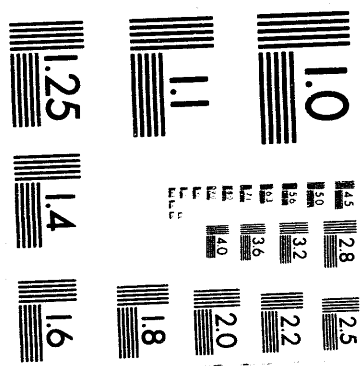
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SAND94-0377C
Conf-931079--21

Large-Scale Testing of In-Vessel Debris Cooling Through External Flooding of the Reactor Pressure Vessel in the CYBL Facility*

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ABSTRACT

The possibility of achieving in-vessel core retention by flooding the reactor cavity, or the "flooded cavity", is an accident management concept currently under consideration for advanced light water reactors (ALWR), as well as for existing light water reactors (LWR). The CYBL (CYlindrical BoiLing) facility is a facility specifically designed to perform large-scale confirmatory testing of the flooded cavity concept. CYBL has a tank-within-a-tank design; the inner 3.7 m diameter tank simulates the reactor vessel, and the outer tank simulates the reactor cavity. The energy deposition on the bottom head is simulated with an array of radiant heaters. The array can deliver a tailored heat flux distribution corresponding to that resulting from core melt convection. The present paper provides a detailed description of the capabilities of the facility, as well as results of recent experiments with heat flux in the range of interest to those required for in-vessel retention in typical ALWRs. The paper concludes with a discussion of other experiments for the flooded cavity applications.

*This work was supported by the U.S. Department of Energy under cintract DE-AC04-94AL85000

INTRODUCTION

Flooded cavity is a passive accident management concept under consideration for advanced light water reactors (ALWR) and the now deferred Heavy Water New Production Reactor (NPR-HWR); it is also under consideration for existing reactors (Jedruch 1992; Henry, et al. 1993a,b). By flooding the reactor cavity and immersing the reactor pressure vessel in water, in case of a core meltdown accident, the expectation is that boiling heat transfer outside of the bottom head will be efficient enough to dissipate the fraction of the decay heat of the molten core imposed of the bottom head, thus leading to a benign termination of the accident with the core retained in the reactor vessel.

The boiling process outside of the bottom head area is quite unique. It can be described as boiling from a large, downward-facing curved surface. For boiling from upward facing surfaces, vapor can rise away from the surface by buoyancy. The dominant scale is the bubble size which is an intrinsic surface tension scale typically measured in centimeters. In the case of downward-facing surfaces, the bubbles, or slugs of vapor, have to traverse the entire surface to the edge of the surface. Therefore, in addition to the surface tension scale, the body scale may also be important. In this case the vapor generation upstream may affect the boiling process downstream (Chu, et al. 1992). The curved surface also introduces the effect of changing inclination.

According to the classical study of Nishikawa et al. (1984), at high heat fluxes (> 17 W/cm^2), nucleate boiling is essentially independent of surface inclination. However, critical heat flux (CHF) was found to decrease monotonically with inclination (0^o: upward-facing, 180^o: downward-facing) (Guo and El-Genk, 1991; Vishnev et al., 1976; Beduz et al., 1988). Anderson and Bova's experiment (1971) in R-11 also found that the critical heat flux varied inversely with surface dimension for dowanward-facing circular disks. While the result of these small scale experiments suggest reasons for concern, other more recent experiments give rather encouraging results. The integral experiments of Henry et al. (1993a) demonstrated that subcooled nucleate boiling heat flux from a 30 cm diameter curved surface exceeds 100 W/cm^2. Steady state experiments by Kymalainen et al. (1992) and quenching experiments by Chu et al. (1994) showed that the critical heat flux from downward-facing surfaces is in the range of 50 W/cm^2. These values are quite favorable as compared to the estimated heat dissipation requirement of 10-20 W/cm^2 by Henry et al. (1993a).

Because the success or failure of in-vessel retention has a profound effect on the progression of severe accidents, it is essential that there be a solid, technical understanding of large-scale, downward-facing , boiling heat transfer before risk assessments or safety qualifications can credit a flooded cavity with ensuring in-vessel melt retention. But since there is no analytical model to extrapolate existing data, large-scale testing is the only viable way for confirmatory testing. For this reason the DOE New Production Reactor Program funded Sandia National Laboratories to develop a reactor-scale facility and to perform confirmatory testing of the effectiveness of boiling heat transfer of the flooded cavity design for NPR-HWR. The facility is named CYBL, CYlindrical BoiLing facility. Despite the indefinite deferral of the NPR-HWR program Department of Energy, Office of Nuclear Energy (DOE-NE) continues to sponsor the testing program because of the importance of CYBL in ALWR applications.

THE CYBL TEST FACILITY

The CYBL test apparatus is basically a tank-within-a-tank (Figure 1). The inner tank simulates the reactor vessel and the outer tank simulates the flooded reactor cavity. The cavity between the two tanks is flooded with water. Energy deposition by the molten core on the reactor vessel bottom head is simulated using a radiant heat lamp array. There are windows on the side and bottom to observe the boiling process. The test fixture is installed over an observation pit and housed in a three story metal building.

The outer tank is made of 0.96 cm thick, 316 L stainless steel, is 5.1 m in diameter and 8.4 m high. The inner tank or the test vessel is 3.7 m in diameter and 6.8 m high (the diameter of a typical ALWR is about 4 m). The test vessel has a torispherical bottom head conforming to the contour of the NPR reactor vessel. The major (or crown) radius of the bottom head is 3.3 m; the minor (or knuckle) radius is 0.66 m. The cylindrical section of the test vessel is made of 1.3 cm thick 316L stainless steel, and the head is formed from 1.6 cm thick 316L stainless steel, with final thickness no less than 1.3 cm. The inside of the bottom head is coated with Pyromark^{R} black paint (for radiation absorption) with a nominal absorptivity of 0.9, and the inside of the cylindrical section is insulated. With the tank-within-a-tank design, a test vessel of a different head shape can easily be installed if such a need arises.

CYBL has fifty-one observation ports with radius of 30 or 60 centimeters. In addition, there are a large number of instrumentation ports, (Figure 2).

The radiant lamp array is assembled from twenty heating panels. Each panel measures 0.3 m by 1.2 m, consisting of a flat aluminum reflector and two bus bars for installing up to sixty three 480 V, 6 kW linear quartz lamps. The reflector and the bus bars are water cooled. The panels are organized into twelve individually controlled heating zones. Currently, the lamp panels are mounted flat and positioned 0.9 m above the vessel bottom; level with the upper rim of the bottom head. The panels can also be coarsely contoured to the shape of the test vessel. By adjusting the power input to each zone, the density of lamps on each heating panel and the array configuration, the heat flux distribution on the bottom head can be customized to the needs of the experimenter. The maximum local flux was experimentally determined to be approximately 40 W/cm^2. The power for lamp array comes from the Radiant Heat Facility at Sandia. The maximum available power is 4.3 MW, but it can be upgraded to 6 MW. A set of water cooled cables are used to deliver power as well as cooling water to the lamp array.

A water purification system with a storage tank provides the de-ionized water for the experiment. The resistance of the test water is typically at 4-6 mega-ohm/cm. The water is kept in a storage tank when not in use. The steam generated by the experiment is vented by two 20 cm steam pipes into a water cooled condenser. The condensate is re-heated in a collection tank using a 72 KW immersion heater and returned to the test fixture.

The water for cooling the lamp panels and the condenser comes from a 1.2 million liter reservoir tank. A turbine pump delivers the cooling water at a maximum rate of 4000 liters per minute.

The data acquisition system has three-hundred channels, one-hundred of which can be scanned at a rate of one cycle per second. These fast channels monitor the vessel surface temperature and the cooling water flow rates and temperature. The computers can "scram" the lamp array within one second if there is any indication of departure from nucleate boiling or loss of coolant to the lamp panels.

There are two-hundred and fifty thermocouples to measure the vessel and water temperature. Local heat fluxes are calculated from temperature gradients in the vessel wall.

The power to each heating zone is monitored, recorded and controlled by computers. Pressure, flow rates, and temperatures required for mass and energy balance are also measured. Heat flux, temperature, power and other key parameters of the experiment are displayed in real time to allow the experiments to be run interactively. A 10-camera video system monitors and records the boiling process.

Flow visualization using dye injection, particle tracking, and optical methods are possible. Gamma ray desitometry equipment is available for use.

Construction of CYBL started in October 1992. It took about four months. Support systems and instrumentation took another two months. Shakedown tests were conducted between April and June of 1993, with maximum heat flux up to 8 W/cm^2. Two NPR experiments were performed in July of 1993.

NPR EXPERIMENTS

The required heat dissipation rate for NPR has been estimated at 16 W/cm^2 (Jedruch, 1992); therefore, the two experiments were performed at this heat flux. The first, NPR-A, is a uniform heat flux test at 16 W/cm^2. The second test, NPR-B, has an average heat flux of approximately 16 W/cm^2 but with an edge to center heat flux ratio of approximately two to simulate melt convection effects. The experimental results will be presented in two sections: (1) heat transfer results, and (2) observation of the boiling process.

NPR Experiment Heat Transfer Results

Plotted in Figure 3 is heat flux versus arc distance along the bottom head surface for the uniform heat flux case (NPR-A). Arrays A/B and E/F are two orthogonal thermocouple arrays on the bottom head. The crown region (the gently curved central region) of the bottom is from 0 cm to 146 cm, and the knuckle region (the sharply curved region) of the bottom head is from 146 cm to 218 cm. The heat flux is uniform over the entire crown surface, and there is a gentle drop of 30% to within 10 cm of the rim of the bottom head.

The surface temperature distribution for NPR-A is shown in Figure 4. The highest temperature is in the bottom center region. The temperature drops from approximately 123°C at the bottom center to approximately 120°C over an arc length of 150 cm.

The average bulk water temperature, as measured by five thermocouples located 15 cm from the bottom head, in an arc following the contour of the bottom head is 98.9^{o}C. The saturation temperature corresponding to the pressure at the bottom head area is at 109^{o}C. Therefore, the bulk water is subcooled by 10^{o}C. This subcooling is mainly the result of pressure increase corresponding to the 5 meters of gravity head above the bottom head area. The increase in saturation temperature corresponding to the pressure increase is actually 12 degrees. The slightly lower subcooling (from 12^{o} to 10^{o}C) is probably due to density driven convective mixing as well as condensation. This subcooling effect is a scale related effect that can only be observed in large-scale. As shown in later sections, this subcooling has a significant effect on the boiling process.

Plotted in Figure 5 are the heat flux distributions for the the "edge-peaked" experiment (NPR-B). The heat flux varies from 8-10 W/cm^{2} in the center to over 16 W/cm^{2} near the edge, a heat flux ratio of approximately two. In this case, the center temperature reduces to 120^{o}C and the edge temperature increases by about one degree (as compared to the uniform heat flux case), (Figure 6).

With only two experiments it is difficult to determine the best method to correlate the boiling data. Shown in Figures 7 and 8 are two possibilities. In Figure 7, the heat transfer coefficient, h_b, is calculated using the surface-to-bulk temperature difference. In Figure 8, the heat transfer coefficient, $h_{s,bc}$ is calculated using the surface-to-saturation temperature difference; the subscript bc indicates that the reference saturation temperature used corresponds to the value for the <u>b</u>ottom-<u>c</u>enter location. It appears that with either definition, the heat transfer coefficient increases with arc distance. It is also interesting to note that the heat transfer coefficient for the two heat flux distributions are quite similar. Despite a factor of 2 change in heat flux in the center bottom area, the heat transfer coefficient varied by no more than 10%. The interpretation of these trends must await more extensive data as they are obtained and examined.

For the 16 W/cm^{2} uniform heat flux test, the surface temperature excess (over the local saturation temperature) at bottom center is about 14^{o}C. This value is in good agreement with our previous data from quenching 61-cm disks (Chu et al., 1994) and the data of Nishikawa et al. (1984). However, the observed improvement of heat transfer with increasing inclination (distance) is opposite to the trend of the Nishikawa experiment.

Observations of the Downward-Facing Boiling

An examination of the video record of the experiments indicates that the boiling process near the bottom center is cyclic in nature, having four distinct phases: direct liquid/solid contact, bubble nucleation and growth, coalescence, and vapor mass dispersion (ejection). Because of the axi-symmetrical configuration, the flow patterns are axi-symmetric. The coalescence of bubbles produces a vapor patch of tens of centimeters in diameter in the bottom center area, (Figure 9a). The dispersion of this vapor mass first takes the form of an expanding flat ring, (Figure 9b), rising along the surface. However, eventually the configuration becomes unstable and the ring thickens and breaks into smaller arc segments. The broken vapor segments condense in the surrounding subcooled water leaving essentially no trace. The radial location of this condensation zone is quite well defined; the corresponding radius increases with heat flux. As a result, the boiling process beyond the condensation zone is to a large degree decoupled from the cyclic pulsation of the bottom center region, and is observed to be essentially steady in nature. Furthermore, because of the condensation process, possible effects that may arise (for example, vapor-blanketing) due to the accumulation of upstream vapor generation may be reduced.

CURRENT STATUS AND FUTURE ACTIVITIES OF CYBL

With the completion of the NPR experiments, the CYBL facility came under the sponsorship of DOE-NE. In July DOE-NE sponsored a workshop to solicit input for a testing program for CYBL with participants from industry, universities, DOE, and NRC (Nuclear Regulatory Commision). The result is a DOE-NE sponsored series of experiments in support of the ALWR program with tests in the range of 20 W/cm^2. This is the currently estimated heat flux required for ALWR applications (Henry et al., 1993a). These experiments are expected to be completed in the first half of 1994.

The section presents a brief discussion of other possible activities in support of the flooded cavity applications. The activities can be divided into two categories: (1) baseline design data, and (2) design and operation specific issues.

Experiments that will contribute to the development of basic design data include

A. Basic Heat Transfer Data
These experiments are currently being performed at CYBL with heat flux ranging up to 20 W/cm^2, both uniform heat flux and "edge-high-center-low" experiments.

B. Effect of Water Level
Water level is likely to be an important variable in view of the observed gravity head subcooling effects. This is especially important for potential LWR applications, because for some LWRs the amount of water for flooding may be limited.

C. Heat Flux Distribution due to Melt Convection
Current understanding of high Rayleigh number convection is limited. However, research in this area is progressing with numerical simulation sponsored by NRC and NSI (Russian Academy of Sciences), and experimental data from the COPO and Rasplav experiments (CSNI, 1993). There may be a need for new experiments incorporating these results.

D. Model Development Experiments
Some experiments with parameters outside of the range of applications that might nevertheless contribute to a more complete picture of the downward-facing boiling problem may also be useful. One example would be the "center-high-edge-low" heat flux boundary condition. There is currently NRC supported work at Pennsylvania State University on downward-facing boiling at 1/10th reactor scale. There might be area where complementary experiments can be performed to understand the scaling problem.

There are also design and operation specific issues that are best studied in large-scale:

A. The effect of vessel penetration

B. Steam Relief
Reactor vessel insulation and in the case of Boiling Water Reactors, the vessel skirt may trap vapors unless properly designed for steam relief.

C Boiling Enhancement Features
Henry et al. (1993b) suggest the use of flow diversion baffles to improve the boiling process. NSI (Anfinogenov et al., 1993) studies propose the use of surface features to enhance boiling heat transfer outside of the reactor pressure vessel bottom head.

D. Sub-cooling and Re-circulation Path Effects

E. Bottom Head Curvature Effects
U.S. reactors have hemispherical heads whereas some Russian and Finish designs have torispherical heads.

SUMMARY

The need for reactor-scale confirmatory research of the flooded cavity accident management strategy has been described, and the suitability of the CYBL facility is illustrated. The first set of experiments at CYBL showed that the NPR flooded cavity is a viable design.

The NPR experiment shows that the boiling process outside the bottom head is "subcooled nucleate boiling." The subcooling is largely due to the gravity head of the water above the bottom head. The degree of subcooling is somewhat modified by the interactions between the boiling process and the convective flow in the flooded cavity.

The boiling process in the bottom center region of the bottom head is found to be rhythmic in nature. The rhythmic central region is decoupled from the outer region due to the condensation of the dispersed vapor masses from the central region. The limited data obtained thus far indicate that the bottom center region has the lowest heat transfer coefficient, and the heat transfer coefficient appears not to be a strong function of heat flux. However, these observations must be considered to be preliminary because of limited data.

The paper concludes with a discussion of possible confirmatory experiments that could be performed at CYBL in the areas of basic design data, and design and operation specific issues for the flooded cavity.

CYBL

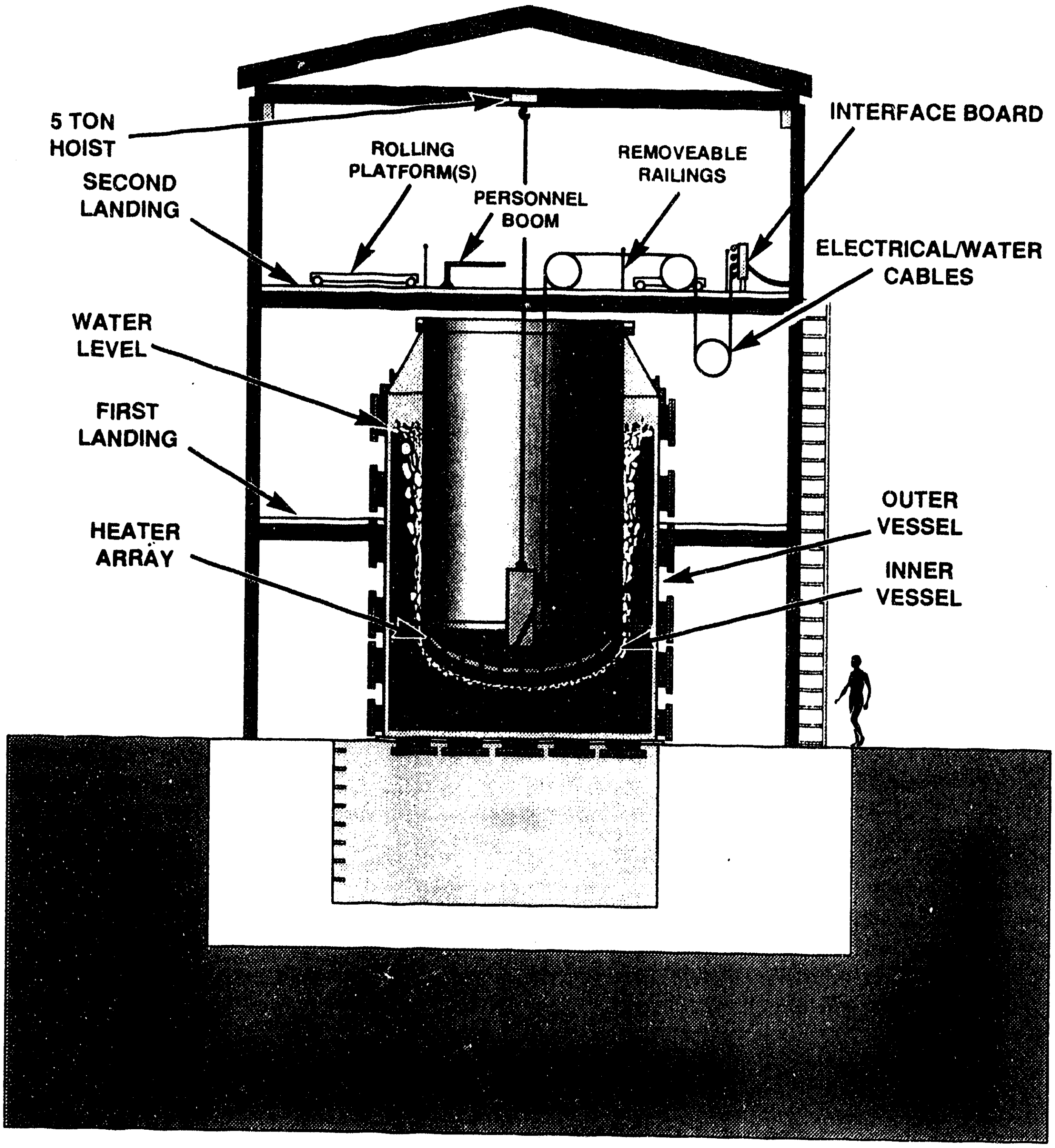


Figure 1. Schematic of CYBL

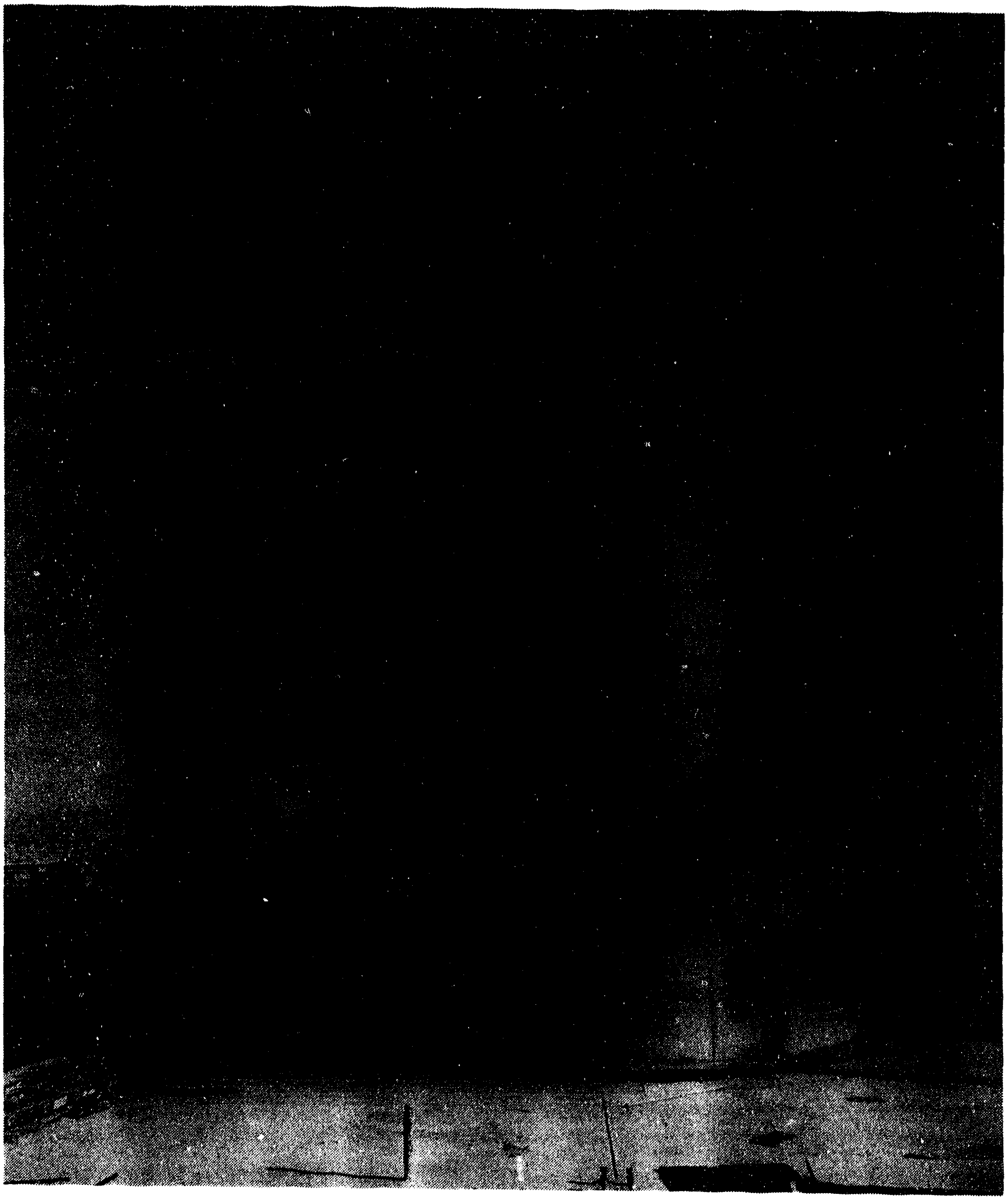
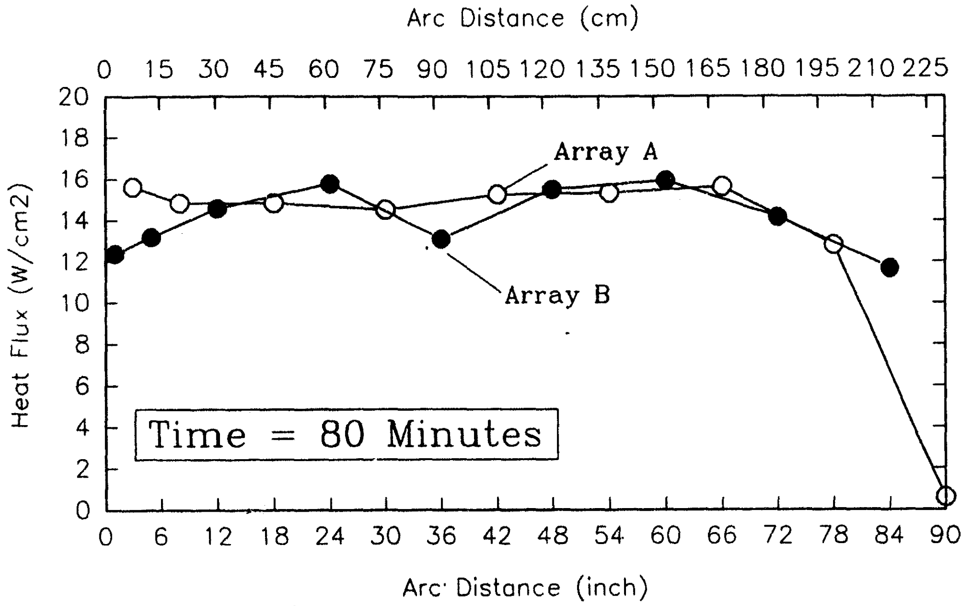


Figure 2. CYBL Test Vessel



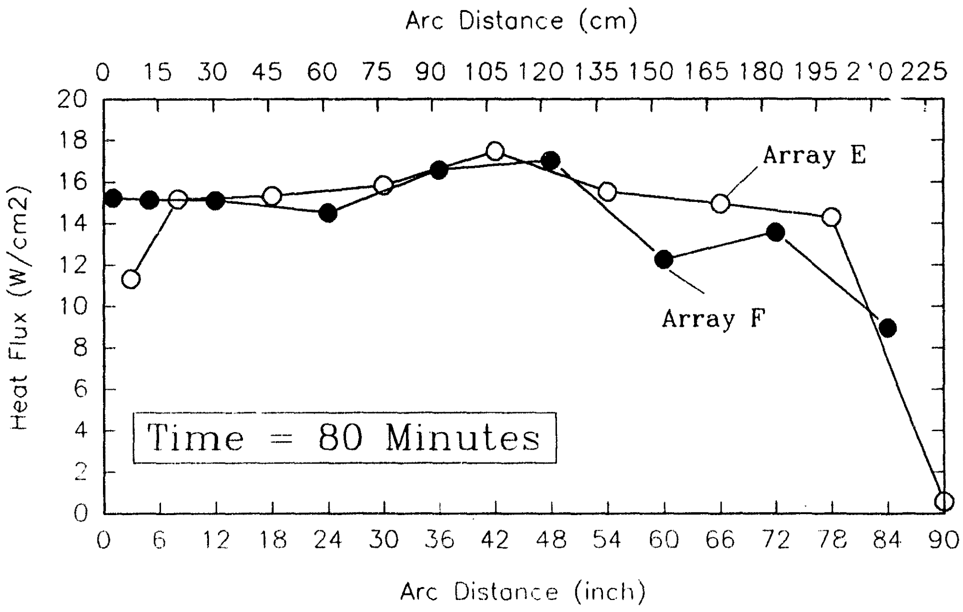
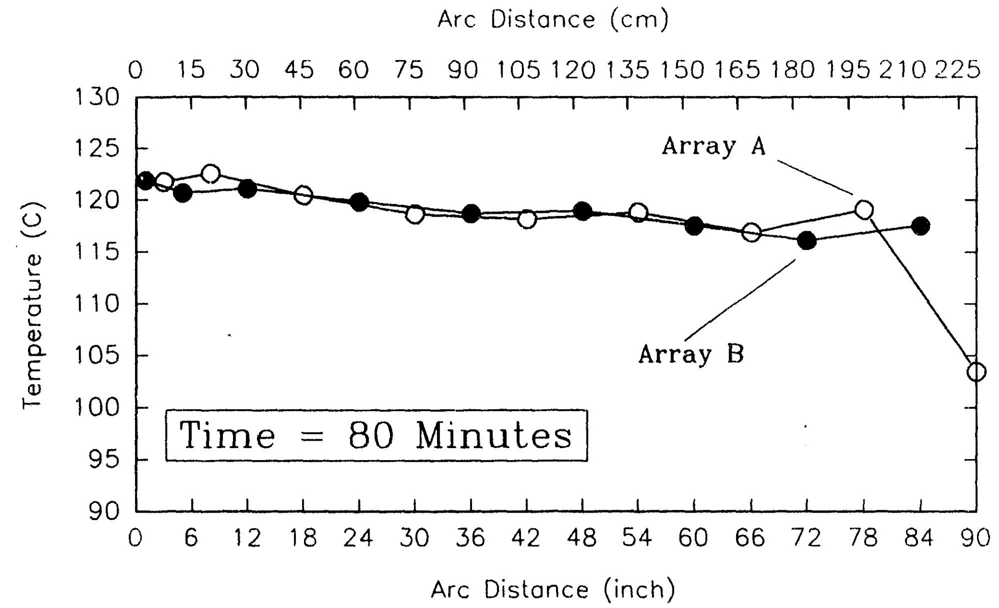


Figure 3. Surface Heat Flux Distribution, Arrays A/B and E/F Experiment NPR-A



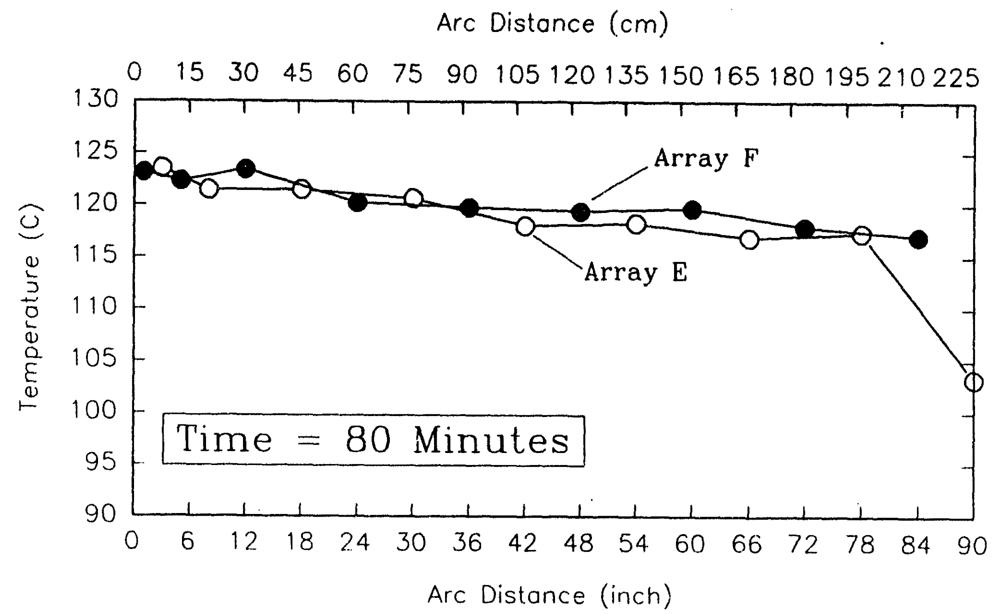
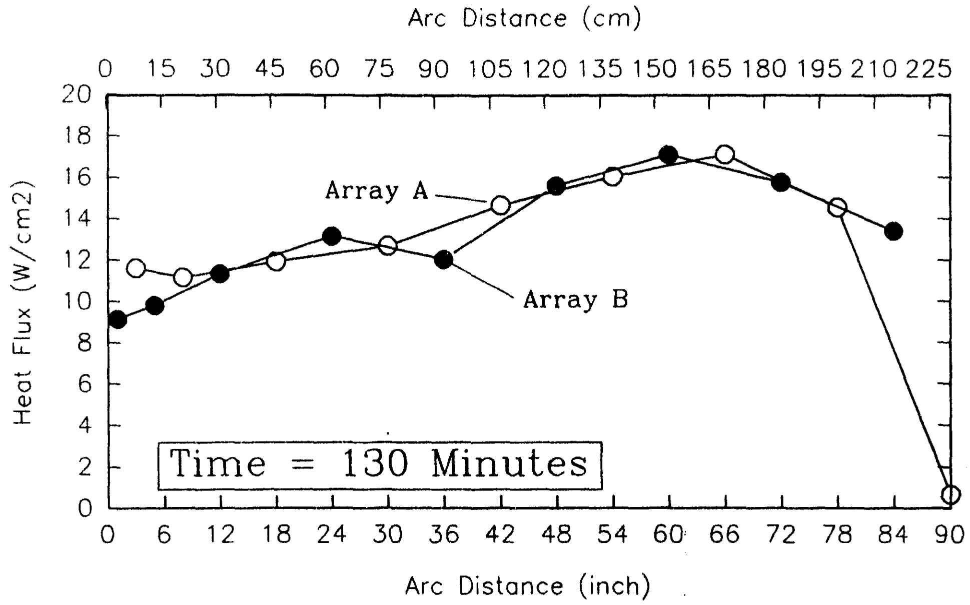


Figure 4. Surface Temperature Distribution, Arrays A/B and E/F Experiment NPR-A



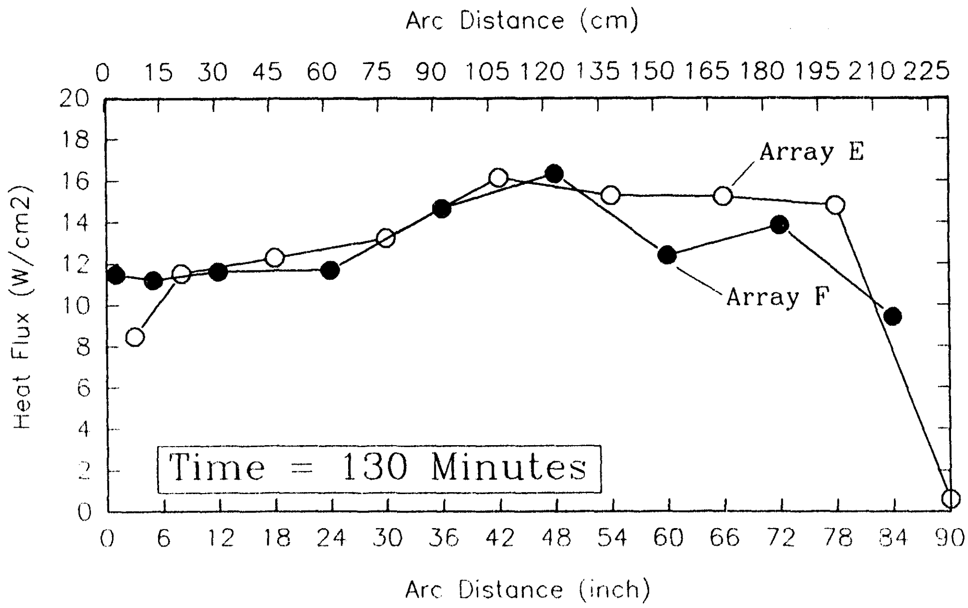
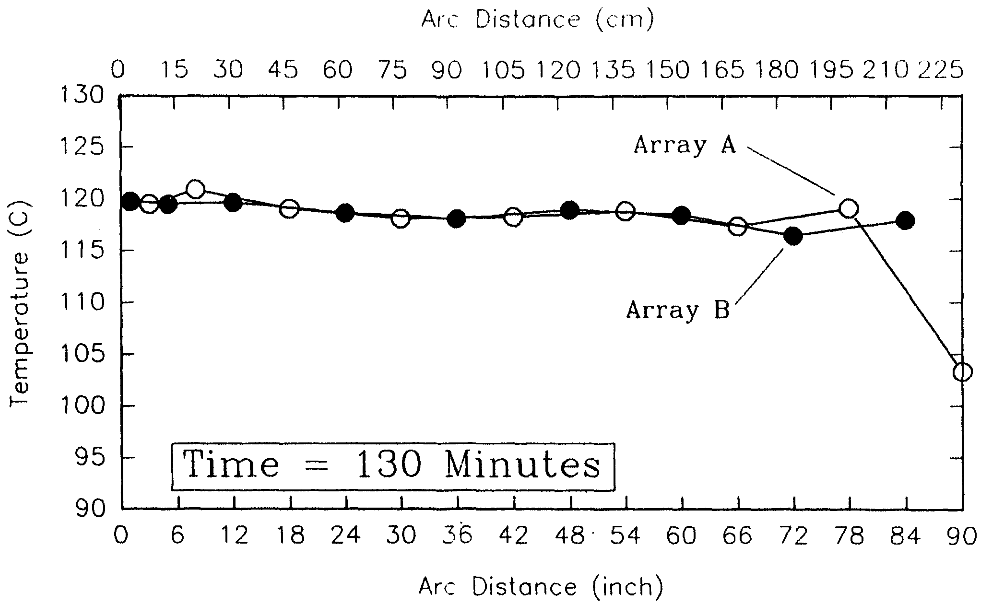


Figure 5. Surface Heat Flux Distribution Arrays, A/B and E/F Experiment NPR-B



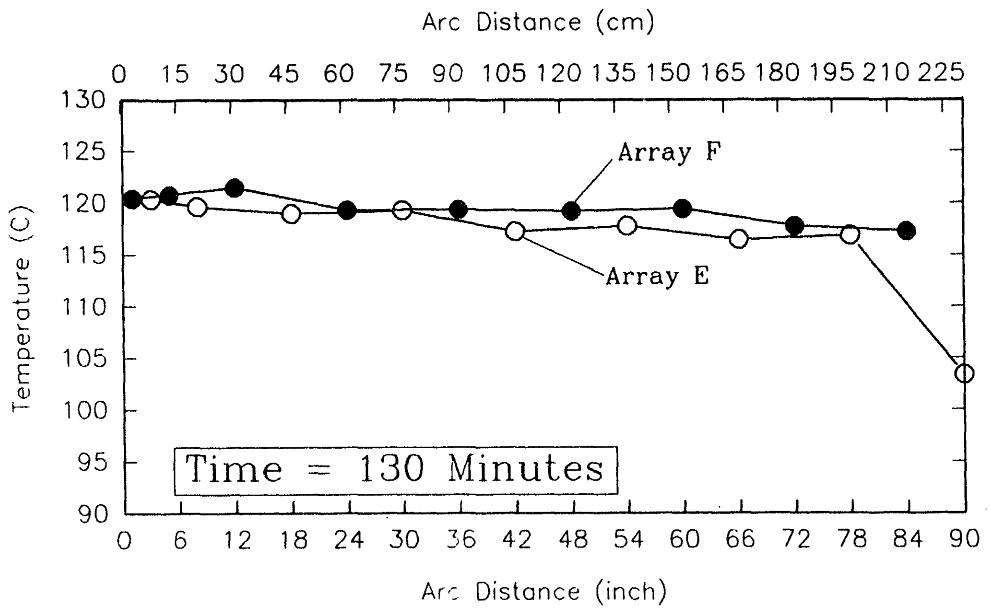


Figure 6. Surface Temperature Distribution Arrays, A/B and E/F Experiment NPR-B

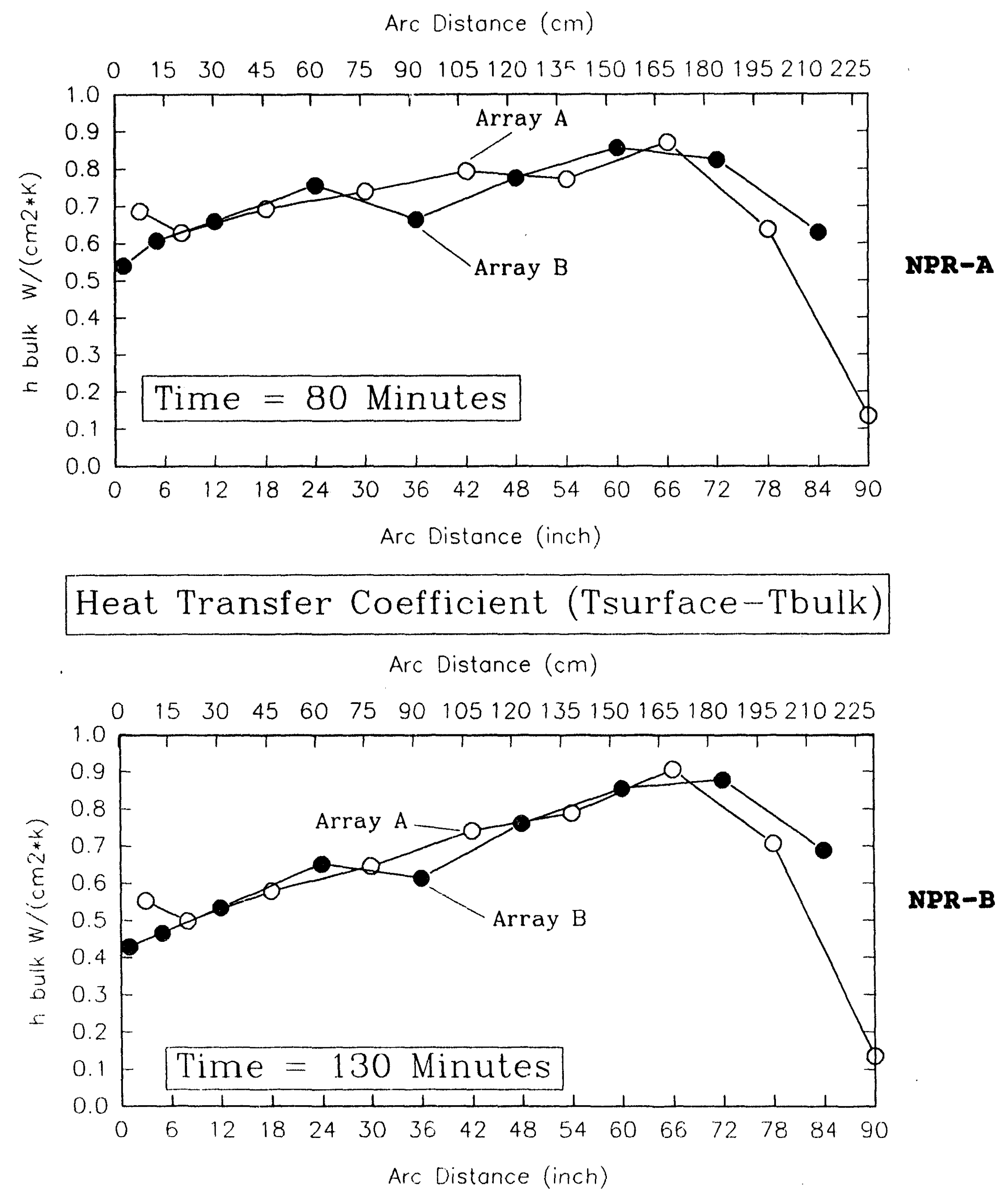


Figure 7. Heat Transfer Coefficient, h_{bulk} (Based on Surface Temperature Excess Over Bulk Temperature) NPR-A and NPR-B

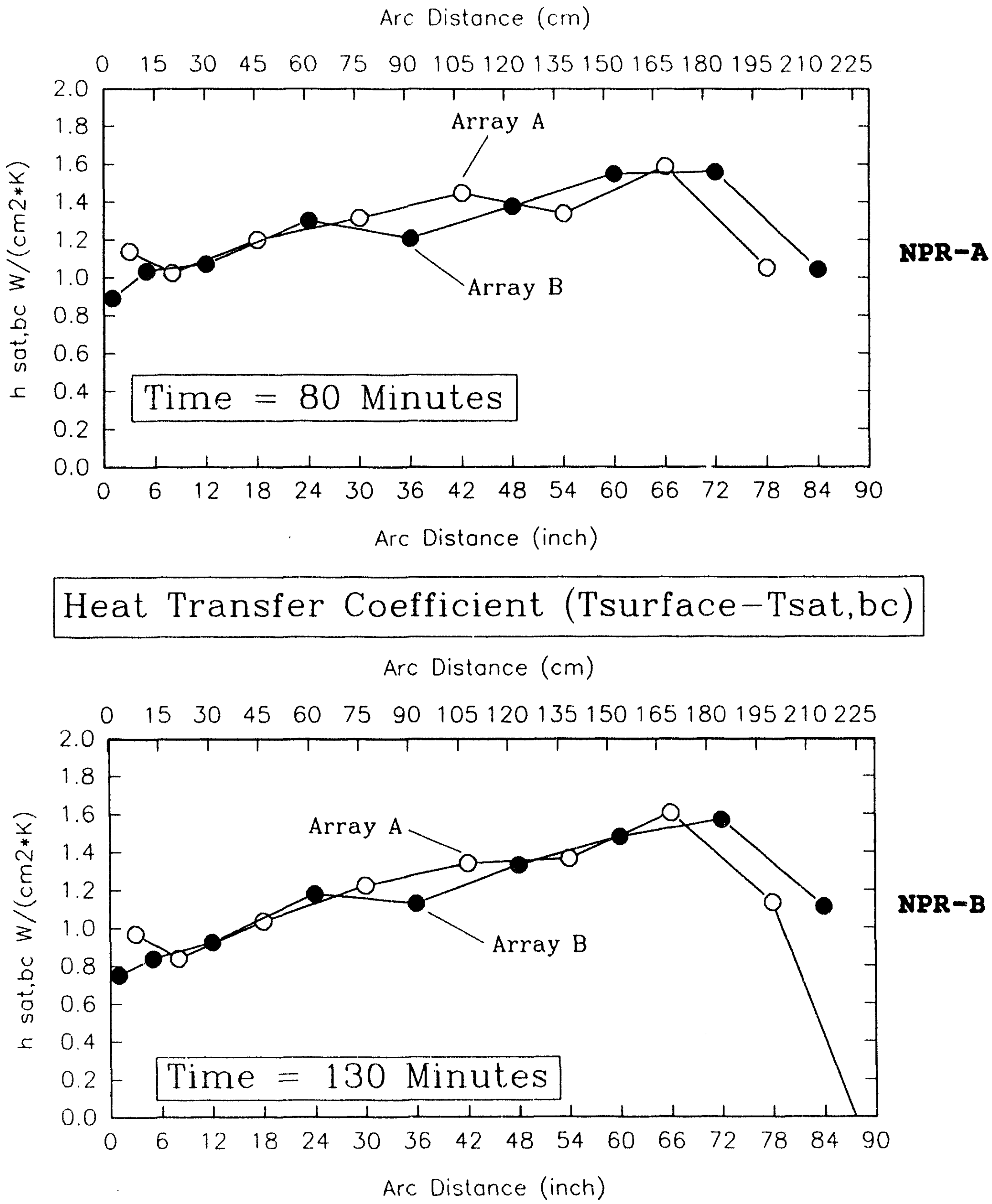
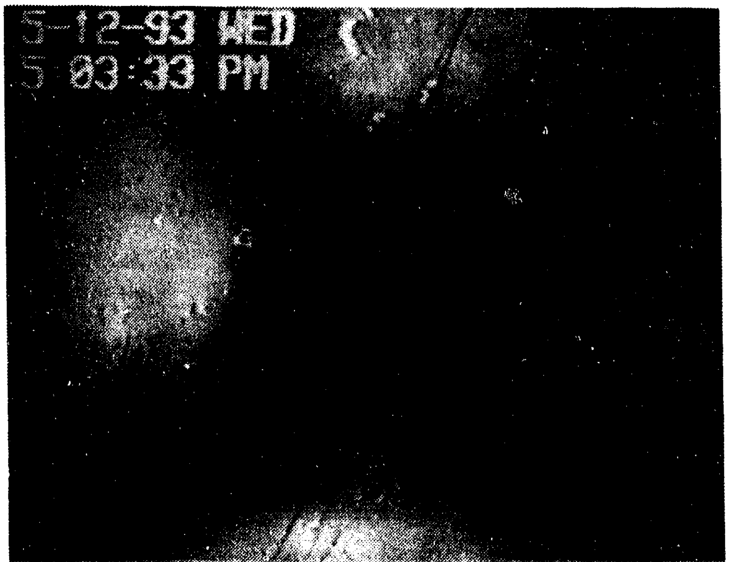


Figure 8. Heat Transfer Coefficient, $h_{s,bc}$ (Based on Surface Temperature Excess Over Saturation Temperature at Bottom Center) NPR-A and NPR-B



9a

9b

Figure 9. Example of Bottom Center Vapor Mass (9a) and Dispersed Vapor Ring (9b), 8-9 W/cm^2

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