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Experimental and Analytical Studies of a Passive Shutdown Heat Removal System for Advanced LMRs*

by

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ABSTRACT

A facility designed and constructed to demonstrate the viability of natural convection passive heat removal systems as a key feature of innovative LMR Shutdown Heat Removal (SHR) systems is in operation at Argonne National Laboratory (ANL). This Natural Convection Shutdown Heat Removal Test Facility (NSTF) is being used to investigate the heat transfer performance of the GE/PRISM and the RI/SAFR passive designs. This paper presents a description of the NSTF, the pretest analysis of the Radiant Reactor Vessel Auxiliary Cooling System (RVACS) in support of the GE/PRISM IFR concept, and experiment results for the RVACS simulation. Preliminary results show excellent agreement with predicted system performance.

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DISCLAIMER

INTRODUCTION AND SUMMARY

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 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 to 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.

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 (NSTF) at ANL that simulates an air-side, full-scale, segment of corresponding reactor systems, specifically the GE/PRISM and RI/SAFR IFR concepts.

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. 1-1, 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 or collector 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:

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 $Re = 0.25 - 1.50 \times 10^5$.
5. Provide variable gap widths of 152 mm (6-in.) to 457 mm (18-in.) between the guard vessel and duct wall.

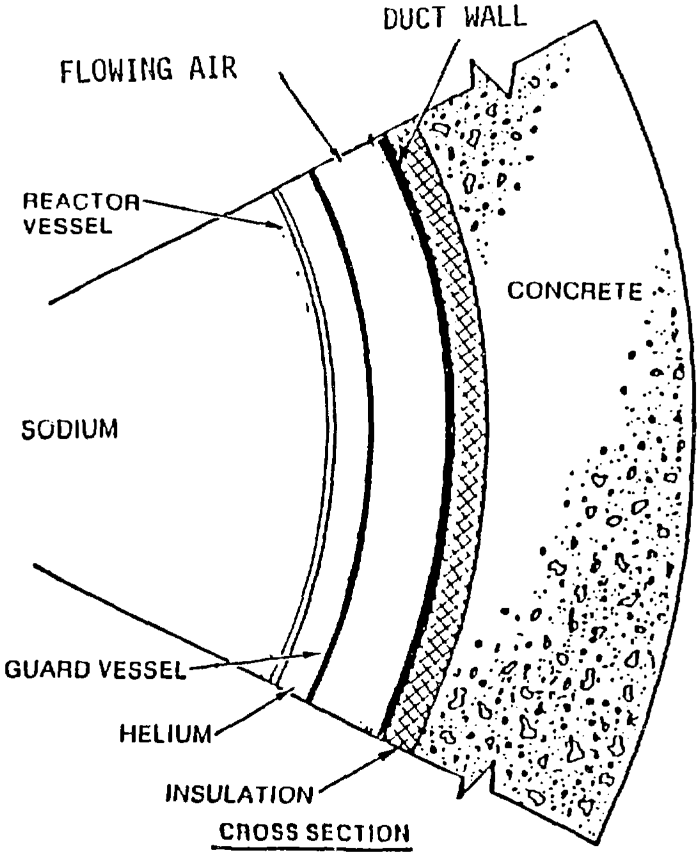


Figure 1-1. Cross Section of Air Cooling System

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 NSTF 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 (uniform) guard vessel wall temperature to 800K (1000°F) or (2) constant (uniform) 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 1-2 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

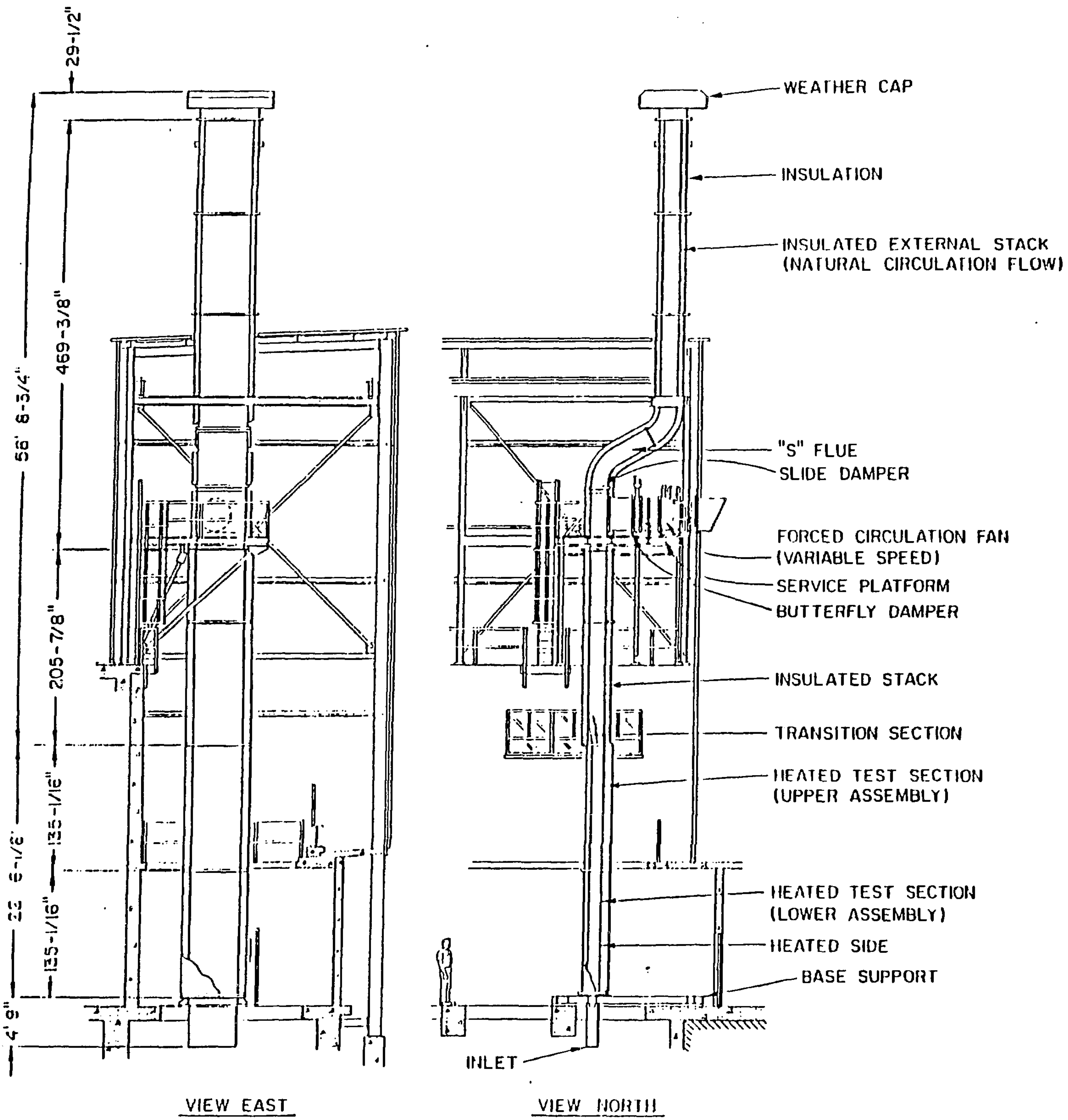


Figure 1-2 ANL NSTF Assembly Configuration

(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. The RVACS 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 installed on the duct wall will simulate one of the heat transfer enhancement designs for IFRs.

Figure 1-3 shows the partially assembled heated region. There are a large number of thermocouples and instrument ports available for measurements of temperature, pressure, and radiative flux at various axial and transverse locations.

Heater Control and Data Acquisition Systems

Figure 1-4 schematically illustrates the heater control and data acquisition systems for the facility. The heaters are driven by SCRs under computer control based on signals from system thermocouples. As shown in Figure 1-5, 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.

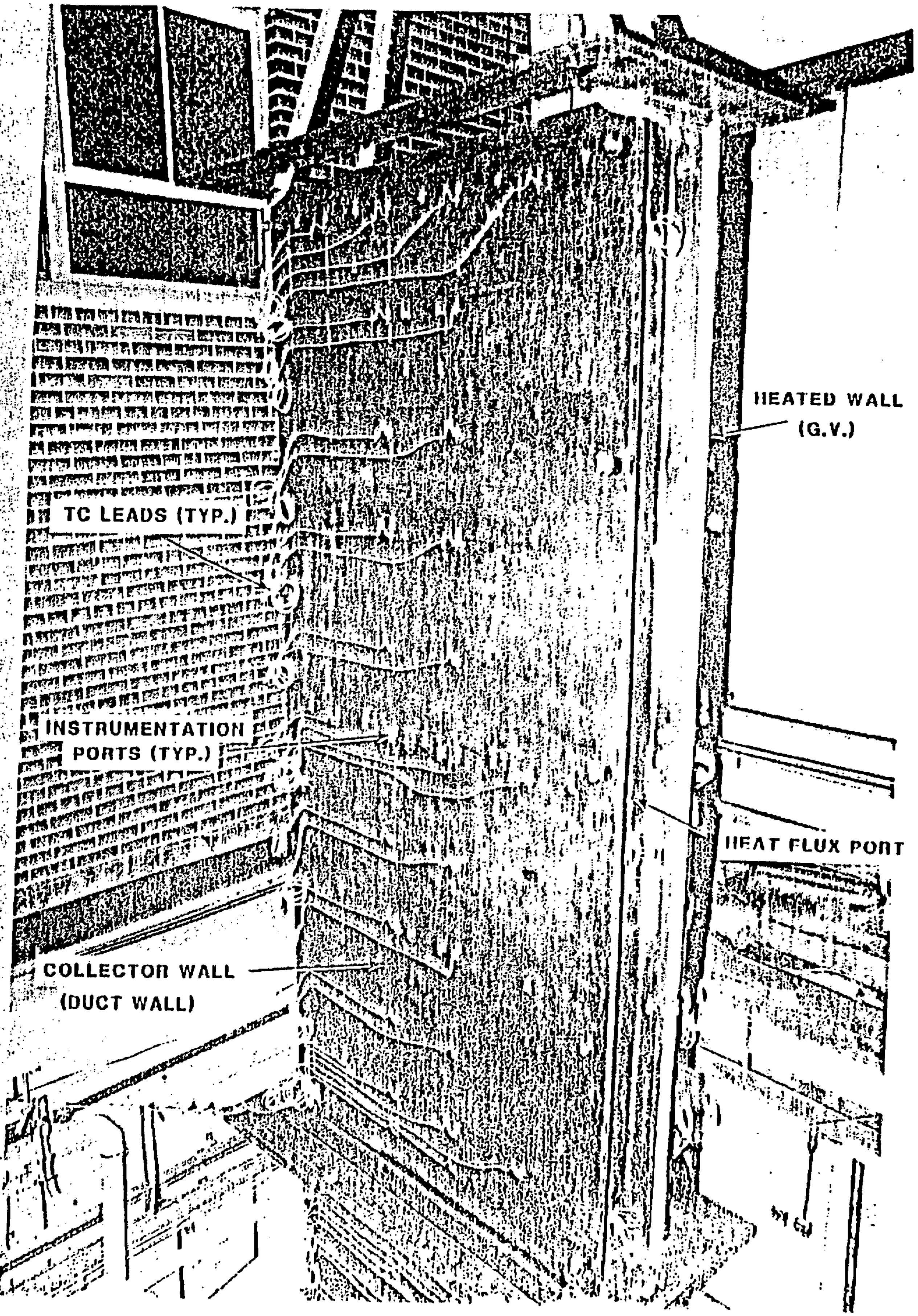


Figure 1-3. Partially Assembled Heated

HEATER CONTROL AND DATA ACQUISITION

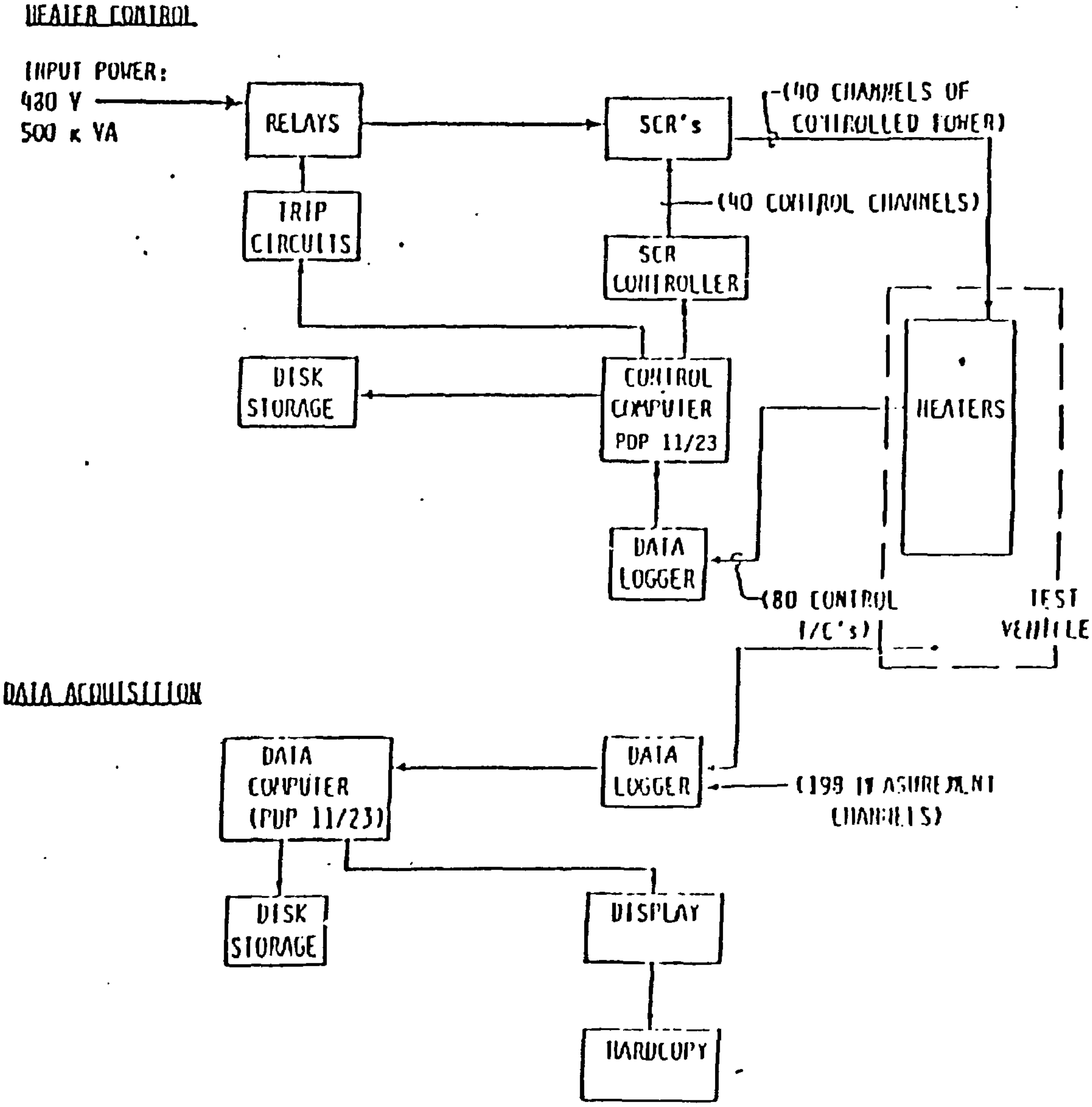


Figure 1-4. Heater Control and DAS System

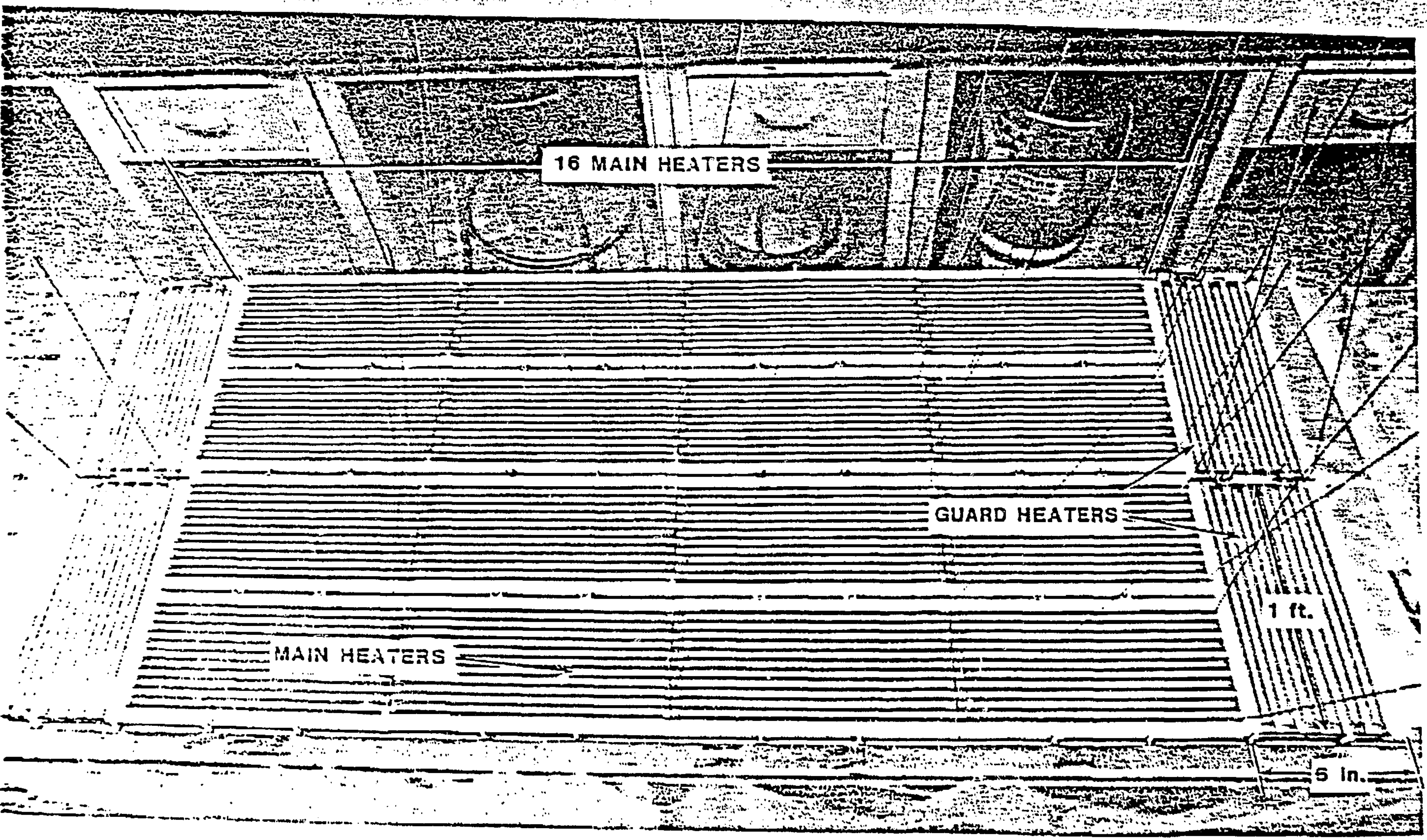


Figure 1-5. Heater Module

The data acquisition system (DAS) is capable of sampling 300 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 CRTs and hardcopy. The computer has been programmed to use on-line data to compute system parameters for real-time display and hardcopy.

Instrumentation

Instrumentation of the ANL NSTF 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. Instrumentation consists of thermocouples, Pitot-static traversing probes, a Pitot-static air flow "rake", differential pressure transducers, radiation flux transducers, an anemometer and air pressure and humidity gages.

Pretest Analysis and Experiment Test Plan

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 1-6, 1-7, and 1-8. 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 were 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)

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

This experiment matrix is summarized in Tables 1 and 2. The detailed RVACS/RACS test plan matrix is presented in Table 3.

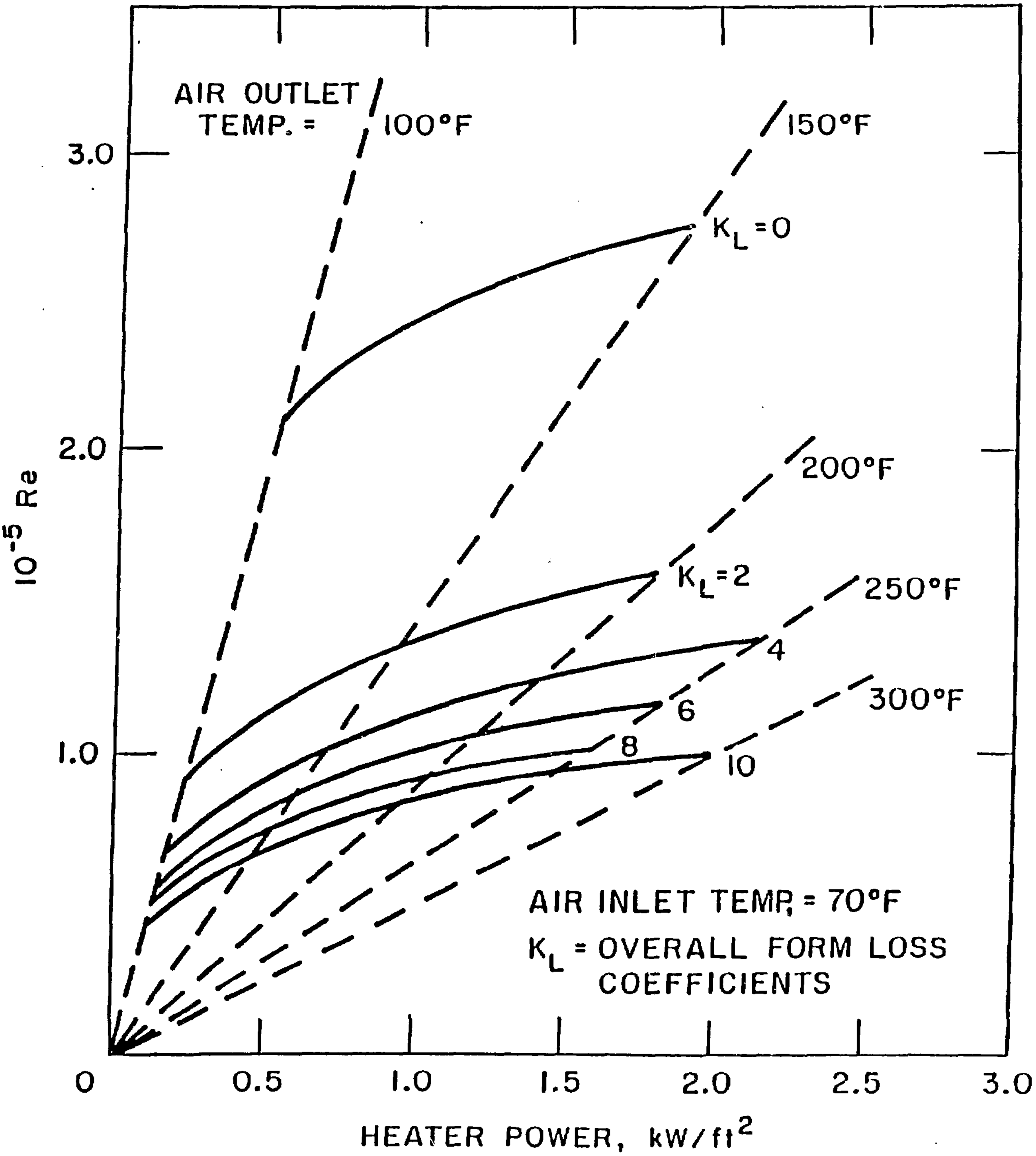


Figure 1-6. Test Assembly Performance Map

FIGURE 1-7. RVACS PERFORMANCE FOR VARIOUS VALUES OF APPLIED HEAT FLUX

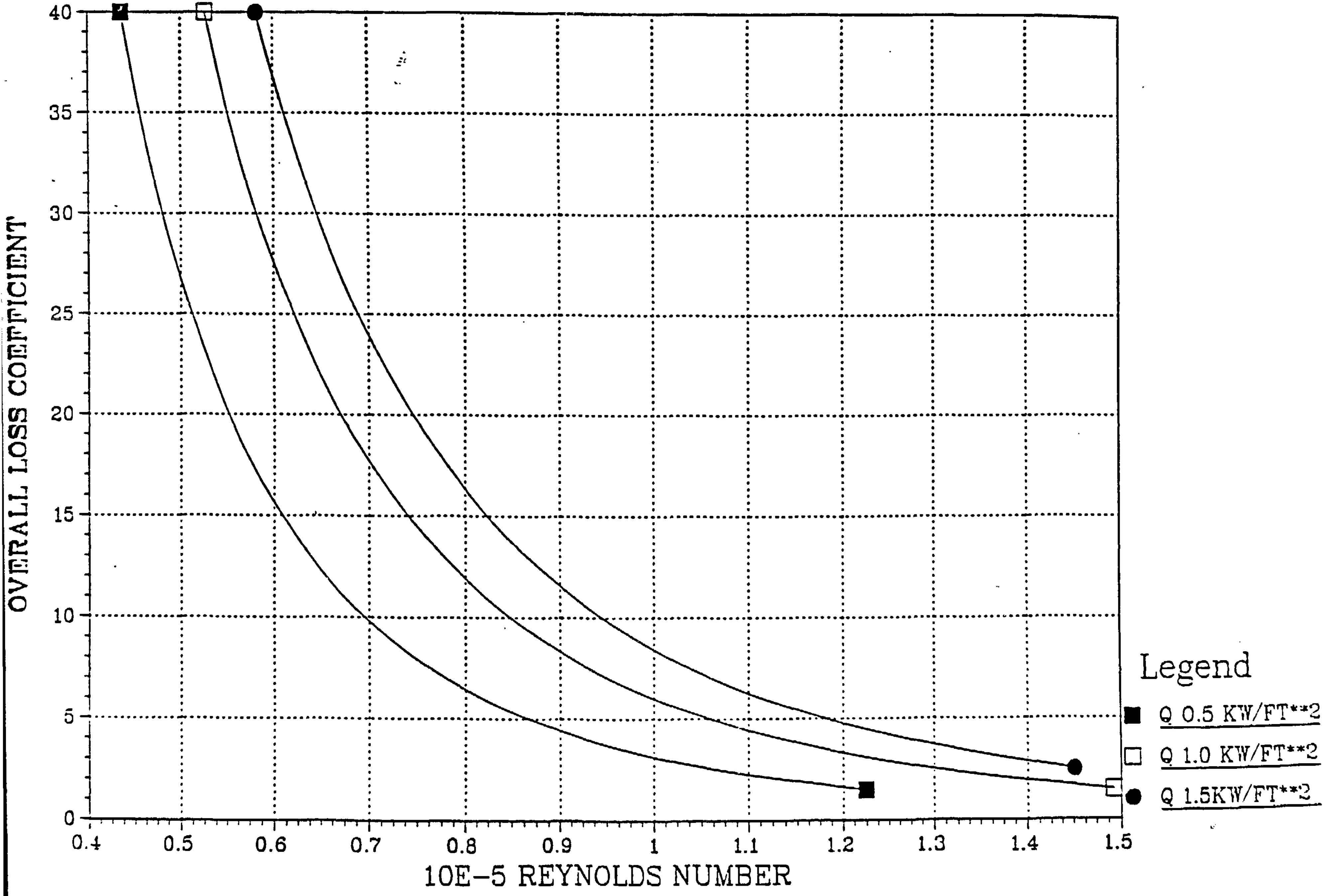


FIGURE 1-8

RVACS PERFORMANCE FOR FOR VARIOUS GUARD VESSEL TEMPERATURES

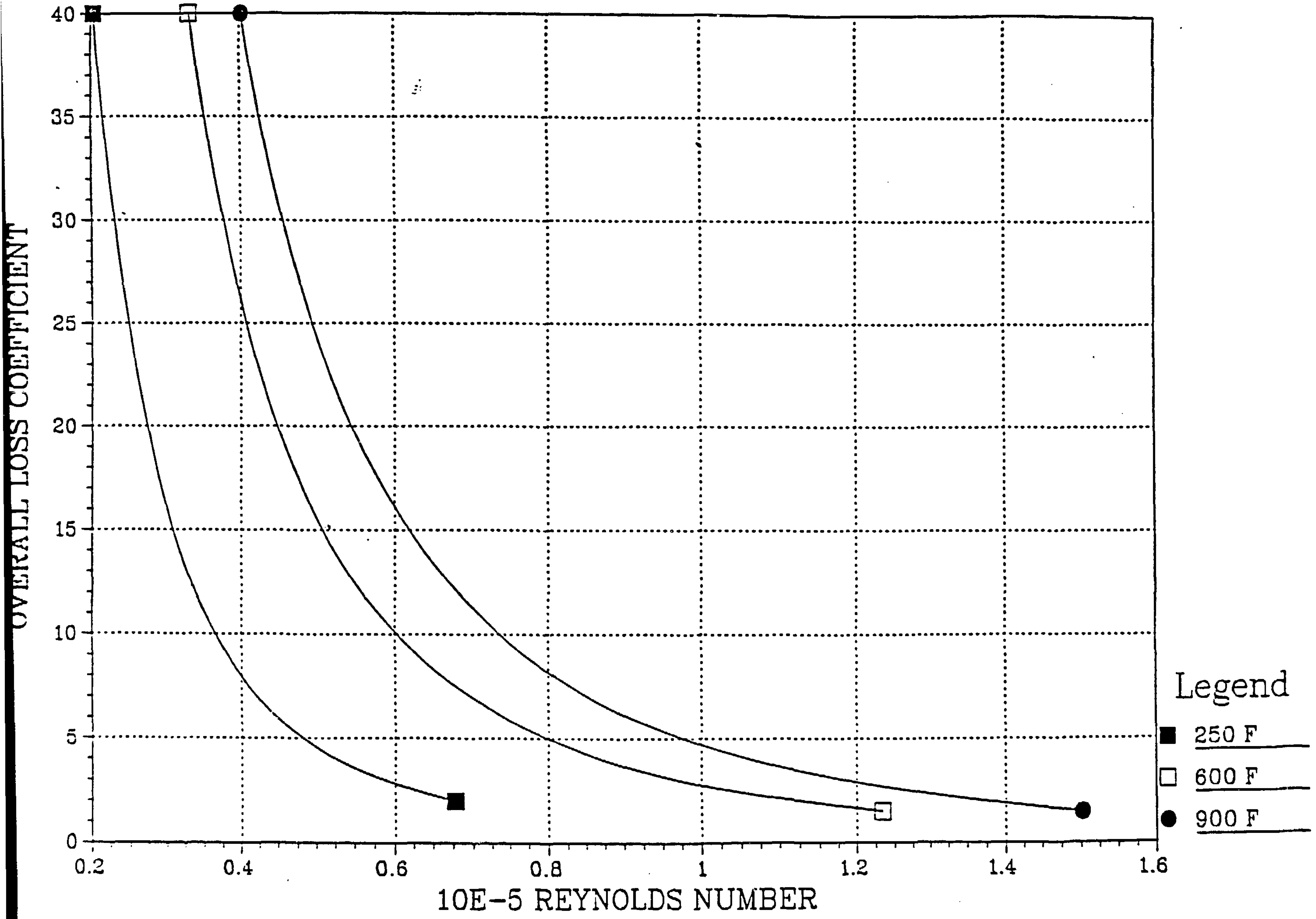


Table ~~2-3.~~ 1. RVACS Experiment Matrix

Predicted Constant GV Temperature Performance

T, °F \ K Re	Free Convection			Forced Convection	
250	24 0.25×10^5	4.5 0.5×10^5	1.5 0.75×10^5	-- 1.0×10^5	-- 1.5×10^5
600	NA	16 0.5×10^5	6 0.75×10^5	3 1.0×10^5	-- 1.5×10^5
900	NA	25 0.5×10^5	9.5 0.75×10^5	4.5 1.0×10^5	1.5 1.5×10^5

Table ~~2-2~~ 2. — RVACS Experiment Matrix

Predicted Constant GV Heat Flux Performance

K Re Kw/ft^2	Free Convection ←			→ Forced Convection	
0.5	27 0.5×10^5	8 0.75×10^5	3 1.0×10^5	-- 1.5×10^5	-- 2.0×10^5
1.0	NA	14 0.75×10^5	6 1.0×10^5	1.5 1.5×10^5	-- 2.0×10^5
1.5	NA	19 0.75×10^5	8.5 1.0×10^5	2 1.5×10^5	1.5 ?

Table 3. RVACS/RACS TEST PLAN MATRIX

	Comments
1.0 Initial System Checkout and Characterization	
1.1 Zero Flow, Zero Power - Simulate test run data acquisition and on-line processing for a "steady-state" condition.	Checkout for all instrumentation and DAS systems.
1.2 Zero Power, Forced Convection for range of Re = 0.3 to 2 x 10^5 (V $\simeq$ 3 to 20 ft/sec).	Characterize flow profiles in cold condition.
• check for system leakage.	
• Measure velocity profiles at six axial locations and 5-8 lateral positions.	
• Record and process all system variables for "small" time increments correlated to traverse positions.	
1.3 Power on, Forced Convection	Verify heater operations and control modes, bakeout heaters, characterize forced convection operation as basis for subsequent data analysis.
• Set fan to V$\approx$ 15 ft/sec (Re = 1.5 x 10^5)	
• Heater Tests and Bakeout (constant temperature	
• Zoned Power Tests.	
• Stepwise heater operation for electrical integrity, one zone at a time, control mode -- constant temperature at 250°F, 600°F, 900°F. Heater temp less than 1600°F.	Note the increase in radiative heat flux ($\sim T^4$) to collector wall as function of temperature.
• Record and process all system variables for "short" time increments, including velocity profiles.	T(F) $T^4(R^4)$ 250 2.5×10^{11} 600 1.3×10^{12} 900 3.4×10^{12}
• All-Zone Power Tests	
• Stepwise heater operation, all zones on, "equilibrium" tests for constant temperature control mode at 250°F, 600°F, 900°F periodically.	

Table 3. RVACS/RACS TEST PLAN MATRIX (cont'd)

	Comments
• Record and process selected variables for approach to steady state (will be relatively long-term since this is the bakeout phase).	
• Record and process all system variables at three stages.	Heat flux and heat loss validation.
• Heater Tests (constant heat flux control mode).	
• Repeat all-zone power tests at 0.5, 1.0, and 1.5 kW/ft (5, 10, and 15 kW/m^2).	
• Repeat all-zone power tests for stepwise power increments by "zones" (no. is TBD).	
2.0 Convection Tests	
2.1 All-zone constant temperature control mode at 250°F, 600°F, and 900°F. (see Table 2-3 for matrix)	Acquisition of basic data for performance evaluation of the RVACS no-fin design.
• Vary loss coefficient K from min. (~1.5) to max. (~20) for each temperature setting. The tests will encompass a Re range from 0.25 to 1.5 x 10^5 by a combination of free and forced convection tests. Each temperature setting will be characterized by at least five sets of data within the target flow range.	For free convection at $K \simeq 1.5$ pretest calculations indicate that T_{GV} (°F) — Re — Avg. Q_w (kW/m^2) 250 — 0.75x10^5 — 1.1 600 — 1.2 x10^5 — 5.5 900 — 1.5 x10^5 — 11.5
• Forced flow for Re ≥ 1.0 x 10^5 for 250°F and 600°F tests.	
2.2 Perform a "Long Term" operation, up to ~5 days.	
2.3 All-zone constant heat flux control mode at 0.17, 0.5, 1.0, and 1.5 kW/ft^2 (1.8, 5, 10, and 15 kW/m^2), at K = 1.5, 5, 10 and 20.	
2.4 Zoned constant temperature control mode (stratification simulation) at 400°F, 600°F, 800°F (if required).	

Table 3. RVACS/RACS TEST PLAN MATRIX (cont'd)

	Comments
3.0 Contingency Tests - Phase II	
3.1 During all of the tests above, the outside weather conditions will be monitored (particularly wind velocity and direction). If it appears that experiment data anomalies are related to changing meteorological conditions, procedures will be devised to account for these effects, perhaps by rerunning selected tests during selected meteorological conditions and/or utilizing alternate stack exit design.	
3.2 It is possible that more detailed experiment data will be required for precision in computing performance data, e.g., intermediate values of temperature, heat flux and pressure loss settings.	
3.3 Repeatability Tests, additional combined forced convection, free convection effects.	

Facility Operations and Experiment Results

Following the initial checkout and bakeout operations, the NSTF Phase I (RVACS) experiments were 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 have provided preliminary results including convective heat transfer coefficients, radiative components of heat transfer and air flow rates for varying environmental conditions. Facility operations for the RVACS experiments (through October 12, 1987) were satisfactory with the exception of some downtime for DAS system and heater maintenance. During this period, some 70 constant heat flux runs were performed for times varying between 4 and 40 hours. Of these 70 tests, 56 are considered to have reached equilibrium conditions. In addition, 15 constant temperature runs have been carried out.

Some changes and additions were incorporated into the experiment plan as experience was gained from experiment operations, i.e.,

1. As was postulated during the NSTF design phase, the attainment of equilibrium conditions within a reasonable period of time requires an overpower heatup for several hours prior to reduction to the target power as indicated in the experiment matrices (Tables 1 and 2).
2. Constant guard vessel temperature conditions are more difficult to attain than constant heat flux conditions, ergo the shift in temporal order of experiment operations.

3. The augmentation of the constant heat flux matrix (i.e., the addition of the 0.17 kW/ft^2 parameter) evolved from the realization that the 250°F performance conditions are included by this addition.
4. At constant power operations the facility heat losses are variable with system loss, i.e., as K increases, circulation velocity decreases, producing higher system temperatures. This results in guard vessel equilibrium heat fluxes that are not at the target fluxes indicated in the experiment matrix. This does not compromise experiment objectives. It does affect the method of presentation of experiment results for RVACS performance, as indicated below. It also requires operation of the facility heaters at higher equilibrium power than anticipated. This is well within facility capability. For example, the heatup phase always requires higher total heater power than that required at equilibrium.

The analytical and graphical data descriptive of the RVACS simulation performance are presented in Figures 1-9 and 1-10. It should be emphasized that these graphs represent the raw data (for uniform flux and uniform temperature) as collected. The computational (on-line and off-line) software utilizes this data directly without potential corrections to temperature, power, pressure, and differential pressure measurements pending further investigation and analysis.

Performance predictions for the facility have been made and refined throughout the design and operations phase. These predictions are shown in Figures 1-7 and 1-8. Because the actual equilibrium conditions during testing do not fall on the exact flux or temperature values shown in the experiment matrix (Tables 1 and 2), the pretest analysis is presented in Figures 1-9 and 1-10 in a revised manner, more appropriate to the method of data acquisition.

FIGURE ~~3-2~~ 1-9 NSTF PERFORMANCE FOR VARIOUS VALUES OF APPLIED HEAT FLUX AIR INLET TEMP=70 DEGF–EMISSIVITY=0.7

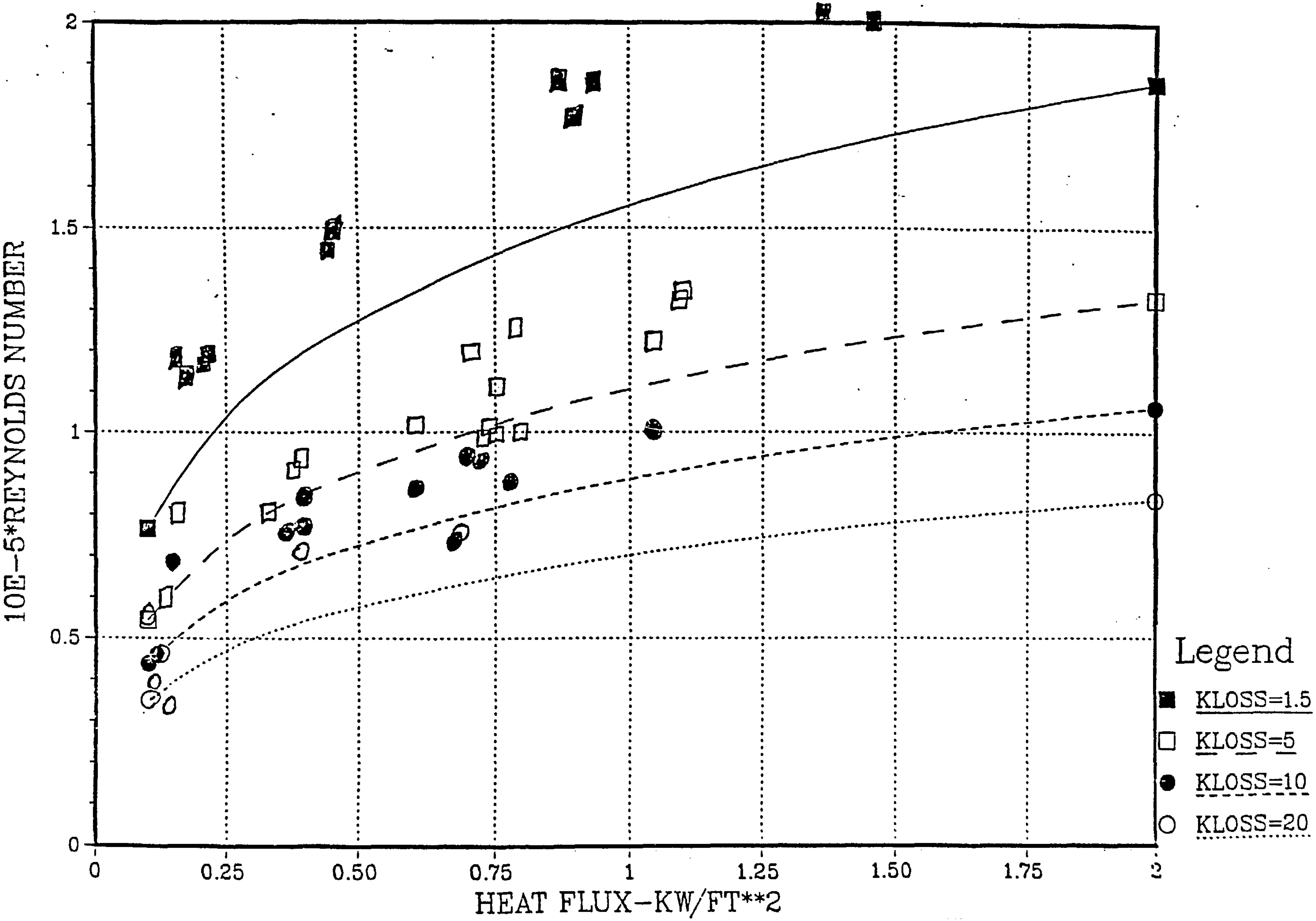
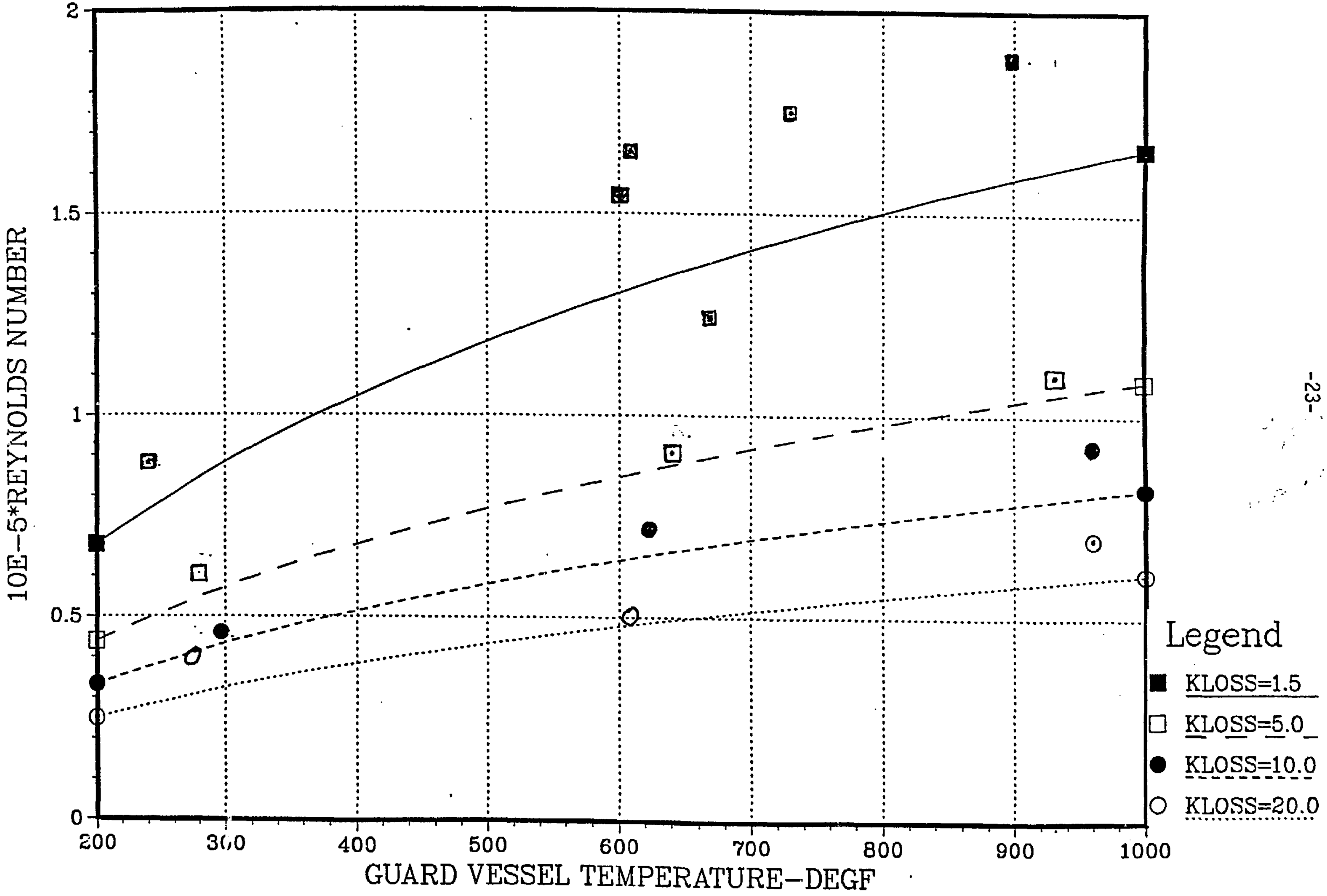


Figure 1-10

NSTF PERFORMANCE FOR VARIOUS VALUES OF GUARD VESSEL TEMPERATURES AIR INLET TEMP=70 DEGF–EMISSIVITY=0.7



The plotted lines of constant system loss represent exactly the same analysis as in Figure 1-7 but with heat flux and temperature as abscissas and Reynolds No. as the ordinate. The experiment values are plotted using the appropriate legend symbol. These points are plotted without corrections for wind velocity and different values of air inlet temperatures, i.e., the performance data has not been analyzed for varying weather conditions. E.g., it was noted early in the operations phase that system mass flow rate increases with wind velocity. These effects remain to be investigated and quantified. It should be noted that 90% of the data points lie above the predicted performance curves with a maximum deviation of (+) 20%, (-) 3%.

A second major objective is the production of correlations for the measured heat transfer coefficients. Although several alternative forms are under consideration, one correlation curve of the Dittus-Boelter type is shown in Figure 1-11. The data for several selected runs over the experiment Reynolds Number Range correlates as:

$$Nu = 0.0238\ Re^{0.8}\ Pr^{0.4}\ (Tw/Ta)^{-0.4}\ [1 + (L/D)^{-0.436}]$$

where the Nusselt (Nu), Reynolds (Re), and Prandtl Numbers are evaluated at the local bulk air temperature. The ratio of the local wall absolute temperature to the local air absolute temperature is used to account for the large range of temperature differences encountered during the experiments. The range of Reynolds Number is 0.4 to 2.1 x 10^5 and $L/D \geq 0.56$.

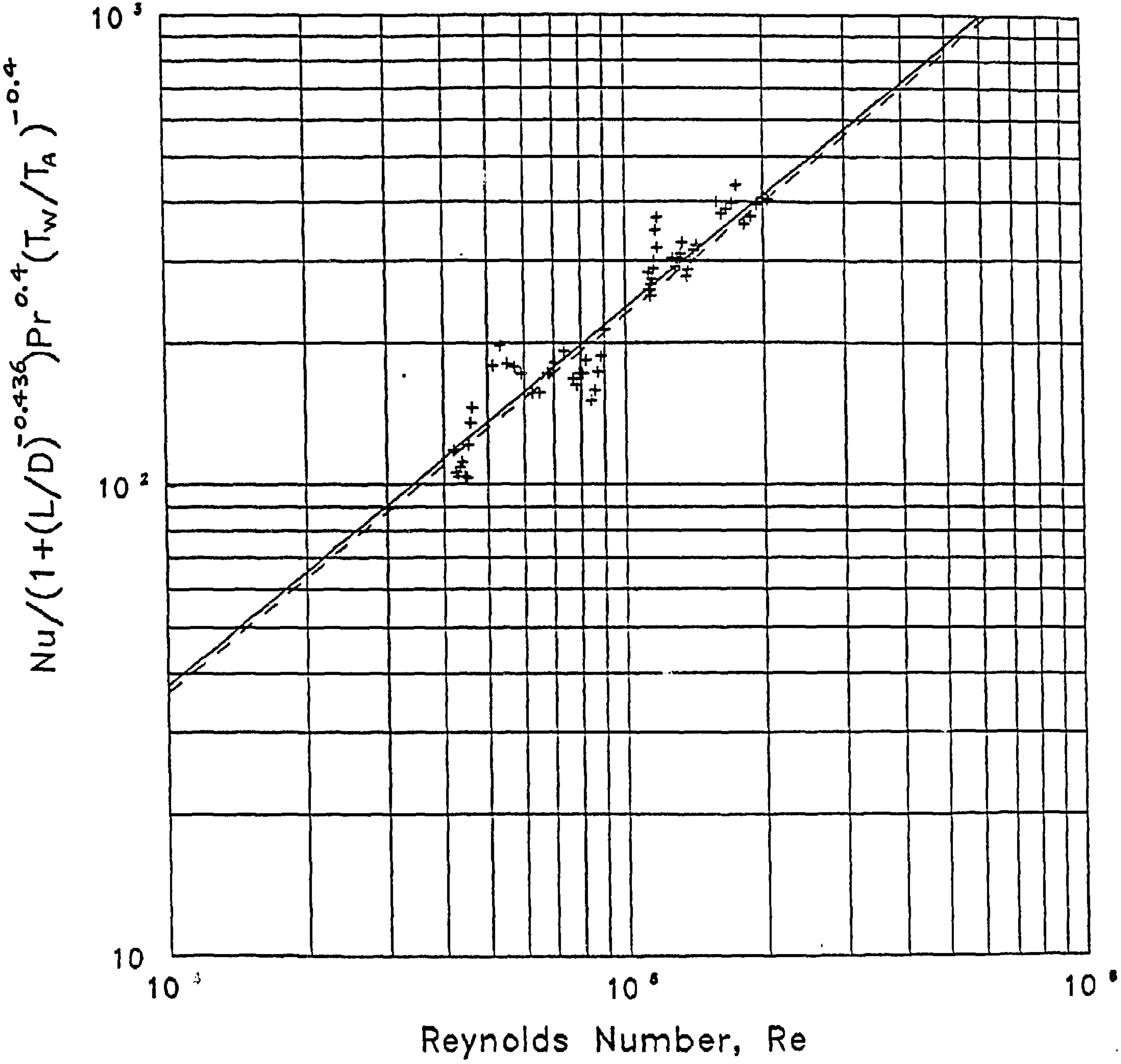


Figure 1-11. Preliminary RVACS Correlation