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Experimental and Analytical Studies of Passive Shutdown Heat Removal Systems*

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Using a naturally circulating air stream to remove shutdown decay heat from a nuclear reactor vessel is a key feature of advanced liquid metal reactor (LMR) concepts developed by potential vendors selected by the Department of Energy. General Electric and Rockwell International continue to develop innovative design concepts aimed at improving safety, lowering plant costs, simplifying plant operation, reducing construction times, and most of all, enhancing plant licensability. The reactor program at Argonne National Laboratory (ANL) provides technical support to both organizations.

The method of shutdown heat removal proposed employs a totally passive cooling system that rejects heat from the reactor by radiation and natural convection to air. The system is inherently reliable since it is not subject failure modes associated with active decay cooling systems. The system is designed to assure adequate cooling of the reactor under abnormal operating conditions associated with loss of heat removal through other heat transport paths.

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Although calculations indicate the viability of this air-cooled shutdown heat removal, uncertainties remain with respect to particular designs. In addition, the effects of changing environmental conditions and material properties including surface emissivity on the performance of the air cooling system are not clearly understood. Thus, needed data are being gathered in the Natural Convection Shutdown Heat Removal Test Facility (NAT-SHRF) at ANL that simulates an air-side, full-scale, segment of the corresponding reactor system.

Test Requirements and Objectives

Early-on it was decided that a principal test requirement be that the facility simulate a full-scale segment of the reactor cooling system. This was done to avoid the need for similitude scaling laws that are often difficult to determine and thereby become controversial.

As shown in Fig. 1, the air cooling system consists of several concentric components with the reactor vessel being the innermost cylinder. The reactor vessel is surrounded by the guard vessel which also serves as containment for the advanced LMR. The space between the reactor vessel and the guard vessel is closed and is filled with an inert gas. Outside the guard vessel is a cylindrical structure referred to as the duct wall. Radial fins or repeated ribs can be attached to the duct wall and/or the guard vessel. Inlet air ducts provide for downward flow of air from the environment to the bottom of the reactor cavity where it turns and flows upward in the annular gap between the guard vessel and the duct wall. The fundamental objective of this test series is to provide a prototypic environment for the air-side from which thermal-hydraulic data, directly applicable to LMR designs, may be extracted.

Consistent with test objectives, and pretest analysis, the basic requirements and conditions for the experiments are established as:

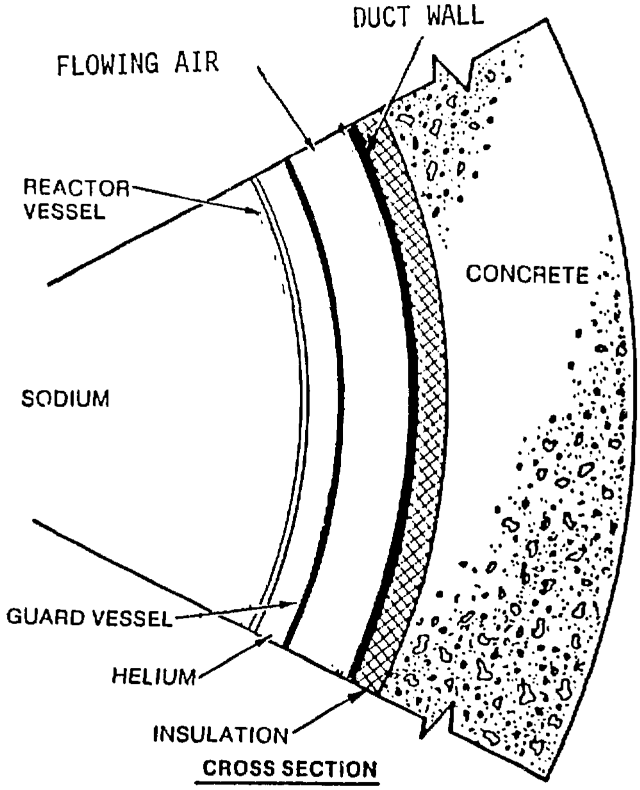


Figure 1. Cross Section of Air Cooling System

1. Geometrically simulate an air-side, full-scale, segment of a reactor system.
2. Provide capability for modes of operation that produce constant or variably controlled guard vessel wall temperatures up to 800 K (~ 1000°F), and either constant or variably controlled heat fluxes up to 21.5 kW/m^2 (2.0 kW/ft^2).
3. Simulate total velocity-head losses from a minimum coefficient (K) of ~ 1.5 to a maximum of ~ 20.
4. Achieve Reynolds Nos. in the range of Re = 0.25 - 1.50 x 10^5.
5. Provide variable gap widths of 152 mm (6-in.) to 457 mm (18-in.) between the guard vessel and duct wall.

Because, in the reactor, this system constitutes the ultimate heat sink for decay heat removal and is the only safety-grade system for that purpose, its viability must be demonstrated conclusively. Thus, it is of paramount importance that data derived from these tests be unequivocally applicable to the LMR design.

Description of the Facility

The NAT-SHRF comprises a structural model, electric heaters, instrumentation, insulation, and a computerized control and data acquisition system. Experiment operation simulates prototypic reactor guard vessel temperatures, air flow patterns, and heat removal conditions that would exist for a LMR during normal reactor operation and/or a shutdown situation. In general, the system will operate in either of two thermal modes: (1) constant guard vessel wall temperature to 800K (1000°F) or (2) constant heat flux to 21.5 kW/m^2 (2.0 kW/ft^2). In addition, the system will accommodate stepwise variation of either mode singly or in combination.

Mechanical Systems

Figure 2 illustrates the basic assembly configuration consisting of an inlet section, followed by a heated zone and an unheated stack. All sections, except the inlet, are thermally insulated to hold parasitic heat losses to 2 percent or less. The heated zone flow channel measures 1320 mm (52 in.) x 300 mm (12 in.) in cross section and is 6700 mm (22 ft.) tall. Provision is made to expand the 300 mm dimension up to 460 mm (18 in.) or reduce it to any desired value.

Above the heated zone the flow channel expands to 1520 mm (60 in.) x 460 mm (18 in.) and two flow paths are provided. The main path for the experiments is upward through a "S" curve and then vertically through the building roof. This provides a stack for natural convection nearly 15,200 mm (50 ft.) in vertical length. The top of the stack is 6100 mm (20 ft.) above the roof; this height was chosen to ensure the discharge is above recirculating winds caused by the building.

The second flow path contains a fan and damper; the fan motor is variable speed. This feature is provided for forced convection tests when the system is cold or at very low temperature and a controlled air flow rate is desired.

Within the heated zone, fins or transverse ribs may be installed on the inner walls. Currently, the design has neither, i.e. the guard vessel and duct wall simulator surfaces are simply smooth, 25.4 mm (1 in.) thick, carbon steel plates. Fins and/or ribs are intended for follow-on tests.

Figure 3 shows the partially assembled heated region. The large number of thermocouples and instrument ports are clearly evident.

Heater Control and Data Acquisition Systems

Figure 4 schematically illustrates the heater control and data acquisition systems for the facility. The heaters are driven by Silicon Controlled

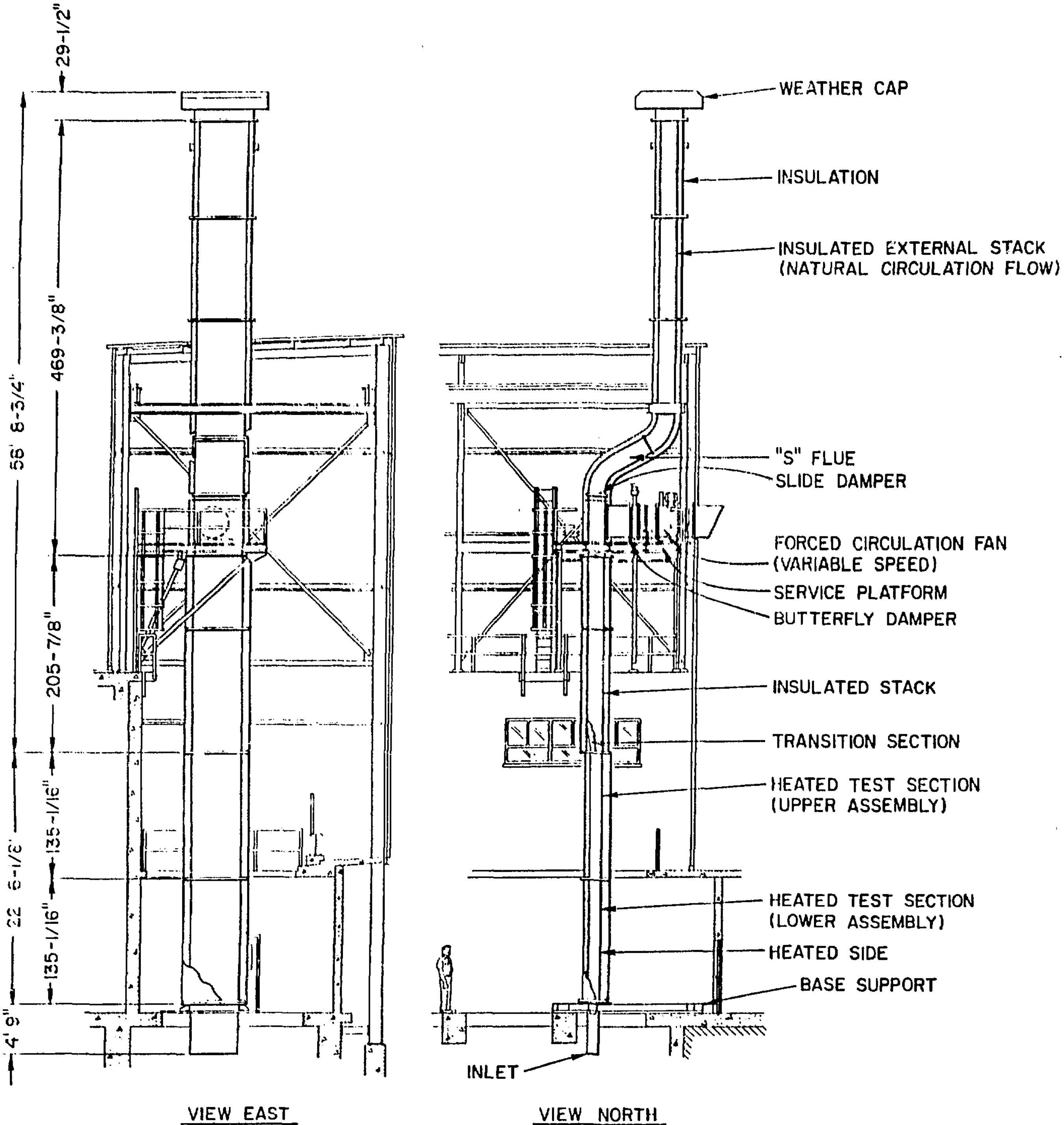


Figure 2. ANL NAT-SHRF Assembly Configuration

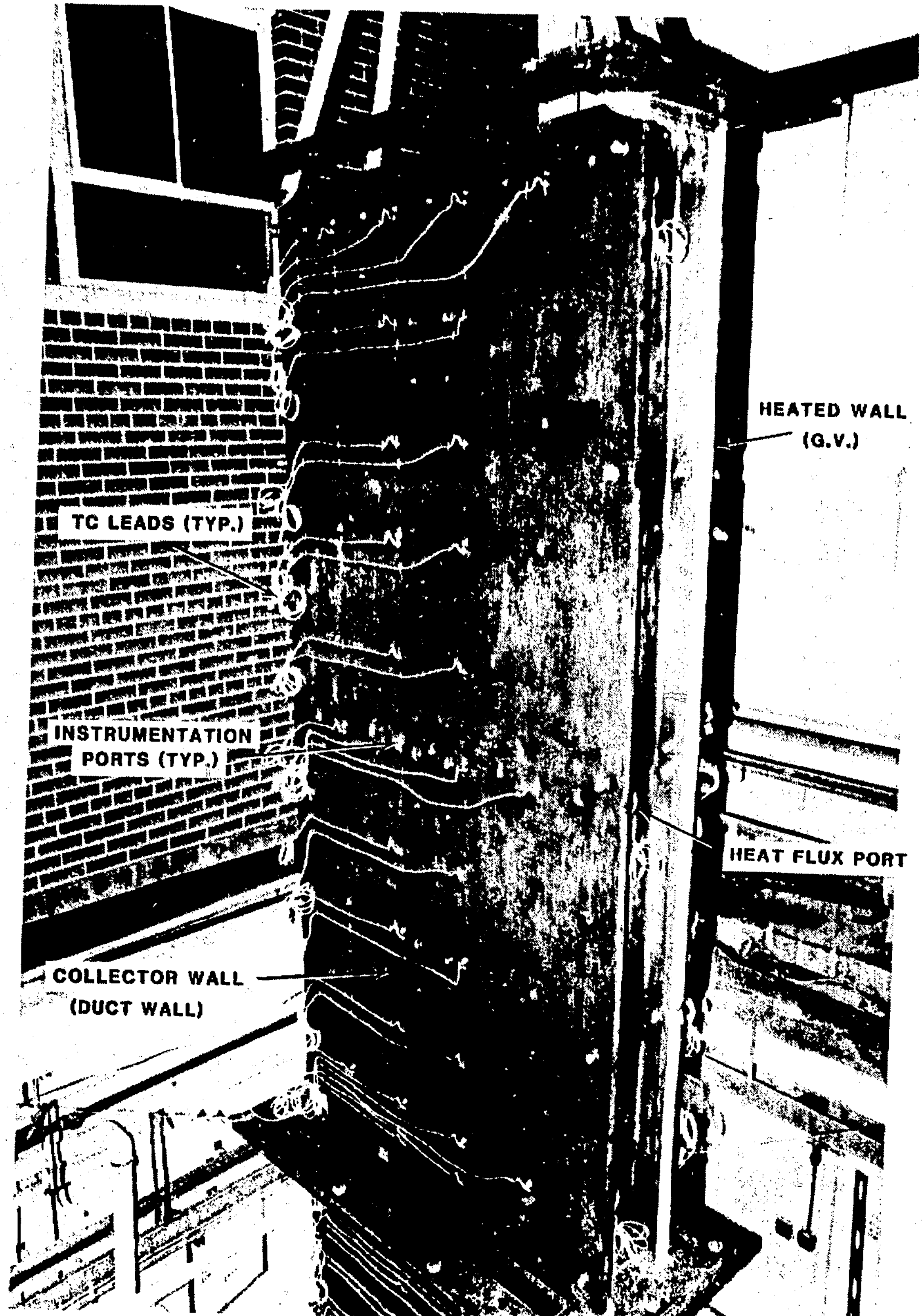


Figure 3. Partially Assembled Heated Zone

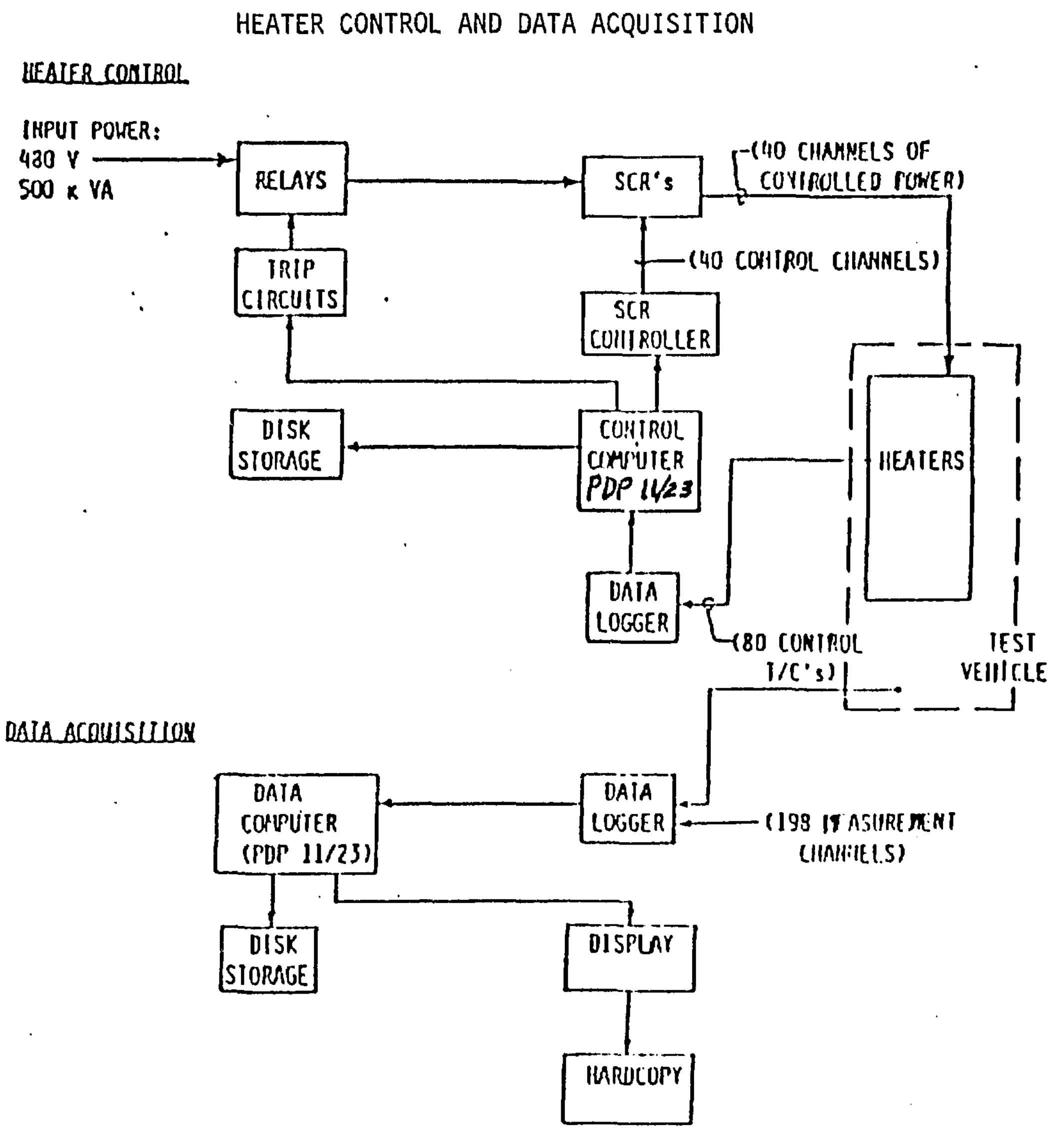


Figure 4. Heater Control and DAS System

Rectifiers (SCR's) under computer control based on signals from system thermocouples. As shown in Figure 5, the rectangular heaters, 300 mm (12 in.) x 150 mm (6 in.), are assembled in groups of twenty and mounted on a 6.4 mm (0.25 in.) thick stainless steel plate. Each such module comprises sixteen central heaters and four edge or "guard" heaters. Electrical power delivered to each of these regions is controlled separately thereby providing capability to compensate for temperature deviations at the edges of the guard vessel simulator. Ten such heater modules are attached to the exterior side of the guard vessel simulator that can provide uniform or variable sources of heat for the tests.

The data acquisition system (DAS) is capable of sampling 198 channels, most of which are dedicated to thermocouples located in the heated zone. The DAS stores all its data on disk and selected channels may also be displayed on CRT's and hardcopy. The computer has also been programmed to use on-line data in certain algorithms to compute system parameters that depend on multiple inputs.

Instrumentation

Instrumentation of the ANL NAT-SHRF is required to measure local surface temperatures, local and bulk air temperatures, local and bulk air velocities, and air volumetric and mass flow rates, the total normal radiative and convective components of the total heat flux, the electric power input to the heaters, and the local and total or bulk heat flux. These data will be used to evaluate the heat removal performance for particular configurations and testing conditions. The primary measurement objective is to determine the local and bulk heat flux transport rates and associated heat transfer coefficients.

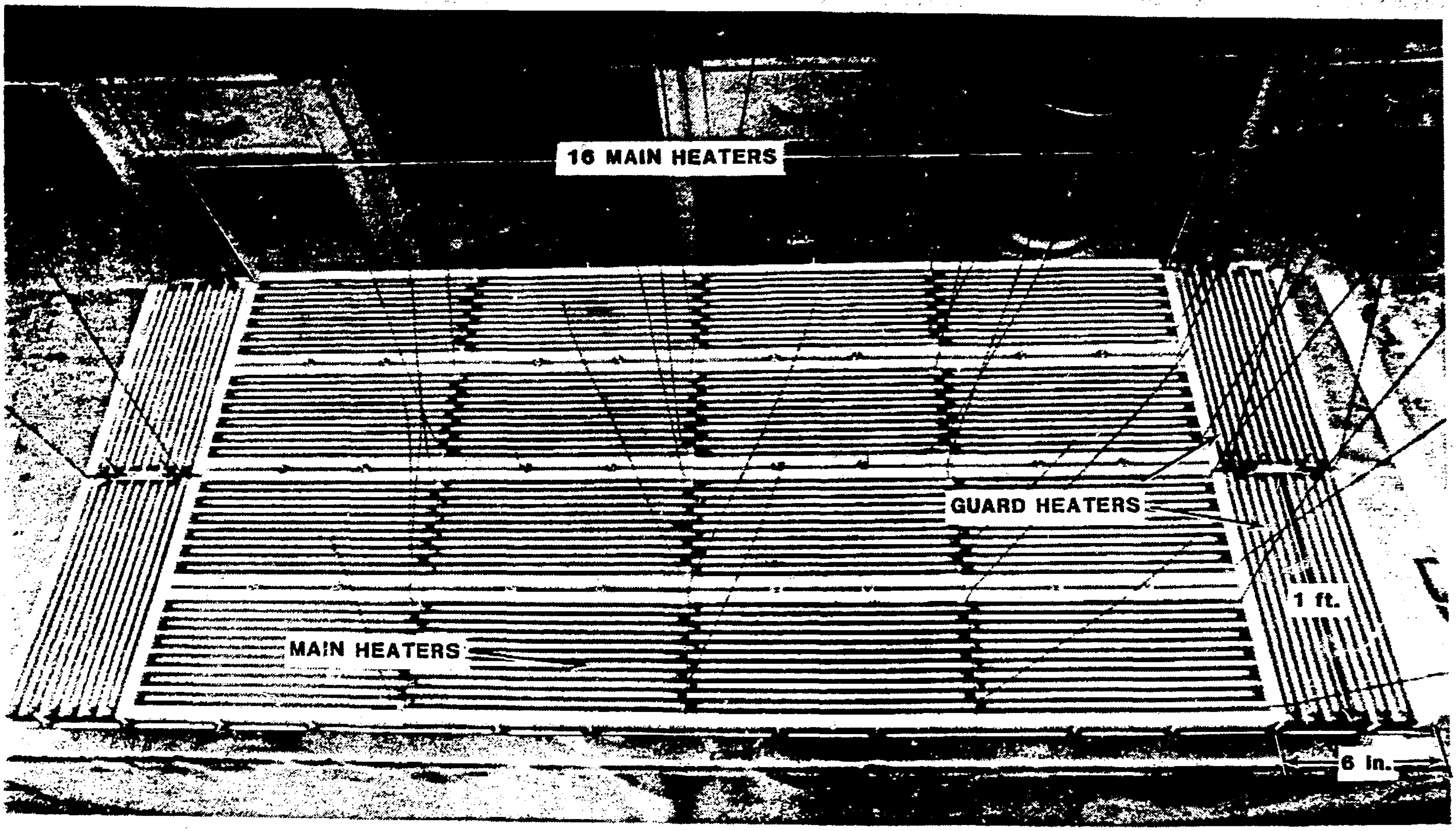


Figure 5. Heater Module

Accurate measurement data are required to determine the thermodynamic state and physical properties of the naturally convected air at various elevations. The fundamental properties of the air that must be accurately measured are the temperature and pressure. The basic instrumentation for those measurements will be radiation shielded thermocouples to measure the air temperature, and Pitot-static tubes used in conjunction with high accuracy differential pressure transducers to measure the differential pressure.

Thus, instrumentation consists of thermocouples, Pitot-static traversing probes, Pitot-static air flow rake, differential pressure transducers, radiation and heat flux transducers, a traversing mechanism, and a wind monitor and humidity instrumentation.

Pretest Analysis and Initial Operation

As stated earlier, the primary goal of these experiments is to provide passive heat removal performance data characteristic of the full-scale LMR design. The test assembly provides a prototypic simulation of a vertical section of the guard vessel wall and the surrounding duct wall. Pretest calculations and parametric studies have provided the predicted performance curves shown in Figures 6, 7, and 8. Verification of these analytical results will provide useful support of the primary experiment goal.

Part of the test operations strategy is based upon these analytical curves, i.e., the parametric values selected for test operations should fully characterize these curves. As indicated by perusal of these pretest results, the following ranges of the primary parameters have been selected for Phase I operations:

Temperature set points: 395K (250°F), 590K (600°F), and 755K (900°F)

System pressure losses: K = 1.5 to 20 (expressed as no. of velocity heads at test section inlet)

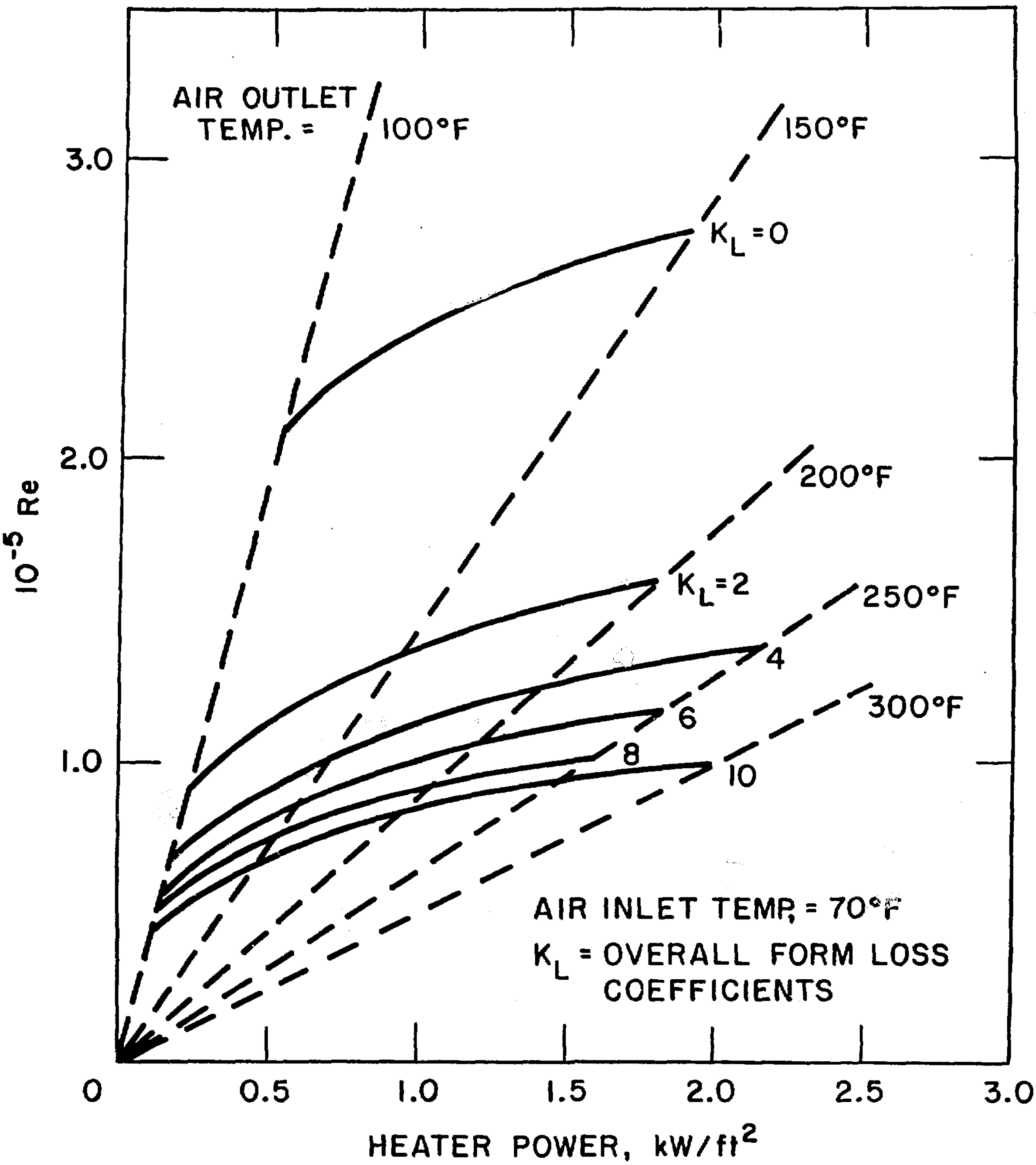
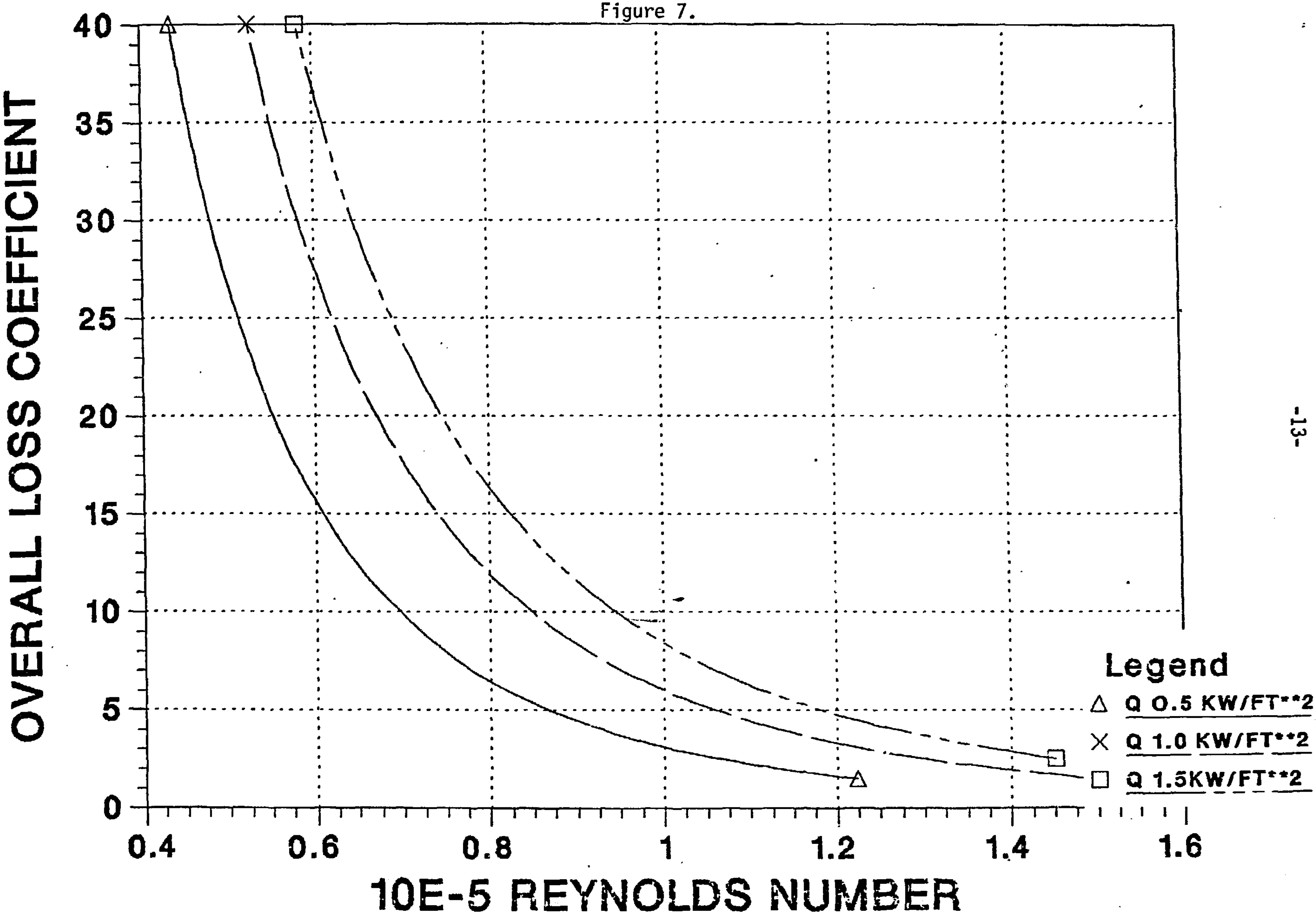


Figure 6. Test Assembly Performance Map

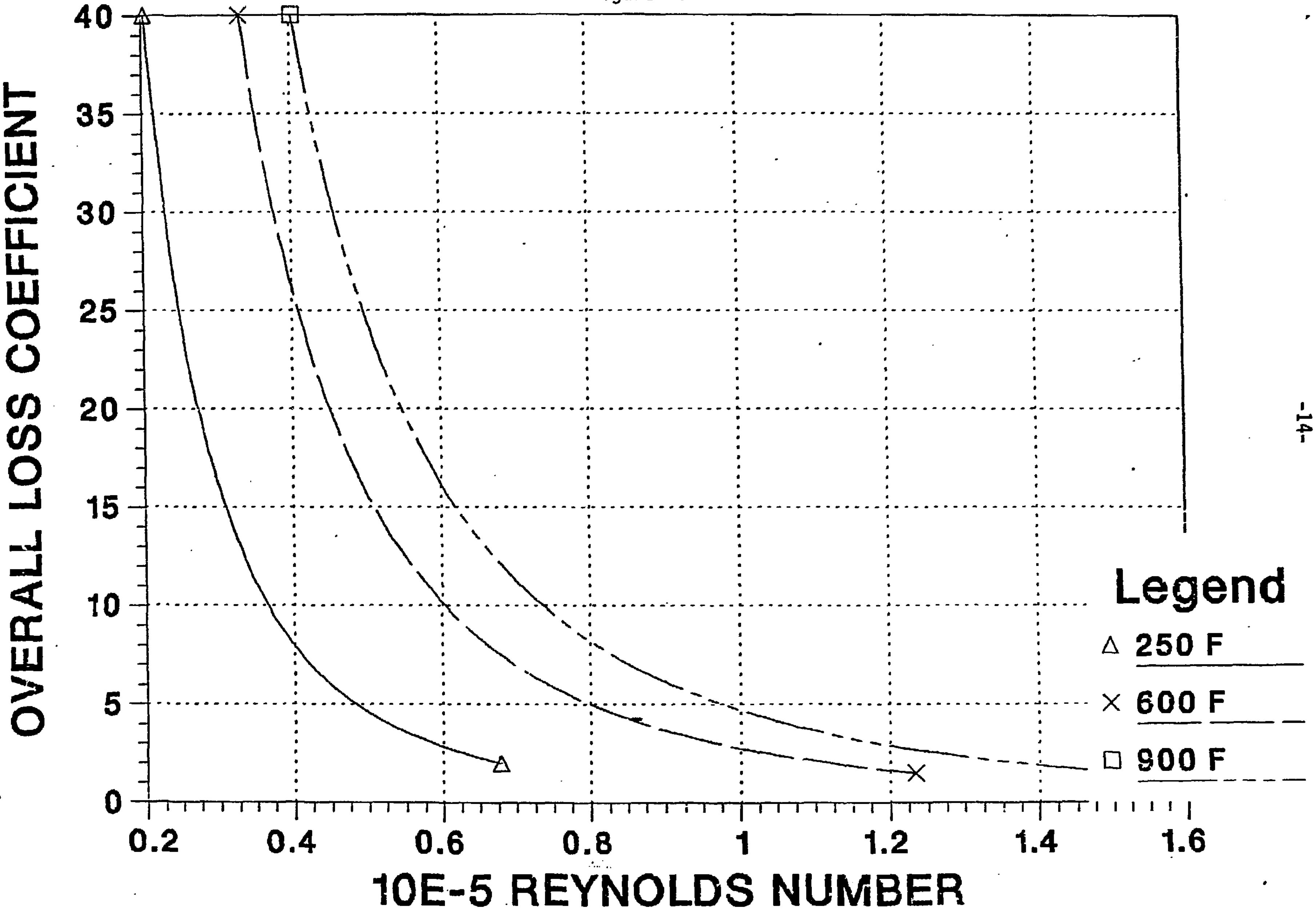
RVACS PERFORMANCE FOR VARIOUS VALUES OF APPLIED HEAT FLUX

Figure 7.



RVACS PERFORMANCE FOR
FOR VARIOUS GUARD VESSEL TEMPERATURES

Figure 8.



Power per unit area set points: 5.4 (0.5), 10.8 (1.0), and 16.1 (1.5) kW/m^2 (kW/ft^2)

Inlet Reynolds Number: 0.25×10^5 to 1.5×10^5

Following the initial checkout and bakeout operations, the Phase I operations are run in two main modes: (a) constant power (uniform heat flux) and (b) constant guard vessel surface temperature (because of the 10-zone incremental power control, this is actually a smoothed saw-toothed wave).

Power operation of the facility began November 23, 1986 and posttest analyses of the data are providing the needed end-point results including convective heat transfer coefficients, radiative components of heat transfer and air flow rates for varying environmental conditions.