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SUMMARY REPORT ON FOUR FOOT SEPTIFOIL COOLING EXPERIMENT (U)

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Date

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SAVANNAH RIVER LABORATORY
AIKEN, SC 29808

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1.0 Introduction

Cooling parameters for some of the SRS reactor internal components are computed using the Transient Reactor Analysis Code, "TRAC". In order to benchmark the code , the Safety Analysis Group of SRL requested EES to conduct an experiment to provide measurements of cooling parameters in a well defined physical system utilizing SRS reactor component(s). The experiment selected included a short length of septifoil with both top and bottom fittings containing five simulated control rods in an "unseated" configuration. Power level to be supplied to the rods was targeted at 2.5 kilowatts per foot. 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, thermal-hydraulic 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.

2.0 Summary

Experimental apparatus was designed and assembled incorporating five simulated control rods four feet long, joule heated inside a five foot length of type "Q" septifoil. The septifoil segment had normal top and bottom fittings. Water at 70C was fed independently to the bottom inlet and along the outside of the septifoil. Water flowing along the outside of the septifoil was in confined flow and provided calorimetry to measure power flow through the septifoil housing. A shadowgraph technique was developed and used to monitor unforced flow of water pumped thermal-hydraulically through the septifoil. Electrical power of 10,000 to 70,000 watts 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. Video camcorders were used to provide video records of six areas of the experiment. All data acquisition sensors and data logging were done with M&TE Category 1 requirements.

At power levels of 36.0 kilowatts,kw, (1.80 kw/ft), 38.6 kw (1.93 kw/ft), and 46.4 kw (2.32 kw/ft), the septifoil was cooled by thermal-hydraulic pumping in a cyclic process. Periods of cycling varied from 30 seconds to 21 seconds during which relatively low velocity water flow would be followed by rapid ejection of water and steam through the septifoil holes, "chugging". The ejection of water and steam from the top corresponded to high water flow up from the bottom of the septifoil. The percentage of heat flowing through the septifoil wall was 11%. At 66.6 kilowatts (3.33 kw/ft), cyclic eruption did not occur and thermal-hydraulic pumping was negligible. Cooling was maintained by copious production of steam. At 67.2 kilowatts (3.36 kw/ft), cyclic eruption did not occur and thermal-hudraulic pumping was negligible. Film boiling occurred generating steam superheated to temperatures up to 582C. Film boiling was evident from high temperatures at the thermocouples and simultaneous increase in electrical resistance of four 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 four simulated rods that had indicated film boiling. Computations of temperature rise of the rods indicated peak temperatures between 710C and 830C.

3.0 METHOD OF ANALYSIS - DESCRIPTION OF EXPERIMENTAL APPARATUS:

3.1 Control Rods

Design of the simulated control rods was constrained by availability of electrical power 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. 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 and they withstood overheating during film boiling without damage.

3.2 Septifoil Assembly

A type "Q" septifoil assembly was obtained and cut 52 inches below the end of the top fitting. The bottom end fitting was cut from the septifoil and attached to the 52 inch segment. In order to simulate oxide present during normal reactor operation of septifoil, the septifoil was taken to a vendor in Atlanta and 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. Insulating standoff loops of 0.060 inch diameter nylon were made and installed on the inside of the septifoil web. To prevent contact between the heaters and the outer septifoil housing, nylon screws were installed through the housing wall. A rubber diaphragm was attached across the septifoil to block water flow out of the top. The septifoil housing, simulated rods, and other components were assembled onto a support as shown in Figure 2. Locations of data sensors on the septifoil are shown in Figure 3 and the septifoil rod identifications are shown in Figure 4.

3.3 Experimental 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 angle. Leveling screws were inserted through the three legs of the support. Support fixtures held the septifoil rods, thermocouples, and pressure transducers in place. Pressure transducers were mounted in dry wells fabricated from PVC pipe. The support with simulated control rods and the 23C water tank are shown in Figure 5.

3.4 Shadowgraph Plenum

The experiment required measurement of unconfined flow into the septifoil. It was important to measure flow without restricting the thermal-hydraulic pumping action of the heated rods inside the septifoil. It was also important to allow water flowing through the septifoil to exit the top holes and mix with water outside the septifoil. These requirements prevented flow measurement by means of trapping exhaust water and measuring flow. A satisfactory method of measuring the flow into the bottom of the septifoil was accomplished by building a double wall glass plenum to house the bottom of the septifoil and flooding this plenum with 70C water while the whole apparatus was positioned in a tank filled with 23C water. Shadowgrams were formed by shining a parallel light beam across the plenum onto a projection screen on the opposite side of the tank. The interface between hot and cold water was visible on the shadowgram. This interface, shown in Figure 6, shows up quite well as a series of dark and light bands caused by the difference of the index of refraction between the hot and the cold water. Water fed to the plenum was controlled to maintain a stable interface. Flow rate of this water was measured to determine the flow through the center of the septifoil.

3.5 Side-wall Calorimetry

Power transferred through the wall of the septifoil was measured by a calorimeter. A transparent tube was installed around the septifoil and sealed to the bottom of the septifoil segment. Water at 70C was fed to this jacket with temperature measurement at the jacket inlet. Water flowed upward along the septifoil and temperature was measured 6 inches from the exit holes of the septifoil. The known flow rate of this water and the measured temperature difference as the water flowed along the septifoil allowed calculation of the power transferred through the wall of the septifoil.

3.6 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.

3.7 Experimental Tank

A tank was fabricated with 1/2 inch thick polycarbonate walls to contain water at 23C for formation of the shadowgrams for thermal-hydraulic flow measurement and to provide safety containment for the experiment. Walls of the tank were reinforced at intervals to ensure adequate structural integrity. The tank was filled with deionized water having a resistivity greater than 2 megohm-centimeters.

3.8 Deionizer

Deionized water for filling the experimental tank and hot water drums 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.

3.9 Data Acquisition System

Data from the 18 thermocouples, 3 pressure transducers, current and voltage signals was logged and visually indicated by a data acquisition system incorporating a Macintosh computer operating "LabView (ver 2.1.1)" software. The software generated data files in "Excel" spreadsheet form and presented a meaningful color coded graphic display, shown in Figure 7. 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.

3.10 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. The small diameter thermocouples were fragile and the extensive amount of handling necessary to position them in the experiment caused a number of failures during early measurements.

3.11 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.

3.12 Conductivity Measurements

Conductivity of water for the experiment was monitored by flow through conductivity cells fabricated by EES for use in reactor flow studies. This conductivity meter consists of a conductivity cell with a cell constant of 0.1 connected to an LCR meter measuring resistance by an alternating current measurement.

3.13 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
- Water Level Controller
- Video and Log Book Recorder
- Intercom Operator
- Test Conductor

4.0 RESULTS:

4.1 Scoping Test

A preliminary scoping test was conducted to test the experimental apparatus and procedures and to determine the basic phenomena to be expected. For this test the septifoil was assembled with five simulated control rods and all temperature and pressure sensors. The power supply was brought slowly from zero power up to 37.5 kilowatts (kw) or 1.9 kw /ft. Operation of all systems was quite satisfactory and careful studies were made of resistance of the simulated control rods to detect any indication of overheating or film boiling. No such indication was detected. At 1.9 kw/ft. thermal-hydraulic pumping of water through the septifoil became periodic 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 of the septifoil. The oscillation period of chugging in the scoping test was nominally 20 seconds. This corresponds to a 14 second boiling interval followed by a 6 second ejection time.

Based on the satisfactory operation of all systems, preparations were made and documentation was prepared to conduct an experiment according to QA task activity requirements as defined in EES QA Manual 1Q28.

4.2 Task Experiment #1

All necessary pretest calibrations and data records were made on equipment and sensors for the experiment. Type E thermocouples were mounted in each channel inside the top holes, at the septifoil inlet and outlet, at the calorimetry inlet (2) and outlet (2), on the surface of rod F, on the septifoil jacket (2) in the bulk water at the top, and at the bottom. Differential pressure transducers were mounted in one of the top slots, in one of the small holes, and in the empty channel above the bottom fitting. The reference side of each transducer was connected to bulk water at the same level. Power from the DC power supply was connected to the experiment through a 35,000 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. Water flow to the calorimeter jacket and to the septifoil feed plenum was provided by gear pumps which pumped water from drums mounted on scales. The weight of water in each drum was continuously monitored throughout the experiment and flow rate was computed from the rate of weight loss.

Power was applied to the rods and set at 12 kw in order to heat the rods, septifoil, and jacket to 70C. Jacket water flow was started and power was raised to 34 kw. Chugging was observed but was not quite as well defined as in the scoping test. Pulsed temperature and pressure rise were not as uniform in period and amplitude. After six minutes, power was slowly increased to 38 kw and chugging continued. Four minutes at this power level produced no observed film boiling. Power was then increased to 66 kw and chugging ceased. No film boiling was observed, but cooling was continued for five minutes with copious evolution of steam. During operations at 66 kw the septifoil feed pumps failed to supply adequate flow to maintain hot water feed for the septifoil. Some cold water entered the septifoil so power was reduced and the experiment was discontinued to modify the septifoil feed pumps.

4.3 Task Experiment #2

Data acquisition for Task Experiment #2 was the same as in Task Experiment #1, and data graphs for Experiment #2 are included in this report. The sequence of power control for the power supply throughout the experiment is shown in Figure 8. As in the first task, power was first set at 12 kw to preheat the components and check for proper resistance of the rods. After components reached 70C, jacket flow was turned on and power was increased to 38.6 kw (1.93 kw/ft.). Cooling was maintained by chugging flow with a period of 30 seconds.Eleven percent of the power was transferred through the septifoil wall. Power was increased to 67.2 kw (3.36 kw/ft) whereupon chugging operations ceased and pressure increased at the top of the septifoil to the values shown in Figure 9. Thermal-hydraulic pumping ceased and some of the hot water inside the septifoil was pushed down to the septifoil inlet causing the septifoil inlet temperature to increase from 70C to 90C as shown in Figure 10. Temperatures in channels F and A increased to values well above 120C starting at 1020 seconds into the experiment, thus indicating presence of superheated steam. Channel F increased steadily to above 500C with one peak value reaching 582C. Channel A reached a maximum temperature of 320C. At 1070 seconds channel G increased abruptly to 175C and channel E started a slight increase which accelerated at 1085 seconds. The presence of superheated steam in these four rods was a clear indication that film boiling had occurred and is plotted in Figure 11. The film boiling was confirmed by increasing resistance in the same rods that showed superheated steam. Rods F and A started increasing resistance at 980 seconds. Rod E started increasing resistance at 995 seconds. Rod B started increasing resistance at 1060 seconds. Figure 12 shows the resistance rise of rods A, B, E, and F. Examination of these rods at the conclusion of the experiment showed that all had become discolored by high temperature at their surfaces resulting from chemical reaction of the very hot surface with steam. Power was decreased to 1.8 kw/ft and chugging operation resumed with a period of 23 seconds as indicated in Figures 13 and 14. Resistance of the rods slowly decreased back to the original values over the next three minutes. Power was increased to 2.30 kw/ft and chugging continued with a period of 21 seconds as shown in Figures 15 and 16. Power was increased to 3.33 kw/ft resulting in pressure rise to above 1 psi as shown in Figure 17. Chugging operation and thermal-hydraulic pumping ceased. Hot water from inside the septifoil was again forced downward resulting in higher temperature at the septifoil inlet as shown in Figure 18 but cooling was maintained through steam production. The absence of film boiling was clearly shown by the stable resistance of the rods as shown in Figure 19. Throughout the test water flow to the calorimeter jacket was constant at 2.1 +/- .1 gallons per minute as shown in Figure 20. For code comparison, the temperatures in and out of the jacket may be used with this flow rate to compute power through the wall. Average flow to the septifoil was approximately 2.5 gallons per minute except at powers of 3.36 and 3.33 kw/ft where flow was zero and film boiling occurred as shown in Figure 21. Figure 22 shows a picture of the top of the experimental tank with steam formation generated during film boiling.

5.0 Recommendations

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

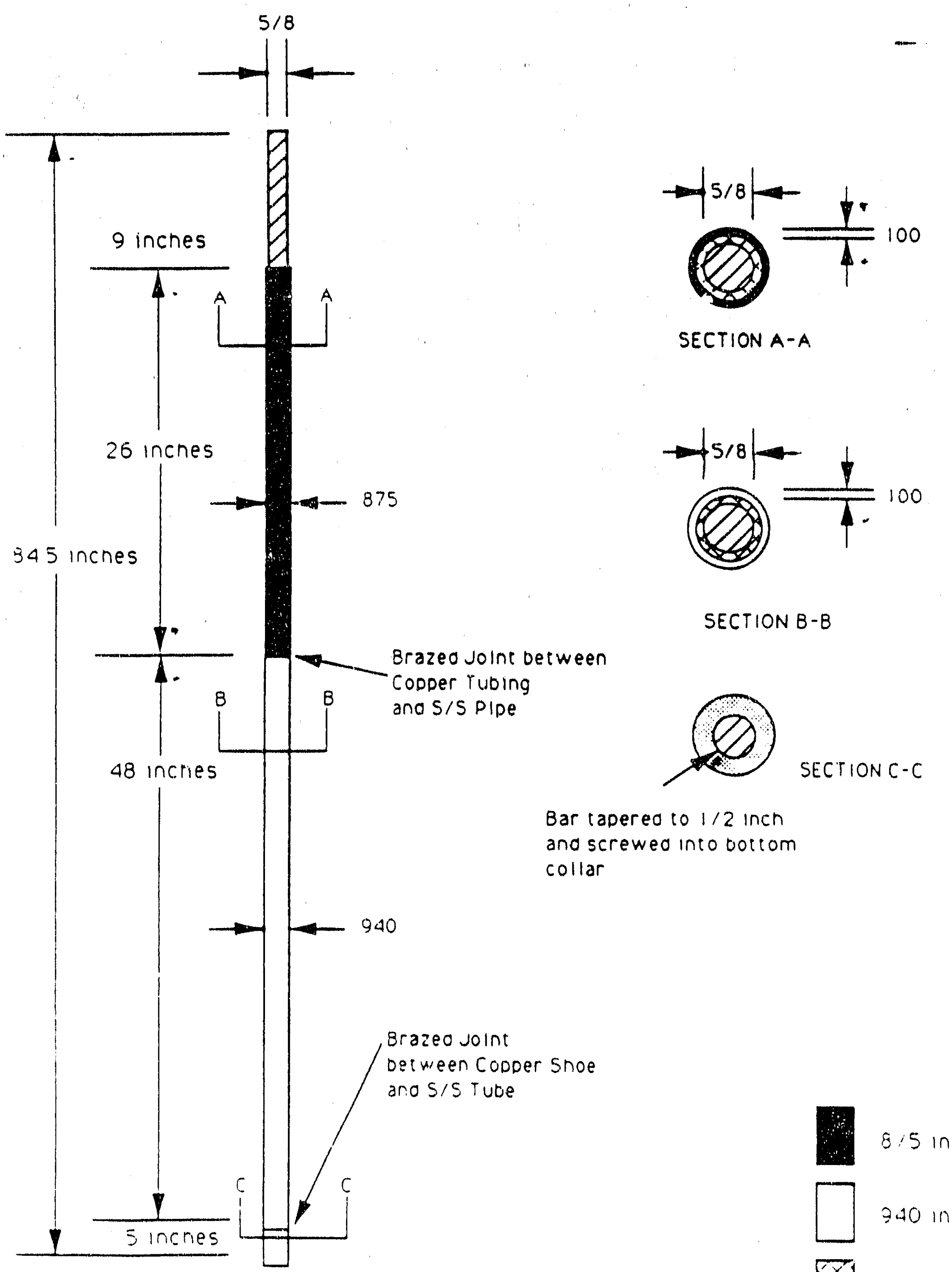
- Thermal conductivity and heat capacity of simulated control rods used in full scale septifoil experiments should be close to the values for the lithium-aluminum control rods in the reactor. These parameters will affect cyclic heat transfer.

- 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.

- 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 TEST



Electrical Resistances

Rod	Resistance (Ω)
A	0.00642
B	0.00618
C	0.00631
E	0.00608
F	0.00649

- 875 inch od Copper Tubing
- 940 inch o.d. 304-L Stainless
- Fiberglass Cloth Insulation
- 5/8 inch Copper Rod, tapering to 1/2 inch Thread at bottom
- Copper Shoe with 1/2 inch Screw Hole

ALL DIMENSIONS IN INCHES

FIGURE 2.

SEPTIFOIL TEST ASSEMBLY

MOUNTED IN SUPPORT

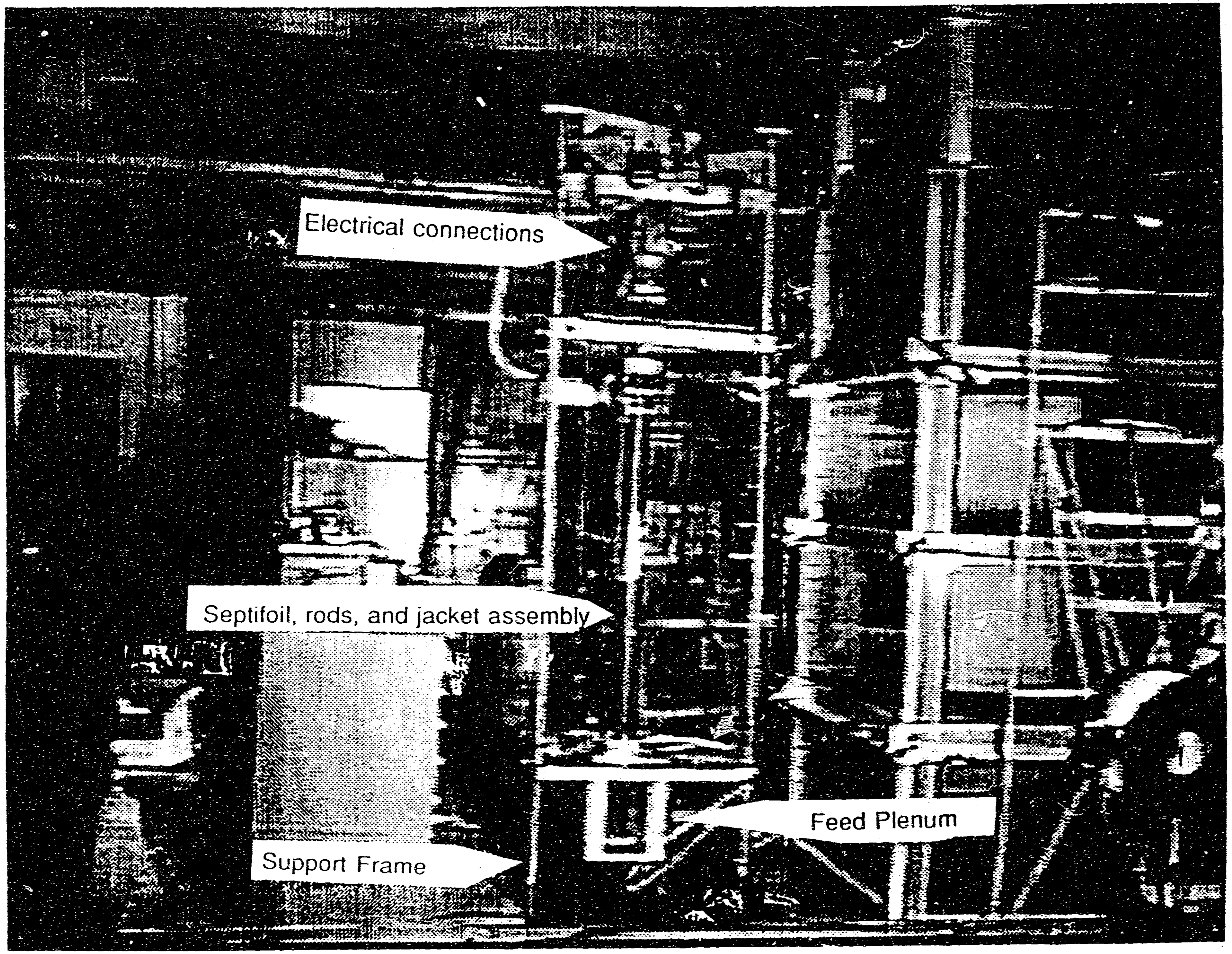

Electrical connections
Septifoil, rods, and jacket assembly
Feed Plenum
Support Frame

Figure 3
SEPTIFOIL COOLING TEST
(FIVE ROD UNSEATED CASE)

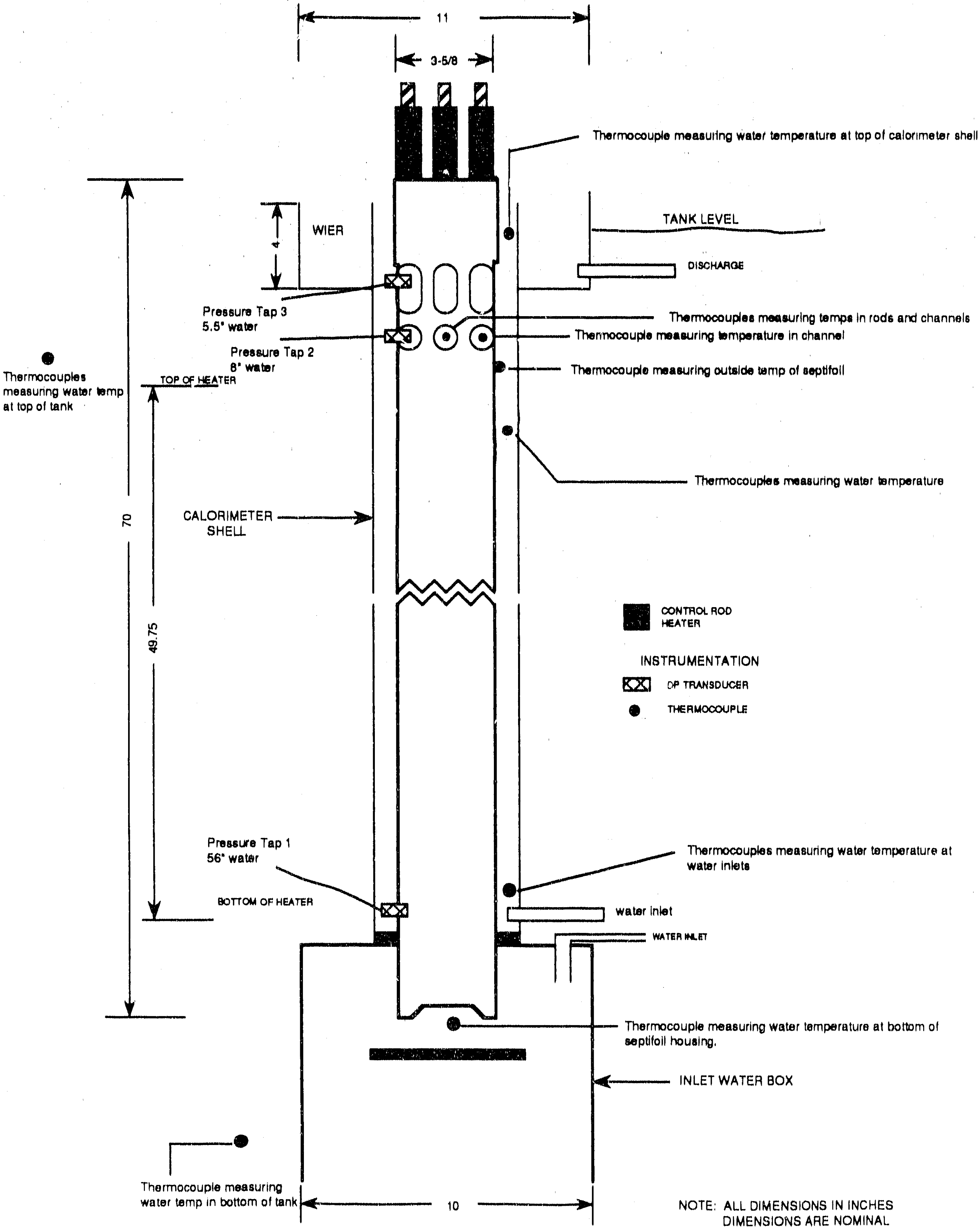


FIGURE 4

SEPTIFOIL CHANNEL IDENTIFICATIONS
(LOOKING DOWN ON TOP)

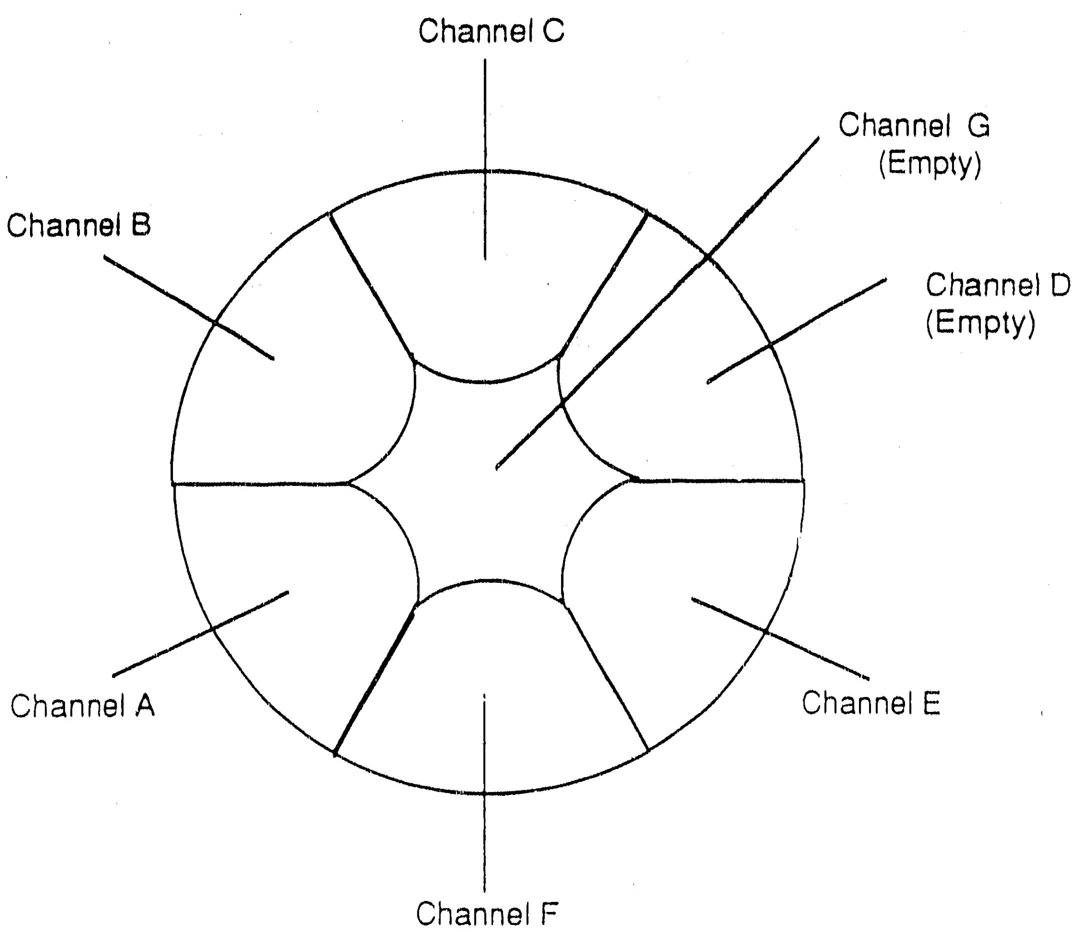


FIGURE 5

EXPERIMENTAL ASSEMBLY

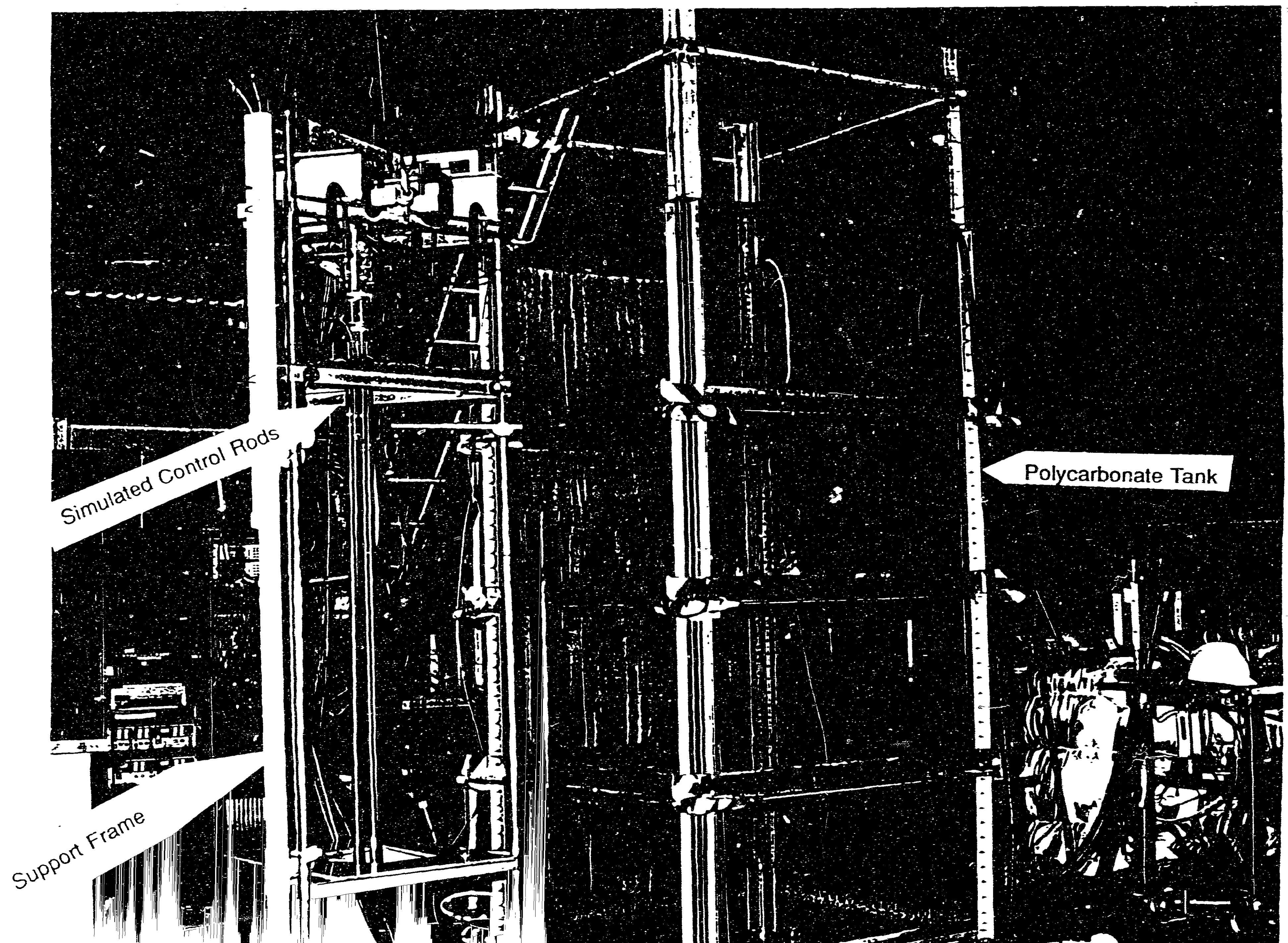

Simulated Control Rods
Polycarbonate Tank
Support Frame

FIGURE 6

SEPTIFOIL FEED WATER SHADOWGRAM

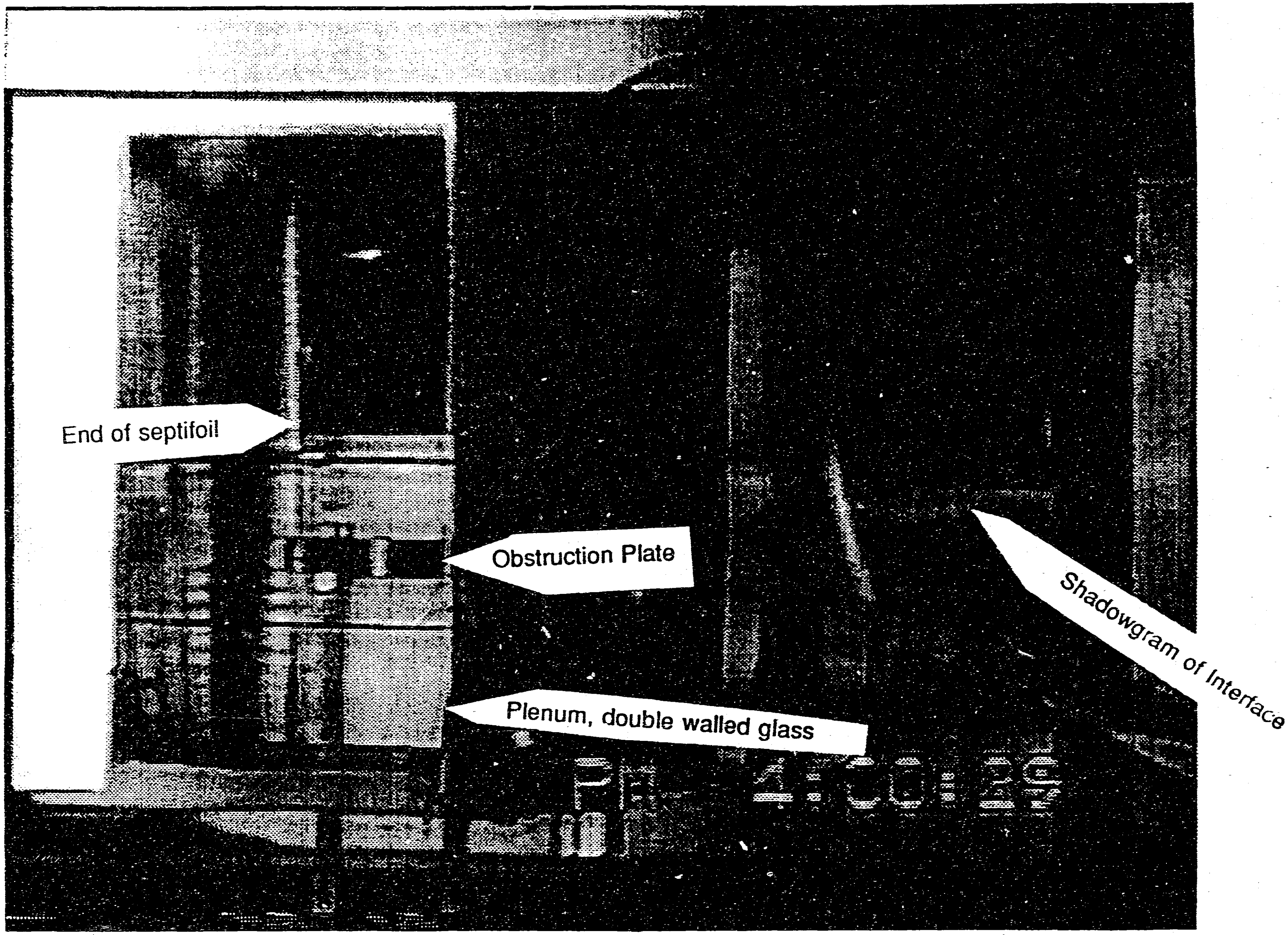

End of septifoil
Obstruction Plate
Plenum, double walled glass
Shadowgram of Interface

FIGURE 7

COMPUTER FRONT PANEL

Front Panel

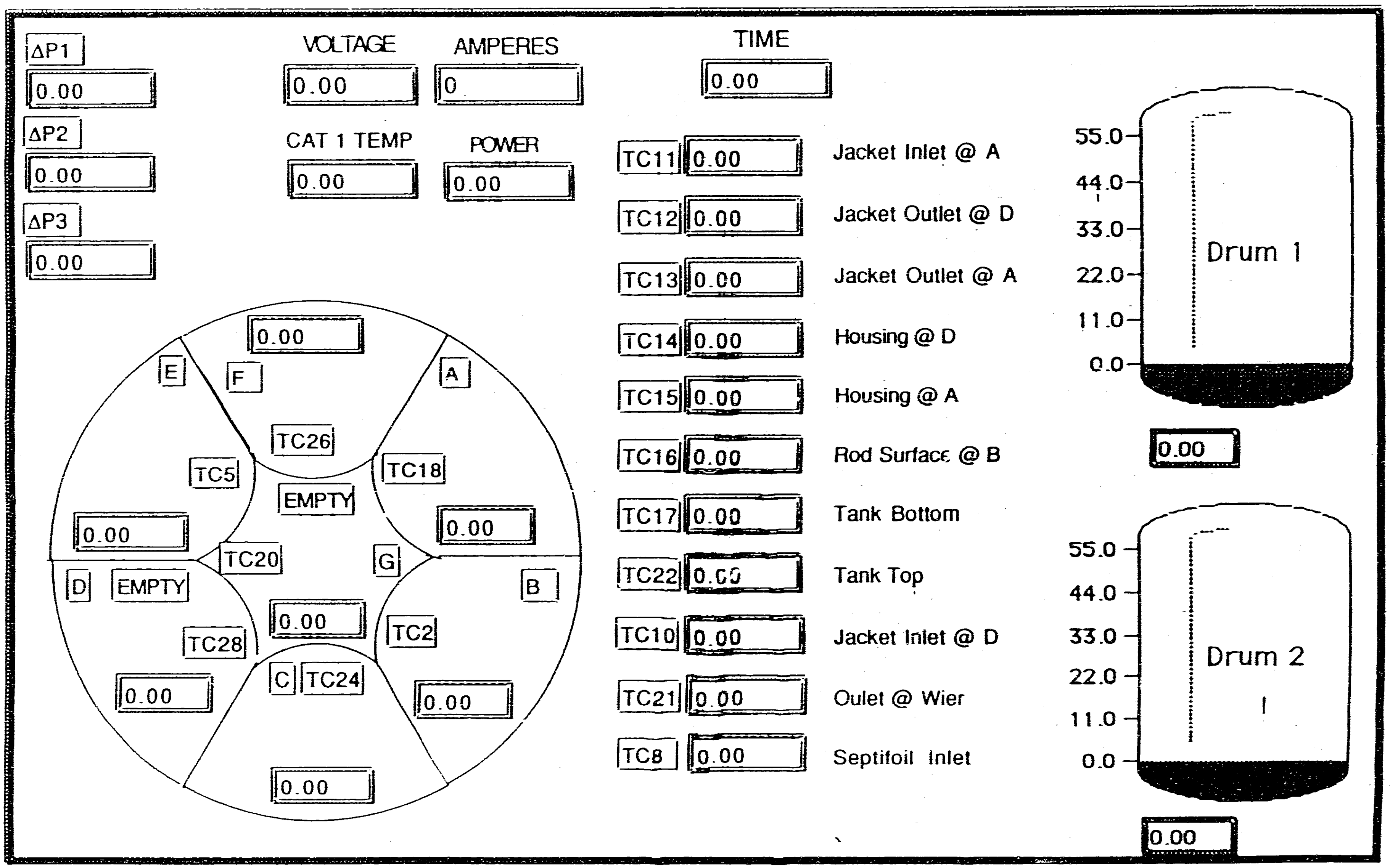
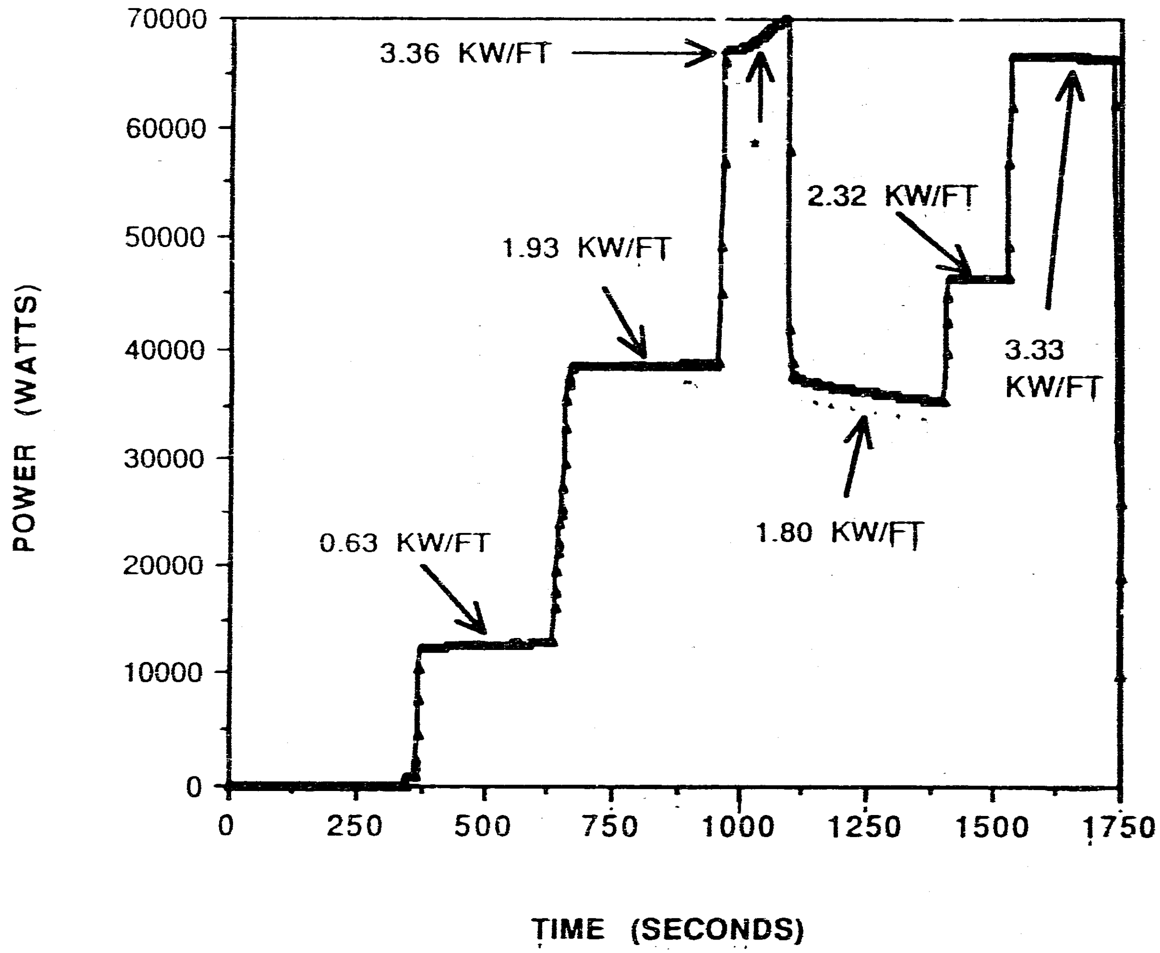

ΔP1
0.00
ΔP2
0.00
ΔP3
0.00
VOLTAGE
0.00
AMPERES
0
CAT 1 TEMP
0.00
POWER
0.00
TIME
0.00
TC11 0.00 Jacket Inlet @ A
TC12 0.00 Jacket Outlet @ D
TC13 0.00 Jacket Outlet @ A
TC14 0.00 Housing @ D
TC15 0.00 Housing @ A
TC16 0.00 Rod Surface @ B
TC17 0.00 Tank Bottom
TC22 Tank Top
TC10 0.00 Jacket Inlet @ D
TC21 0.00 Oulet @ Wier
TC8 0.00 Septifoil Inlet
A
B
C
D
E
F
G
TC26
TC18
TC5
EMPTY
TC20
EMPTY
TC28
TC2
TC24
0.00
Drum 1
55.0
44.0
33.0
22.0
11.0
0.0
0.00
Drum 2
55.0
44.0
33.0
22.0
11.0
0.0
0.00

FIGURE 8

POWER VS. TIME
EXPERIMENT #2



NOTES:

0.63 KW/FT – WATER PRE-HEAT AND ROD RESISTANCE CHECK

1.93KW/FT – CHUGGING

3.36KW/FT – NO CHUGGINC
FILM BOILING AT *
(REF. FIGURES 9,10,11)
RESISTANCE RISE
(REF. FIGURE 12)
POWER INCREASE DUE TO RESISTANCE RISE

1.80 KW/FT – CHUGGING
PERIOD 23 SECONDS
(REF. FIGURES 13,14)

2.32 KW/FT – CHUGGING
PERIOD 21 SECONDS
(REF. FIGURES 15,16)

3.33KW/FT –
NO CHUGGING
NO FILM BOILING
(REF. FIGURES 17,18,19)

FIGURE 9

PRESSURE VS. TIME, FILM BOILING AT 3.36 KW/FT
EXPERIMENT #2

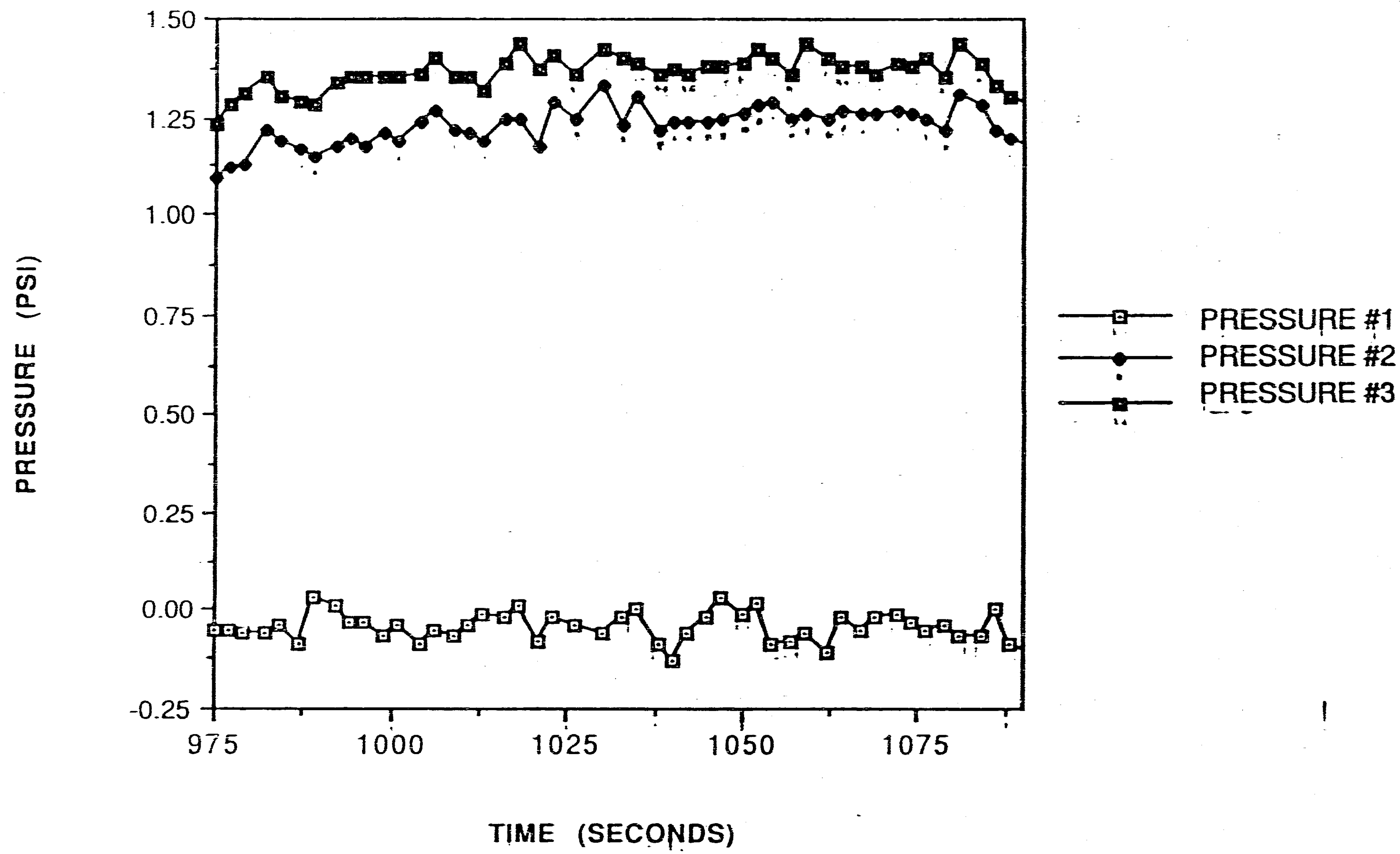


FIGURE 10
SEPTIFOIL TEMPERATURE VS. TIME, FILM BOILING AT 3.36 KW/FT EXPERIMENT #2

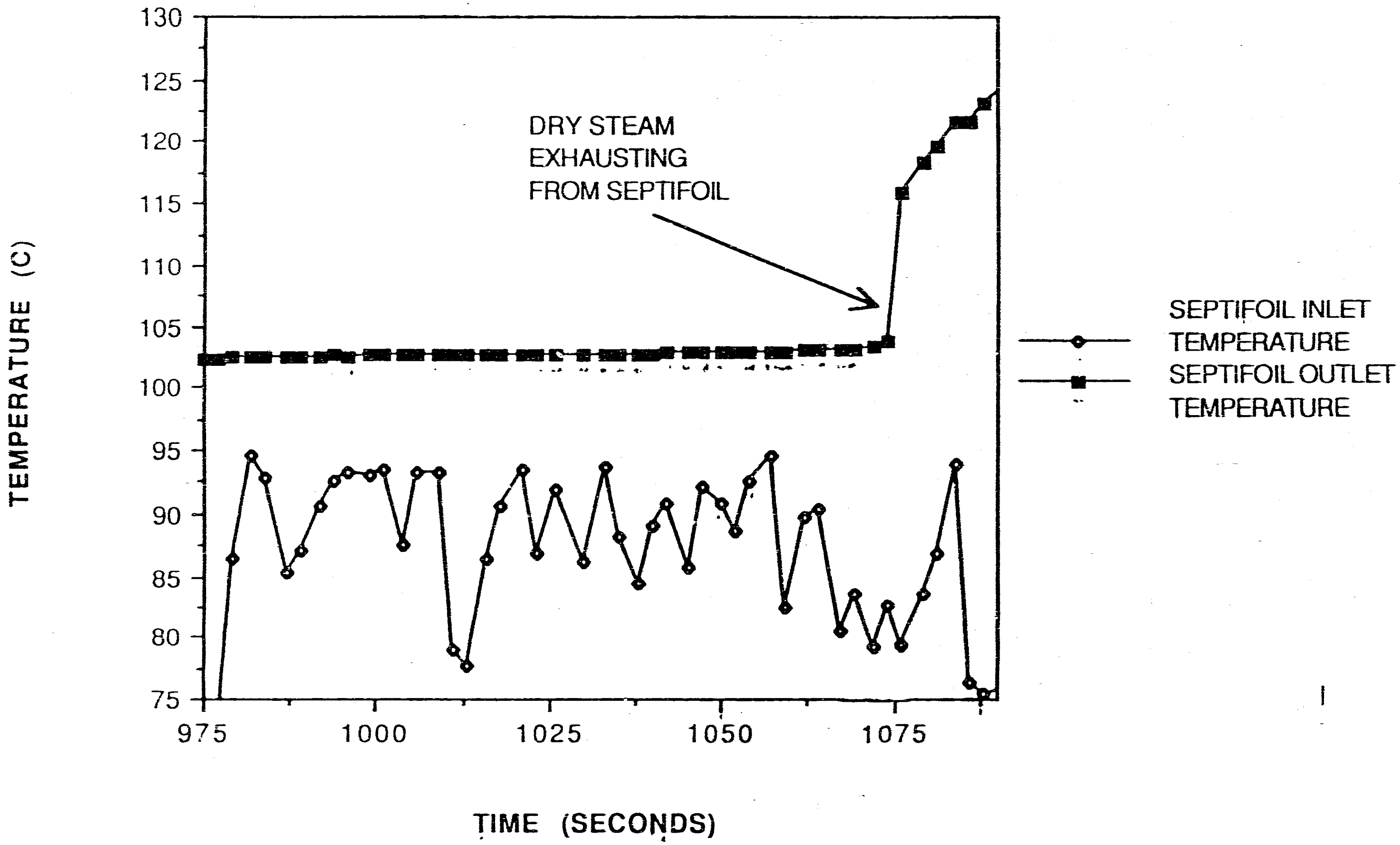


FIGURE 11

CHANNEL TEMPERATURES VS. TIME

3.36 KW/FT, FILM BOILING

EXPERIMENT #2

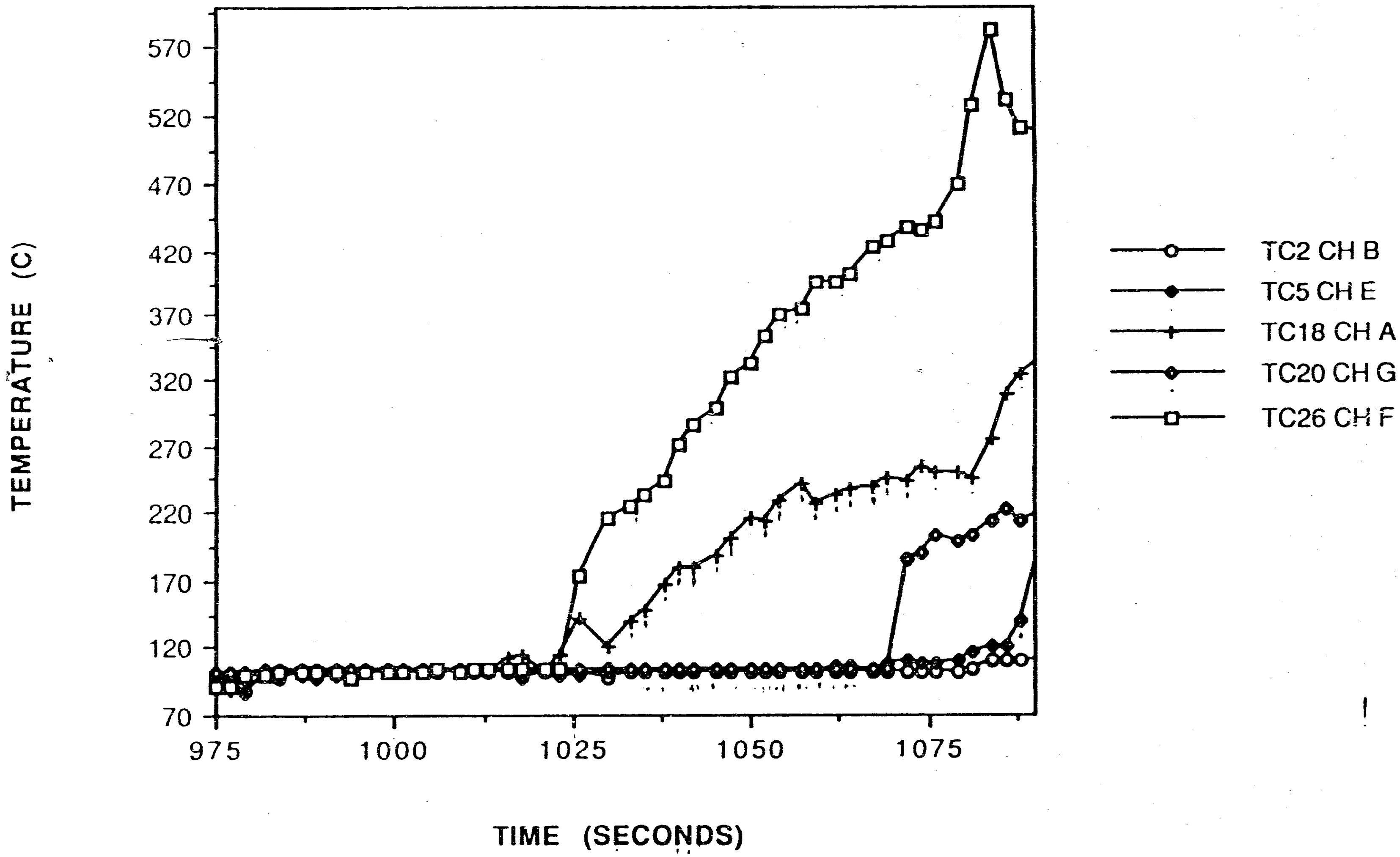


FIGURE 12
ROD RESISTANCE VS. TIME
3.36 KW/FT, FILM BOILING
EXPERIMENT #2

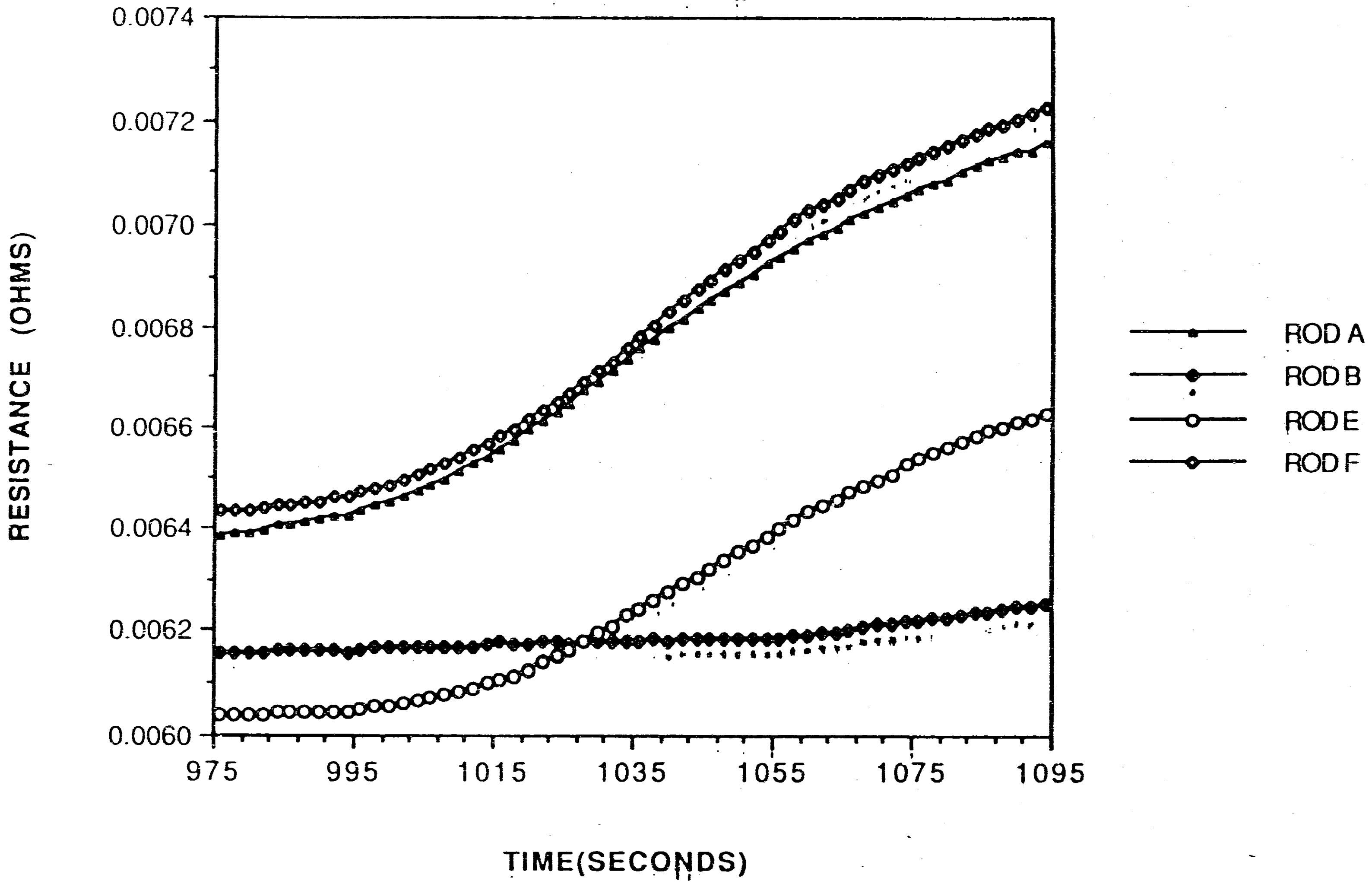


FIGURE 13

PRESSURE VS. TIME, CHUGGING AT 1.8 KW/FT EXPERIMENT #2

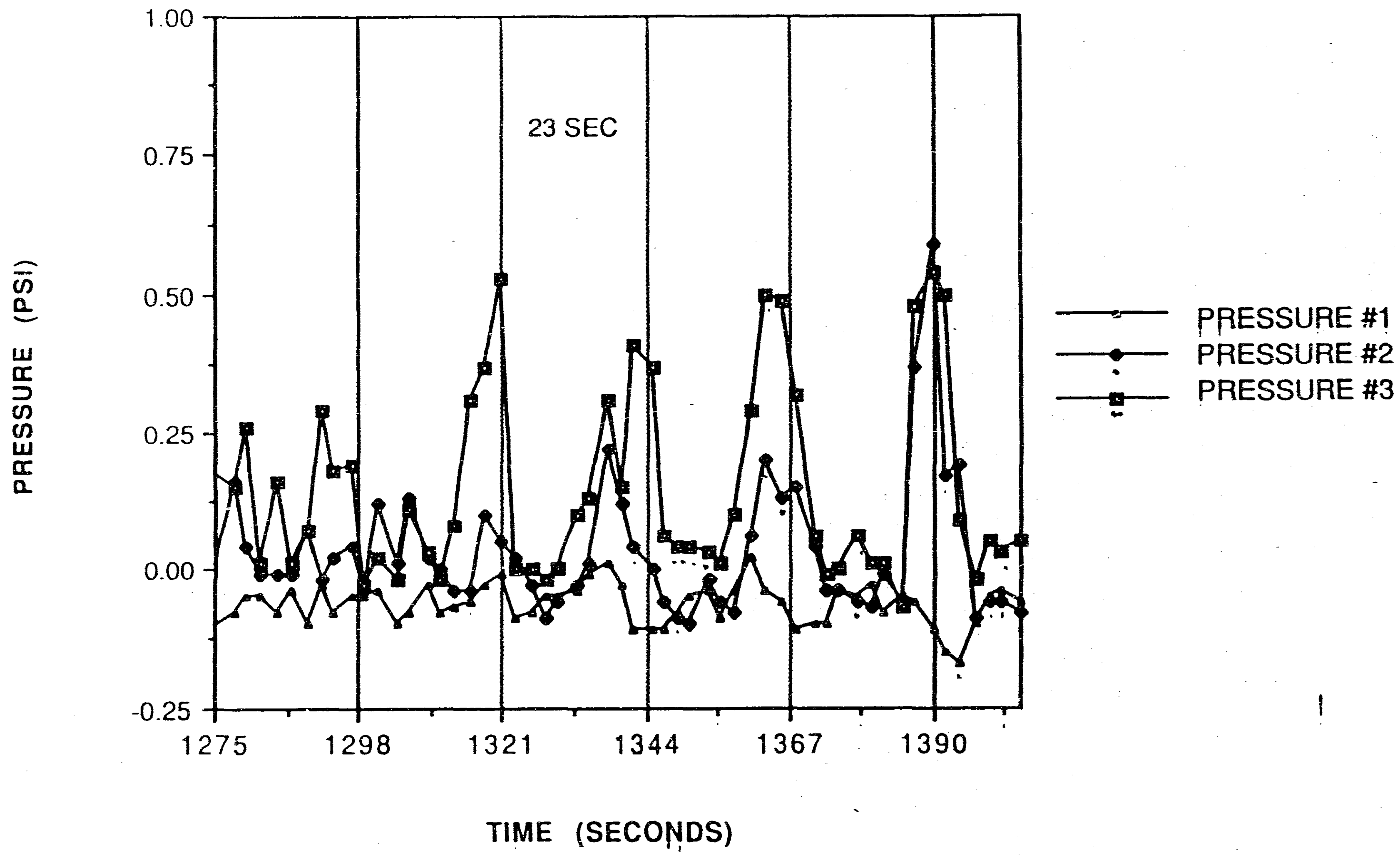


FIGURE 14
SEPTIFOIL WATER TEMPERATURE VS. TIME, CHUGGING AT 1.8 KW/FT
EXPERIMENT #2

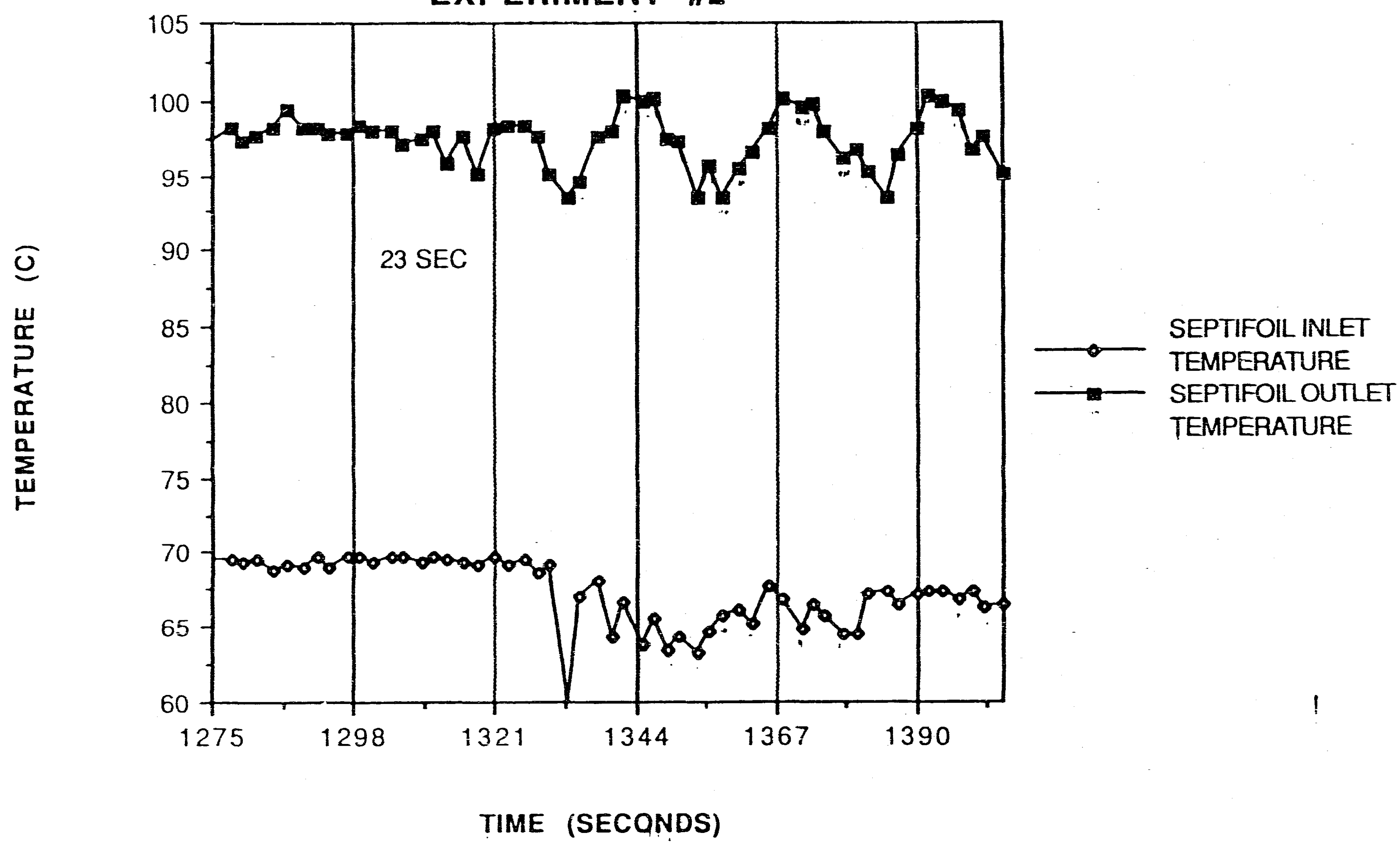


FIGURE 15
PRESSURE VS. TIME, CHUGGING AT 2.3 KW/FT
EXPERIMENT #2

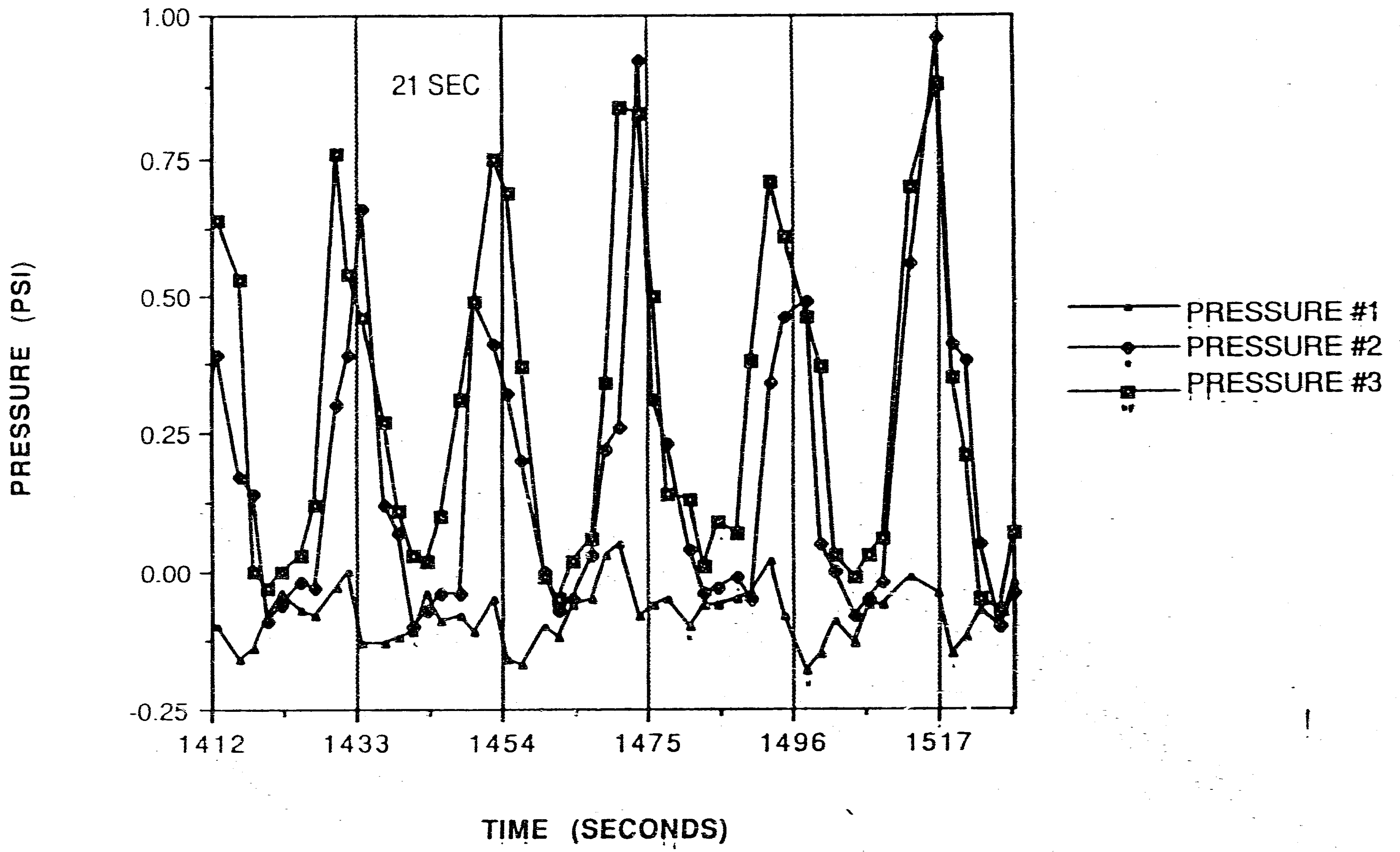


FIGURE 16
SEPTIFOIL TEMPERATURE VS. TIME, CHUGGING AT 2.3 KW/FT EXPERIMENT #2

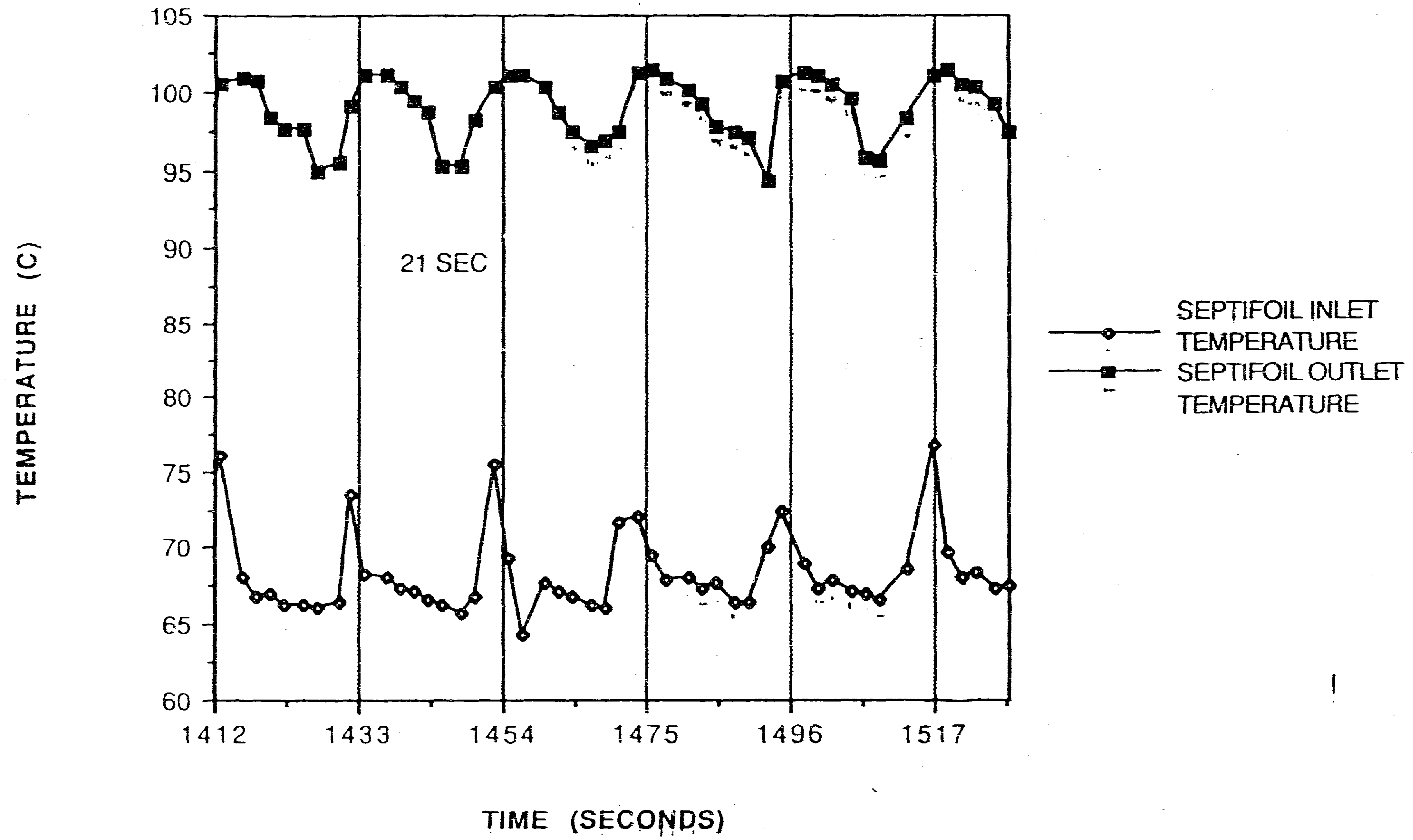


FIGURE 17
PRESSURE VS. TIME 3.33 KW/FT
NO CHUGGING, NO FILM BOILING
EXPERIMENT #2

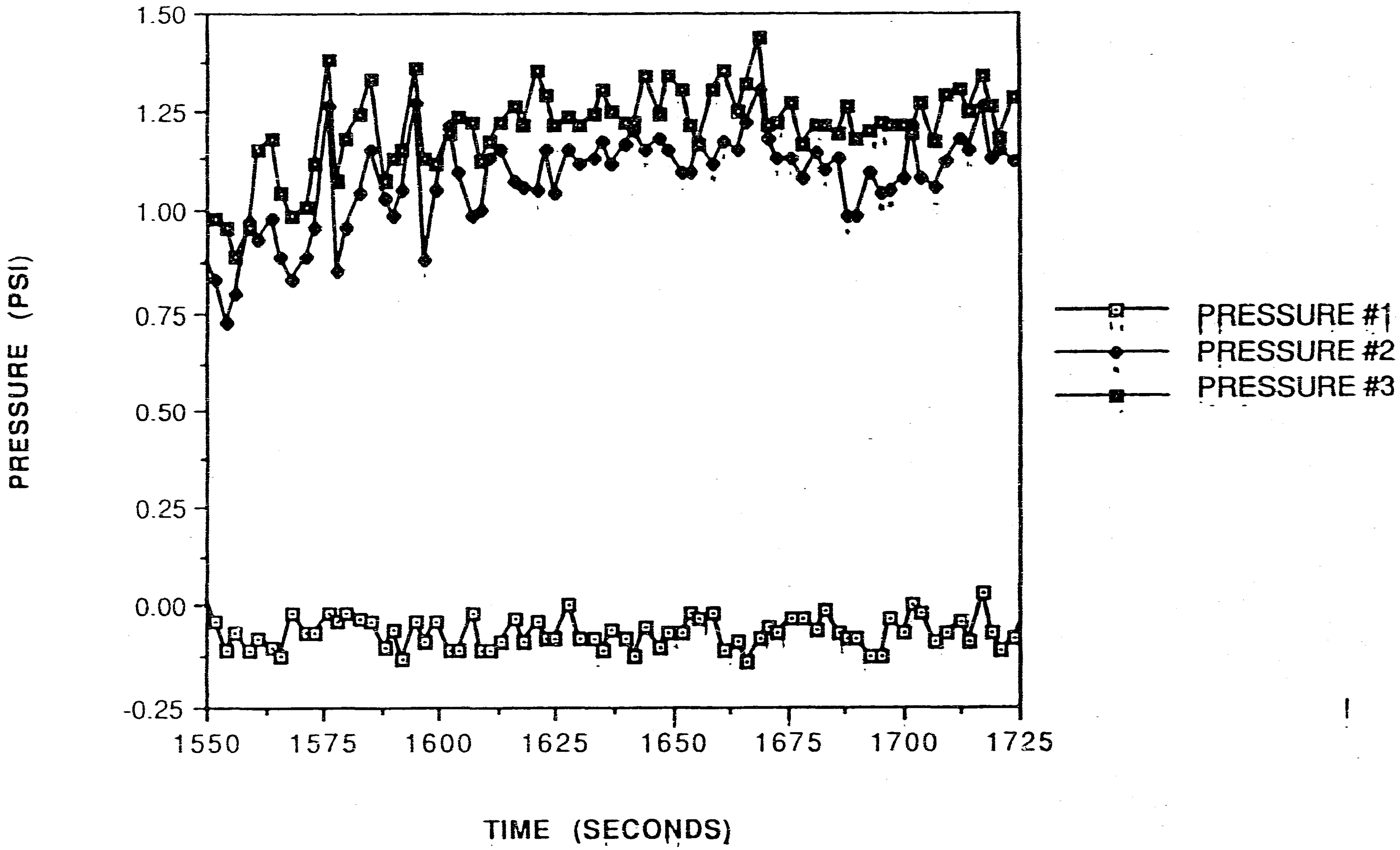


FIGURE 18
SEPTIFOIL TEMPERATURE VS. TIME,
3.33 KW/FT, NO FILM BOILING
EXPERIMENT #2

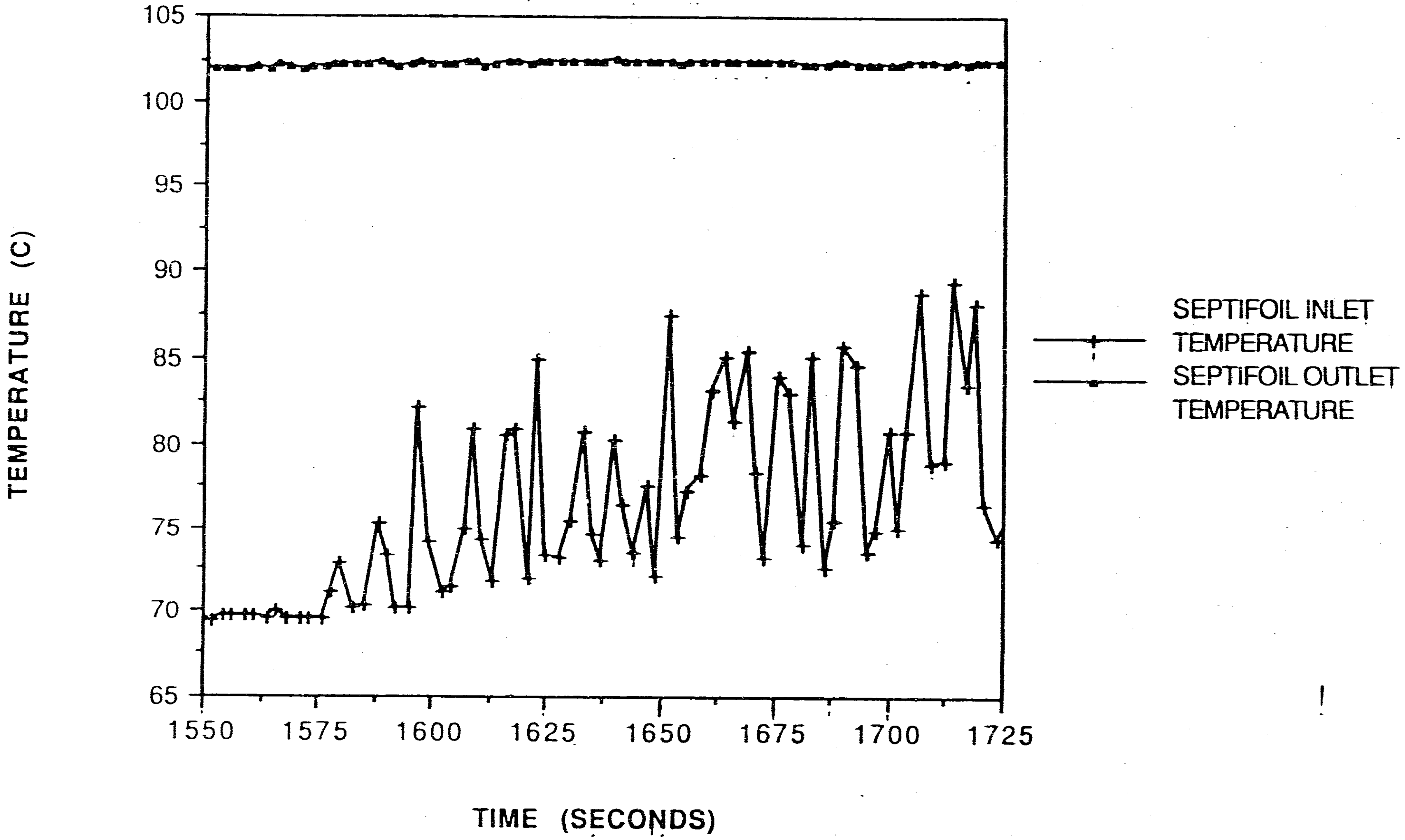


FIGURE 19

ROD RESISTANCE VS. TIME
3.33 KW/FT, NO FILM BOILING
EXPERIMENT #2

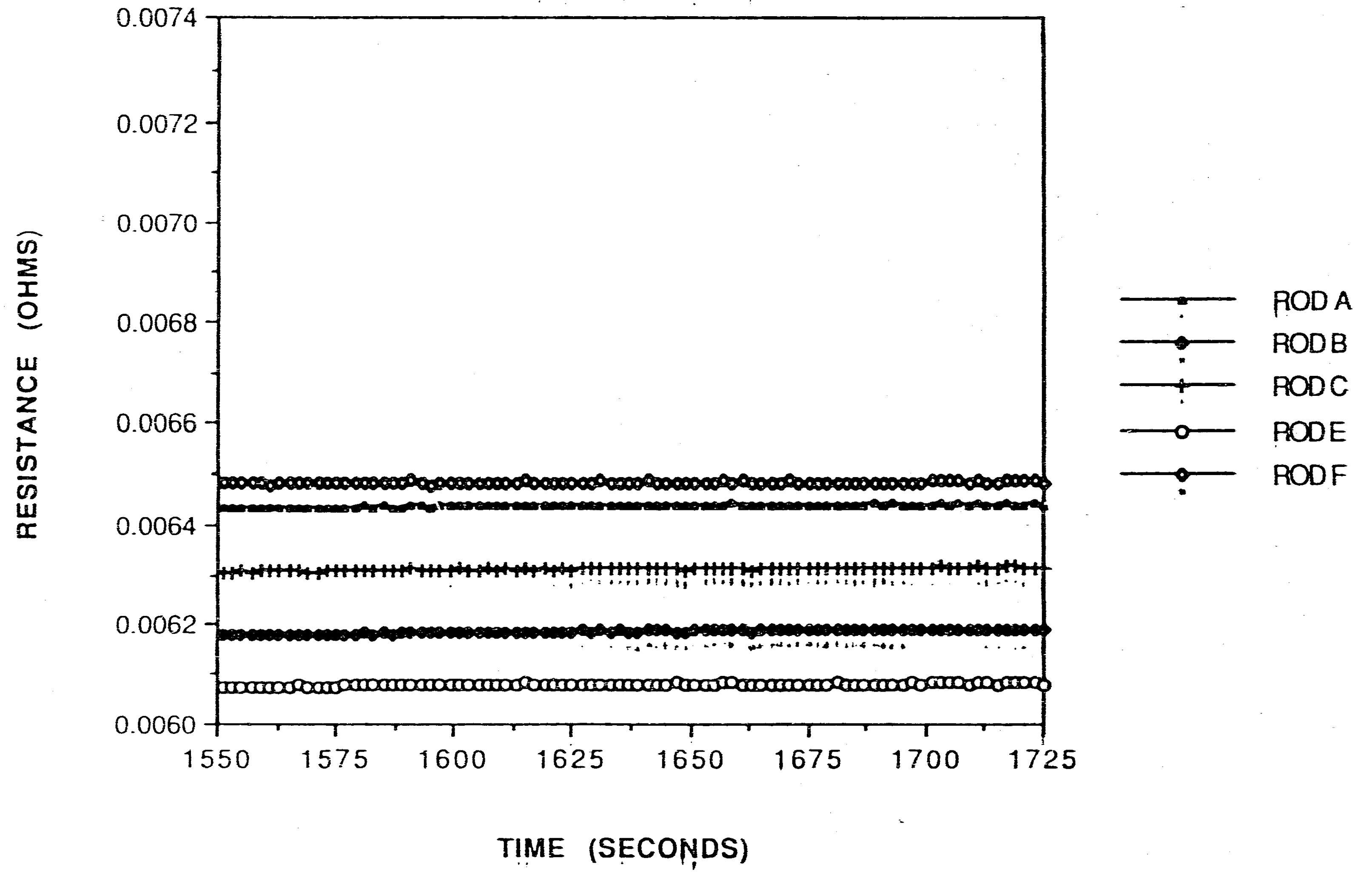


FIGURE 20
WATER FLOW TO CALORIMETER JACKET
EXPERIMENT #2

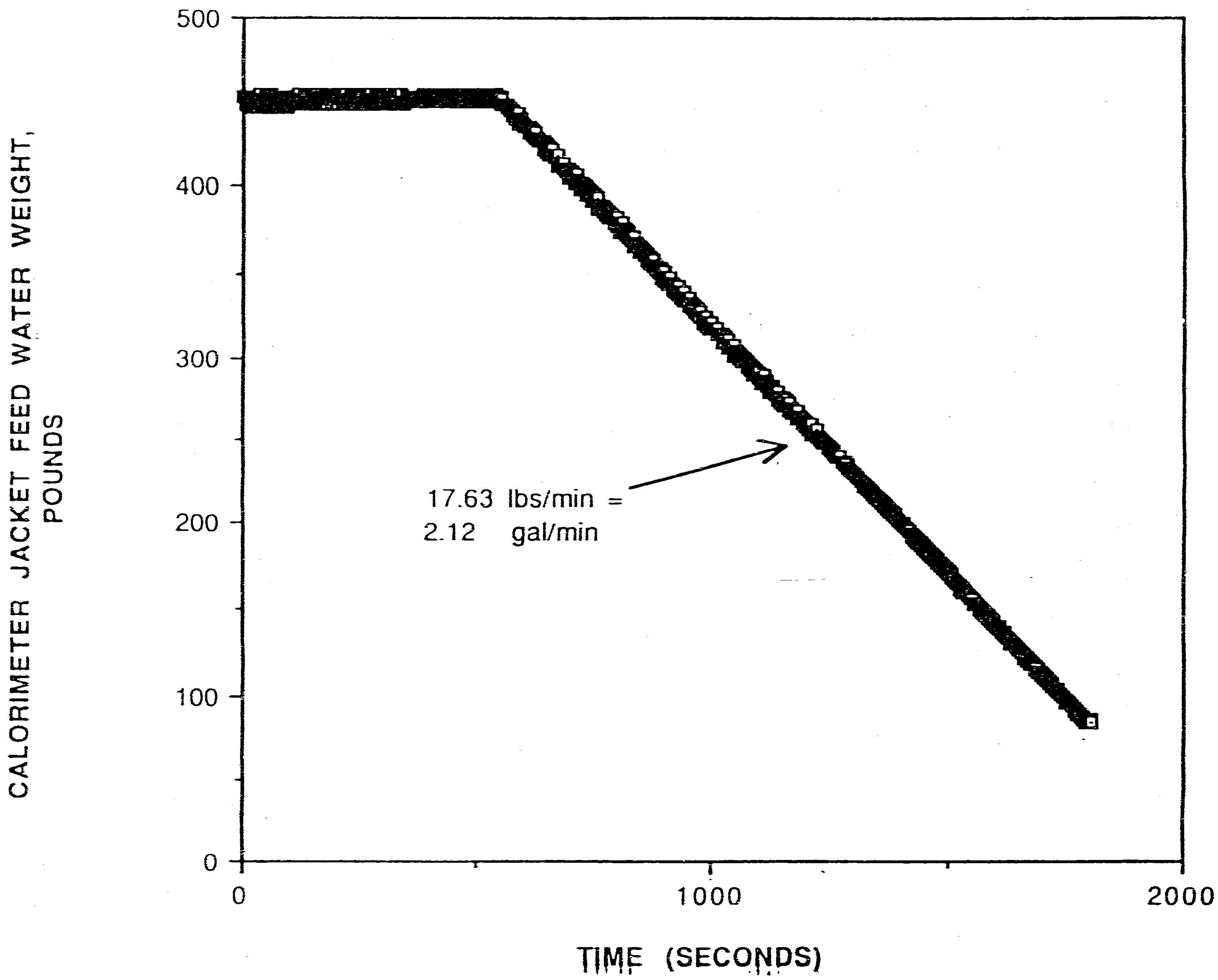


FIGURE 21
SEPTIFOIL WATER FLOW VS..TIME
EXPERIMENT #2

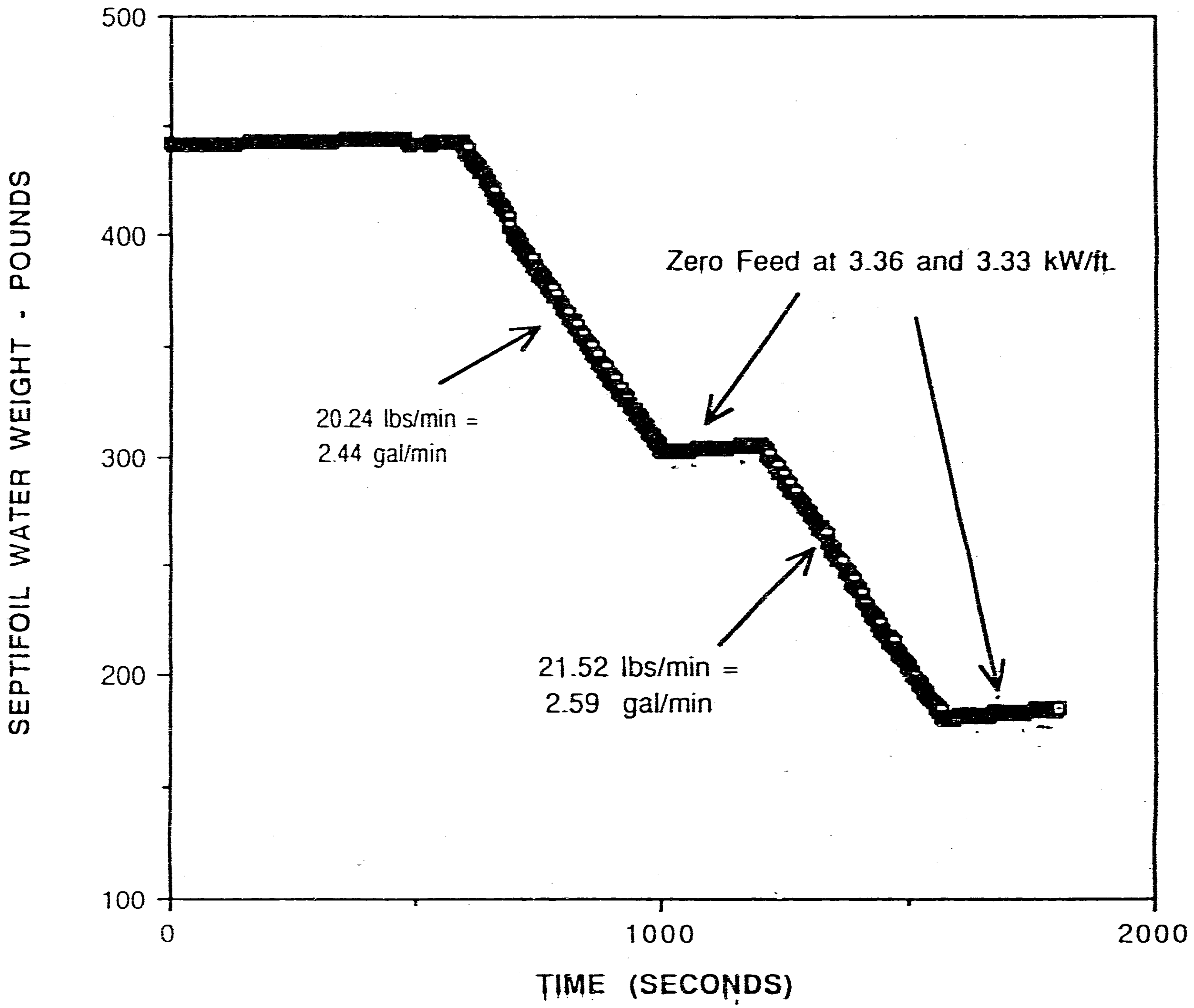
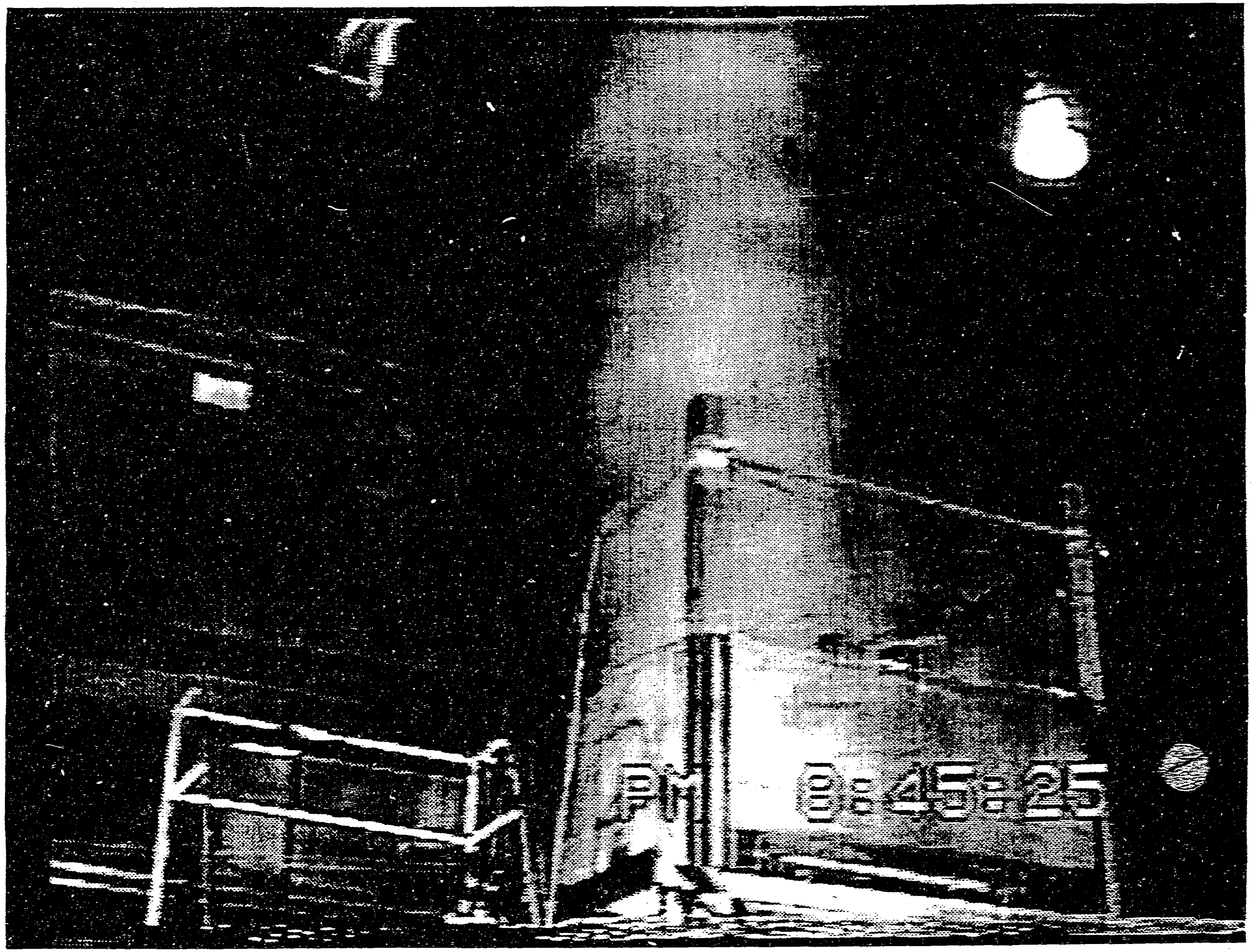


FIGURE 22

STEAM GENERATION AT 3.36 kw/ft


PM 8:45:25

END

DATE
FILMED
6/18/92