5 KW 10/15/91

FIGURE 24
SEPTIFOIL PRESSURE
66.5 KW 10/15/91

FIGURE 25
SEPTIFOIL INLET TEMP
66.5 KW 10/15/91

FIGURE 26
TANK TEMPERATURE
66.5 KW 10/15/91

FIGURE 27
ROD RESISTANCES
66.5 KW 10/15/91

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