N81-14163

THERMAL VACUUM PERFORMANCE TESTING OF THE SPACE SHUTTLE ORBITER RADIATOR SYSTEM

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ABSTRACT

The Space Shuttle Orbiter radiator system thermal vacuum performance test was conducted at NASA-Johnson Space Center in Chamber A of the Space Environment Simulation Laboratory in January-February 1979. The test objective was to verify the radiator system heat rejection performance capability utilizing two development and two flight radiator panels comprising one of the two Orbiter Freon-21 coolant loops. Radiator performance over the range of expected flight conditions was as predicted, and there was no degradation of performance after extended vacuum exposure.

INTRODUCTION

During on-orbit operations of the Space Shuttle Orbiter, heat rejection will be accomplished primarily by the space radiators. The radiators are located on the inside surface of the payload bay doors for protection during launch and reentry. On-orbit deployment is accomplished by opening the payload bay doors and exposing the radiators to the space environment. An optimum thermal coating and high radiation fin effectiveness are used to maximize the radiator heat rejection. However, the limited door area results in some vehicle attitude and heat load combinations which exceed the radiator capacity and prevents adequate cooling of the heat transport fluid, Freon-21. In those situations the topping flash evaporator is automatically activated to provide the additional cooling needed by boiling available excess fuel cell water. The Orbiter also will be constrained from those attitudes where the vehicle heat load results in the combined radiator and topping flash evaporator being unable to maintain the Freon-21 return temperature below the required 4.4°C (40°F).

To verify the Orbiter radiator system heat rejection performance capability for expected orbital attitudes a thermal vacuum performance test was conducted at NASA-Johnson Space Center on four radiator panels and their FCA (Flow Control Assembly), representing one of the two Orbiter coolant loops. The testing was performed in conjunction with the Orbiter integrated ATCS (Active Thermal Control System) test in Chamber A of the Space Environment Simulation Laboratory. A detailed description of the integrated system testing is provided in References 1 and 2.

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SYSTEM/FACILITY DESCRIPTION

The ATCS, containing two independent flow loops, collects, transports and rejects waste heat from the Orbiter subsystems, equipment, and payloads from prelaunch through post landing for each mission. On-orbit heat rejection is accomplished by the use of space radiators. The baseline ATCS radiator system (Figure 1) has 6 radiator panels (3 in each flow loop) attached to the inside of the payload bay doors. Two additional radiator panels (one for each flow loop) can be mounted on the aft section of the payload bay doors for added heat rejection capability. The 3.1 m x 4.6 m (10 ft x 15 ft) panels which are contoured to the payload bay door to maximize the payload volume, consist of two basic designs - forward panels, which are deployed away from the payload bay door after the doors are opened on-orbit and reject heat from both sides of the panel; and aft panels, which are attached to the aft section of the doors and radiate from only the concave surface. The series-connected radiator panels contain parallel flow tubes and are constructed of a low density aluminum honeycomb bonded to thin aluminum face sheets and coated with a special silver Teflon coating. The silver Teflon provides a low absorptance of solar flux and a high thermal emittance. Coolant flow through each set of radiators is controlled by its FCA (one in each loop). The FCA's can be operated manually or automatically to control the radiator system outlet temperature to either 3.3°C (38°F - normal) or 13.9°C (57°F). The 13.9°C (57°F) control temperature is used to dump excess fuel cell generated water through the topping flash evaporator. A more detailed description of the ATCS is presented in Reference 3.

The test was conducted in Chamber A of the Space Environment Simulation Laboratory. Chamber A is the largest of the JSC thermal vacuum test facilities. The working volume of the chamber is 16.8 m (55 ft) in diameter and 27.4 m (90 ft) in height. The radiator system test article layout in conjunction with other ATCS test hardware is shown in Figure 2. Special test support elements supporting the test article were located on the first floor level outside the chamber. Cryogenic and diffusion pumping were used to obtain a chamber pressure of 1.3×10^{-4} N/M^2 (10^{-5} Torr). The chamber's entire liquid nitrogen shroud including the floor was cooled to liquid nitrogen temperatures to obtain the required environment for radiator system performance evaluation. Sublimation repressurization, using dry nitrogen and heaters to minimize water condensation on the radiator panels and insulated surfaces, was used to repressurize the chamber to sea level conditions. During chamber repressurization television and high voltage equipment (infrared simulators) operation was prohibited to prevent corona damage.

Two development and two "flight" radiator panels were installed in the configuration shown in Figure 2. To minimize gravity effects the aft panels were aligned with the plane formed by the panel edges tilted at an angle of 0.15 radians (8.75 degrees) with respect to horizontal with the outboard edge above the inboard edge. The forward panels were placed behind the aft panels with the plane formed by the panel edges in a horizontal position. A liquid nitrogen shroud was installed between the forward and aft panels to prevent radiant interchange between the upward tilted aft panels and the forward panels. The radiator panels were suspended by cables attached to the support structure. Payload bay door thermal simulators were installed below the two forward panels forming an angle of 0.62 radians (35.5 degrees) between the planes of the upper surface of the panels and doors, representing the deployed position of the panels during on-orbit operations. Heaters on the door simulators, simulating the infrared flux originating from the doors, were controlled from a power console located outside the test chamber. The back side of the aft panels and the door simulators were insulated with multilayer insulation to minimize heat leak from these surfaces. Heaters also were installed under the back side insulation of the aft radiator (panel 4) to prevent freezing during test points that required isolation of panel 4 from the coolant loop.

Earth and solar environment simulation was provided by infrared lamps capable of simulating both skewed and orbital cycle flux environments. Flux from the lamps was input to the upper concave surface of the radiators by an array of nine rows of lamps, each under separate computer control. Radiometers to measure heat flux were mounted flush with the upper surface of the radiators in the plane of the radiator. Structure holding the environment simulator and radiators was designed to minimize blockage thereby maximizing radiator panel view to the chamber. Shutoff valves and a modified flight type adapter tube to bypass the aft radiator panel were installed to allow 3-panel radiator system testing. Selection of either the 3- or 4-panel configuration was made from a control panel in the facility control room. Activation and mode selection for FCA operation was provided by a control panel located in the facility control room.

TEST CONDITIONS/PROCEDURE

The tests for the Shuttle radiator subsystem were defined to provide the performance envelope over a range of orbital environments and a range of heat loads. A review of the expected Shuttle mission environments resulted in selection of 12 environments (Figure 3) for simulation in the test. The heat load range tested was based on the ATCS coolant loop limits. The selected radiator heat loads are indicated in Table I, which also gives the environment used with each heat load. Tests were included to define radiator performance for the 6 panel, baseline, configuration and the 8 panel, Spacelab kit, configuration, as well as for both the normal 3.3°C (38°F) and high 13.9°C (57°F) radiator system outlet control temperatures.

Since analysis will be used to evaluate thermal performance in all possible Shuttle attitudes, the test environments were selected to support these future analyses. The test environments were based on both the range of attitudes expected and the orbital transients. The attitude range included both earth and solar orientations and extended from environment 4 (Figure 3), the coldest, to environment 3, the hottest. Environments 1, 2, and 5 simulated earth oriented orbits with fluxes nearly equally spaced between the coldest and hottest. Two environments, 7 and 8, were required to simulate the solar orientation, left side and right side, because only one side of the radiator subsystem was used in the test. Correlation of the analytical models to each of these environments will insure that future analytical predictions for any Shuttle attitude will not be far removed from a test condition. This should result in accurate and reliable performance predictions.

To further enhance the Shuttle radiator analysis, a solar attitude (6) and an earth attitude (5) were each conducted for both the orbital transient environment and at the steady-state orbital average environment. Environment 5 provided a maximum peak-to-peak orbital flux change, and environment 6 gave a maximum flux change on the radiators at the earth's shadow penetration. Comparison of the test results for the transient environments to the results at the steady-state average environment provided a comparison that will allow evaluation of orbital transients using steady-state predictions.

Environment 9 was included in the radiator test to define radiator performance for the varying attitude of PTC (Passive Thermal Control). This attitude, a slow roll about the Shuttle longitudinal axis, is expected to be used frequently on most flights. It is a thermally benign Orbiter environment and nearly mid-way between the hottest and coldest radiator conditions. The remaining environments (10, 11, and 12) were included in the test because they were the reference conditions used in the radiator hardware design.

For each of the tests shown in Table I, the test procedure used was the same. The radiator system configuration was established by positioning the appropriate valves. The environment was controlled by adjusting the quartz lamp and heater intensities. The heat load was controlled by adjusting the supply Freon to the desired flow and temperature. Finally, the data was recorded when the radiator surface and fluid temperatures were stabilized.

Since the test chamber was maintained at vacuum (10^{-5} Torr), the various configurations were remotely controlled. A motor-driven valve was used to allow flow to all 4 panels or to bypass one panel for 3 panel testing. Another motor was used to remotely position the "mode valve" on the FCA to either the 6 or the 8 panel position. On the Shuttle, this valve is positioned manually during ground operations when the Spacelab kit panels are installed or removed. The high or normal radiator temperature control set point was controlled by a switch, similar to the Orbiter crew control, in the chamber control room. The motor-driven valves, and the set point switch had indicator lights to confirm their respective positions.

The desired heat load for each test was established by adjusting the ground coolant flow cart to supply the appropriate Freon flow and temperature at the flow control assembly inlet. Since there are no modulating valves except the radiator flow control valve in the ATCS coolant loop, the Shuttle loop flow should remain constant. The flow control valve was designed to provide a nearly constant flow resistance in any position. Thus, with relatively constant temperatures through the loop, the expected flow was predetermined and adjusted at the cart. With a fixed flow and controlled heat sink outlet temperature, the radiator inlet temperature could also be predetermined for each heat load independent of the environment. Therefore, the heat load was established by setting a predetermined inlet temperature and flow and holding the values constant for each test.

The environment settings were based on pretest calibrations and the radiometer and heater current indications. The total external radiator panel absorbed heat was calculated for each environment and input to the concave panel surface. External environmental flux normally incident on the surface of the forward panels was input on the concave surface during the test. The payload bay door absorbed heat also was calculated and input to the door simulator using electric heaters. From the known heater resistance, the heater current for each of six zones on the door was defined for each environment. For each test, the required heater current in each zone was adjusted and maintained to produce the correct thermal flux on the door simulator. The quartz lamps above the panels provided all the remaining environmental heat to both forward and aft radiator panels. Again, analysis was used to define the total panel absorbed heat, including earth emission, albedo, and direct solar. Reflected solar energy from the door also was included. To provide direct correlation with the computer models, the calculated absorbed heats were defined for each of the five zones per panel as used in the models.

The nine rows of quartz lamps located above the panels had adjustable intensities in 1 bit settings to a maximum of 64 bits. Pretest calibration tests were made to define the affect of each row on the panel zones and facilitate adjustment of the absorbed heat profile across the panel. Unlike the other test settings, the quartz lamp intensities could not be predetermined. Radiometers located between the panels were used to define the final quartz lamp settings. They were positioned to represent the five computer model zones and coated with silver Teflon like the panels so as to read the same absorbed heat as the panels; one set for the forward panels and one set for the aft panels. This approach inherently adjusted for structure re-radiation and any chamber background flux. The radiometers recorded the total absorbed energy which, unfortunately, included that energy radiated from other parts of the curved panel that should not be included in the total external absorbed heat. To accurately represent the required environment, the radiometer indications were adjusted according to the panel temperature. The higher panel temperature required higher radiometer indications to represent the same external environment.

An approximation in the environment simulation that should be noted was the application of all external flux on only the top side of the forward panels. In actual Shuttle operation, a significant part of the absorbed heat will be to the cavity, or bottom side, of the forward panels. A pretest analysis confirmed evaluation of earlier test results and showed that the affect on performance could be neglected. The thermal conductivity across the 1-inch thick forward radiator panel was so high that absorbed heat on either surface had the same affect on the fluid outlet temperatures.

DATA ACQUISITION

A flexible data system using Hewlett-Packard 2112 and 2117 was the primary real time processor of the test data. Throughout the test, all data was recorded continuously on computer tape for subsequent printing in tabular or plotted form. However, it also was possible to observe the data on CRT's (cathode ray tube) in the control room and to activate a printer to obtain an immediate listing of selected data.

For steady-state test points, the CRT observations were used to verify the correct test article configuration, environment, and heat loads. The CRT's were also monitored to determine when steady-state was achieved. A printout of radiator data was obtained at stable conditions. To document and verify that conditions were steady, a second printout was obtained 900 seconds (15 minutes) later and compared to the first printout.

For the transient tests, the CRT's were monitored to verify initial conditions and abbreviated data was printed at 60-second (one-minute) intervals during the two-orbit environment transient. The radiometer readings were included in the 60-second data to insure that the correct environmental transient was applied.

TEST RESULTS

The radiator system test included a total of 49 steady-state and 6 orbital transient test points. Figures 4 and 5 summarize the complete three panel and four panel high load steady-state test results along with the analytical predictions. The test data and analysis results show good agreement. The small differences can be attributed to temperature, flow and heat flux instrumentation inaccuracies, and in some cases a true steady-state condition may not have been obtained due to test time limitations. The test data confirmation of the analysis provides a wide range of data for future radiator performance assessment. Figures 4 and 5 can be used to obtain radiator heat rejection for the twelve different orbit conditions. The highest orbital heat rejection was obtained for environment 4 which allows a radiator inlet temperature of 63°C (145°F) for a radiator return temperature of 3.3°C (38°F).

Six orbital transient test points were conducted to determine the effect of the use of orbital average steady environments in the performance assessment. Considerable peaking above the steady-state values (as much as 12°C (53.6°F) for environment 5) occurs during the sunlight portion of the orbit. Thus, the use of steady-state performance based on orbital average environments must be used with caution. For example, the radiator outlet should not be allowed to peak above approximately 15.6°C (60°F) to prevent overloading the flash evaporator. Therefore, evaluation of radiator peak outlet temperatures can only be inferred from the steady-state performance values.

The low load testing was conducted with environment 4 in which the aft panels view only deep space and the door centerline edge of the forward panels receive earth flux (convex side only). Analysis had indicated that the gravity effects would cause flow reversal in panel 4 before the low temperature limit of panel 1 was reached; i.e., the test low load limit would be dictated by gravity, whereas the flight low load would be limited by temperature. Reverse flow was evident in panel 4 in the lowest elevation tubes as expected. The tubes with reverse flow had inlet temperatures colder than the outlet and much colder temperatures than the other tube inlet temperatures. The coldest temperature observed was -42.4°C (-44.3°F) on panel 1 which is considerably above the freezing point of Freon-21, -135°C (-211°F). Extrapolation of the test data by analysis to the zero-gravity flight condition indicates that an inlet temperature of 5°C (41°F) is required to obtain a tube outlet of -135°C (-211°F). Thus a minimum heat load of approximately 4.7 joules/sec (4000 Btu/hr) could be allowed before fluid freezing occurs.

Fin temperature profiles measured throughout the test were used to calculate the radiator fin effectiveness. The overall average of 0.979 for the forward panels and 0.950 for the aft panels compared favorably with values of 0.975 and 0.944, respectively, from previously run single panel development tests with only cold wall environments.

The test was conducted over a 29 day period with seven chamber depressurization-pressurization cycles. During some re-pressurization sequences, moisture condensation on the chamber cold walls caused "rain" in the chamber and some accumulation of water on the panel concave surfaces. Dust accumulation on the panels was also evident throughout the test. In order to verify that the test conditions of vacuum and temperature as well as the moisture and dust did not change the radiator performance, baseline performance data was taken throughout the test. The baseline data was taken with the lamp arrays off and the radiator flow control valve deactivated to obtain full Freon-21 flow through the panels. The following indicates that the change in radiator performance throughout the test is within the experimental accuracy.

TIME DAY:HR:MIN:SEC	INLET TEMP °C (°F)	OUTLET TEMP °C (°F)
25:15:23:23	48.4 (119.0)	-6.5 (20.4)
29:13:42:33	49.0 (120.1)	-8.2 (17.[illegible])
54:06:04:54	48.8 (119.9)	-4.6 (23.6)

The data taken on day 29 shows a 4.3% improvement over the initial data (day 25) and the data at the end of the test (day 54) shows a 2.3% decrease from the initial values.

CONCLUSION

The testing verified the flight readiness of the Orbiter radiator system thermal performance. Radiator performance over the range of expected flight conditions was as expected and there was not degradation of performance during the test. Extrapolation of the single loop test data indicates that Orbiter heat loads ranging from 17.46 joule/sec (15,000 Btu/hr) to 197.86 joule/sec (170,000 Btu/hr) with a controlled 3.3°C (38°F) return temperature can be accommodated by the radiator system using 8 panels.

REFERENCES

1. Jaax, J. R., "Orbiter Active Thermal Control Subsystem Test," AIAA Paper, September 1980.
2. Jaax, J. R., "Integrated Active Thermal Control Subsystem Test Final Report," Crew Systems Division CSD-SH-143, Johnson Space Center JSC 14182, August 1979.
3. Jaax, J. R., "Orbiter Active Thermal Control Subsystem Description and Test History," Crew Systems Division CSD-SH-126, Johnson Space Center JSC 11295, July 20, 1978.

TABLE I

RADIATOR TEST POINT SUMMARY

HEAT LOAD	FCA SET POINT	ENVIRONMENT (REF. . IGURE 3) 1	2	3	4	5	6	7	8	9	10	11	12
MINIMUM - WITH NO PANEL TEMP. BELOW -123.3°C (-190°F)	NORM				X								
MINIMUM - WITH NO PANEL TEMP. BELOW -123.3°C (-190°F)	HIGH				X								
NOMINAL OFT HEAT LOAD	NORM	4*								4			
MAXIMUM FOR RFCA TO RETURN 3.3°C (38°F) MIXED OUTLET	NORM	X	X	X	X	X	X	X	X	X			
MAXIMUM FROM ORBITAL AVERAGE CASE - RUN W/TRANSIENT ENVIR.	NORM	X				X	X						
MAXIMUM FOR FES TO RETURN 3.9°C (39°F)	NORM	X	X	X	X			X	X	X			
MAXIMUM HEAT LOAD ALLOWED BY LOOP TEMPERATURE LIMITS	NORM	4		4									
FIXED RFCA INLET 4 PANEL 46°C (115°F) 3 PANEL 40.4°C (105°F)	NORM										X		
FIXED RFCA INLET 4 PANEL 44.8°C (113°F) 3 PANEL 39.4°C (103°F)	NORM											X	X
ACCEPTANCE TEST INLET TO RFCA	NORM				X								

*DENOTES 4 PANEL TEST ONLY

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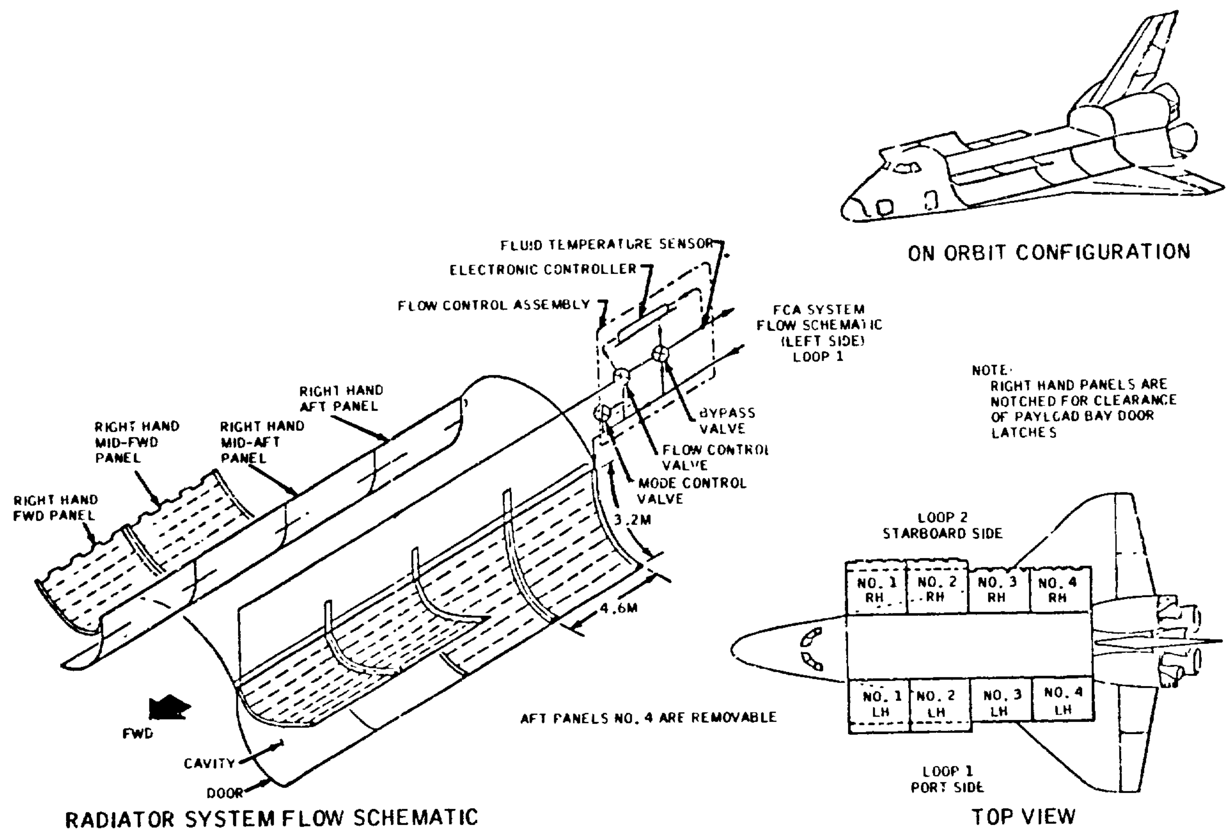

FIGURE 1. ORBITER RADIATOR SYSTEM CONFIGURATION

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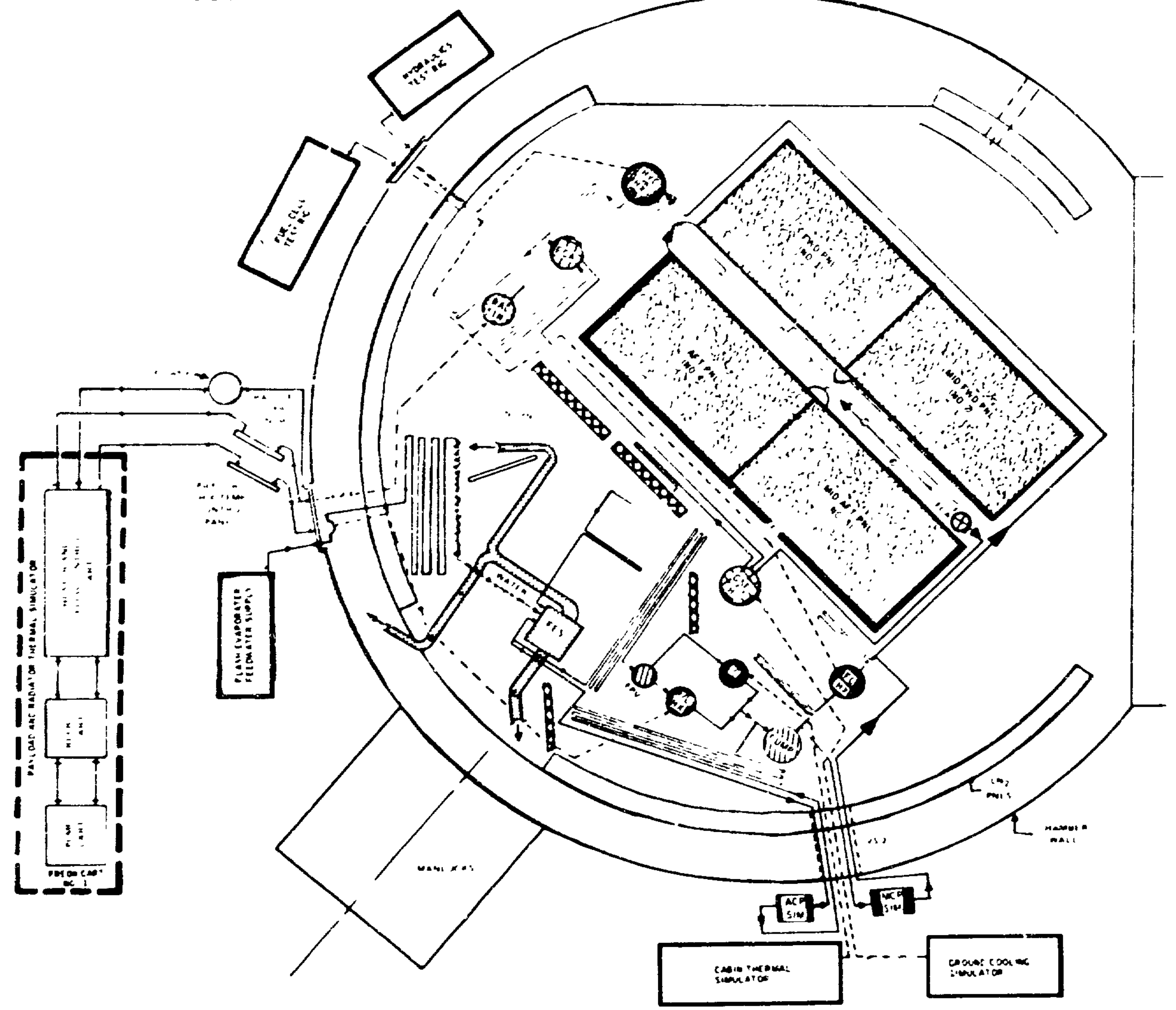

FIGURE 2. INTEGRATED ATCS TEST LAYOUT

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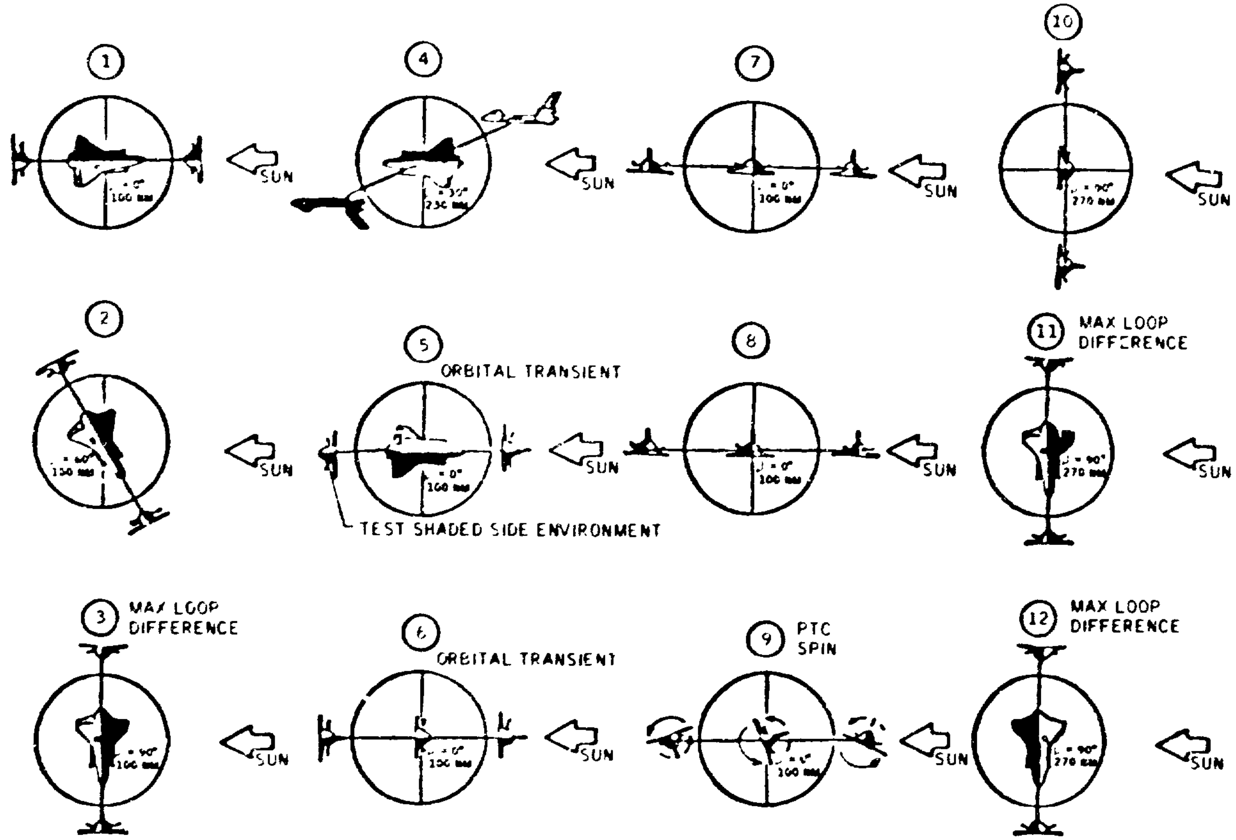

FIGURE 3. ORBITER ATTITUDES FOR RADIATOR PERFORMANCE ASSESSMENT

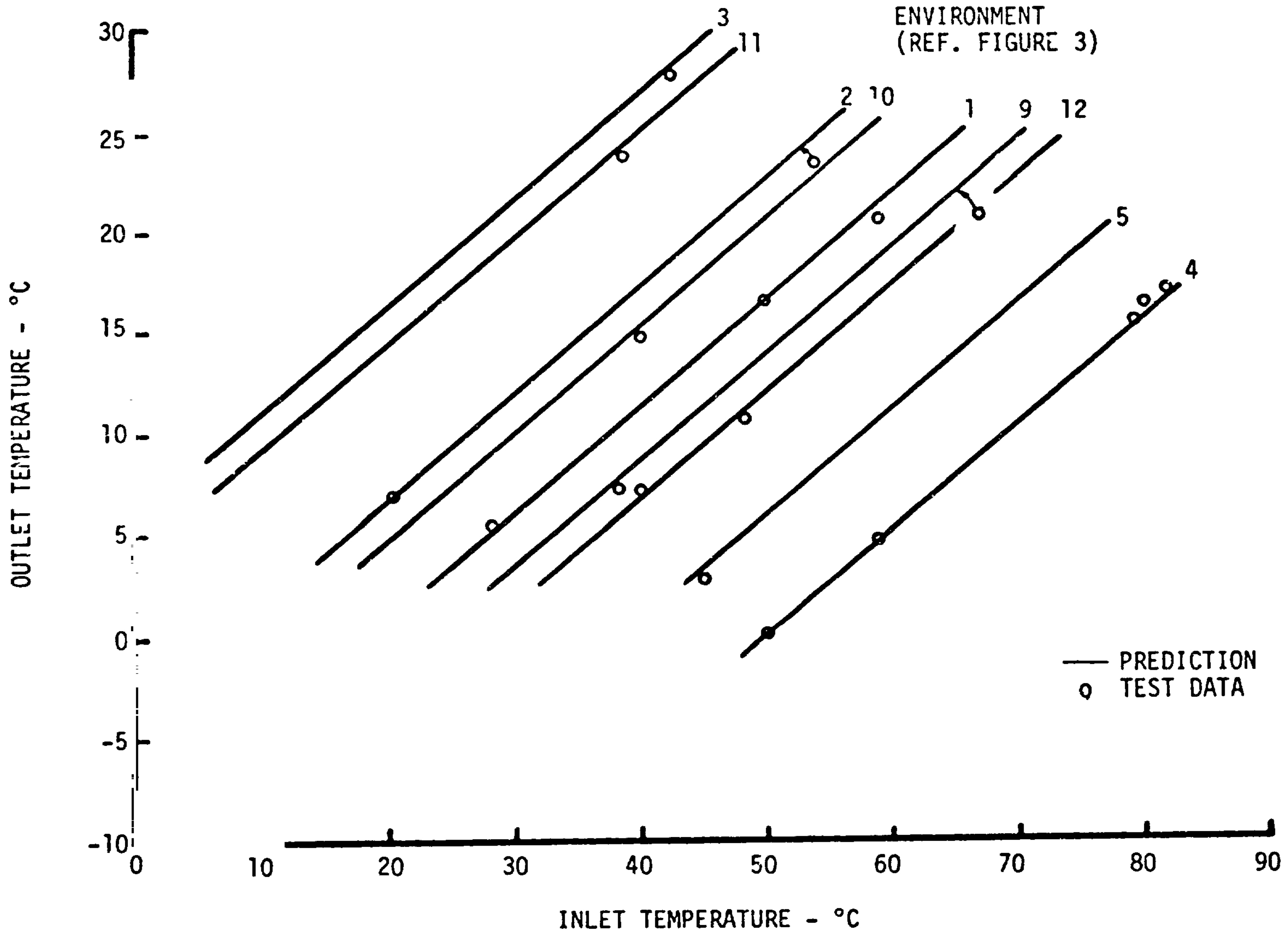

FIGURE 4. COMPARISON OF ANALYSIS AND TEST DATA - 3 PANELS

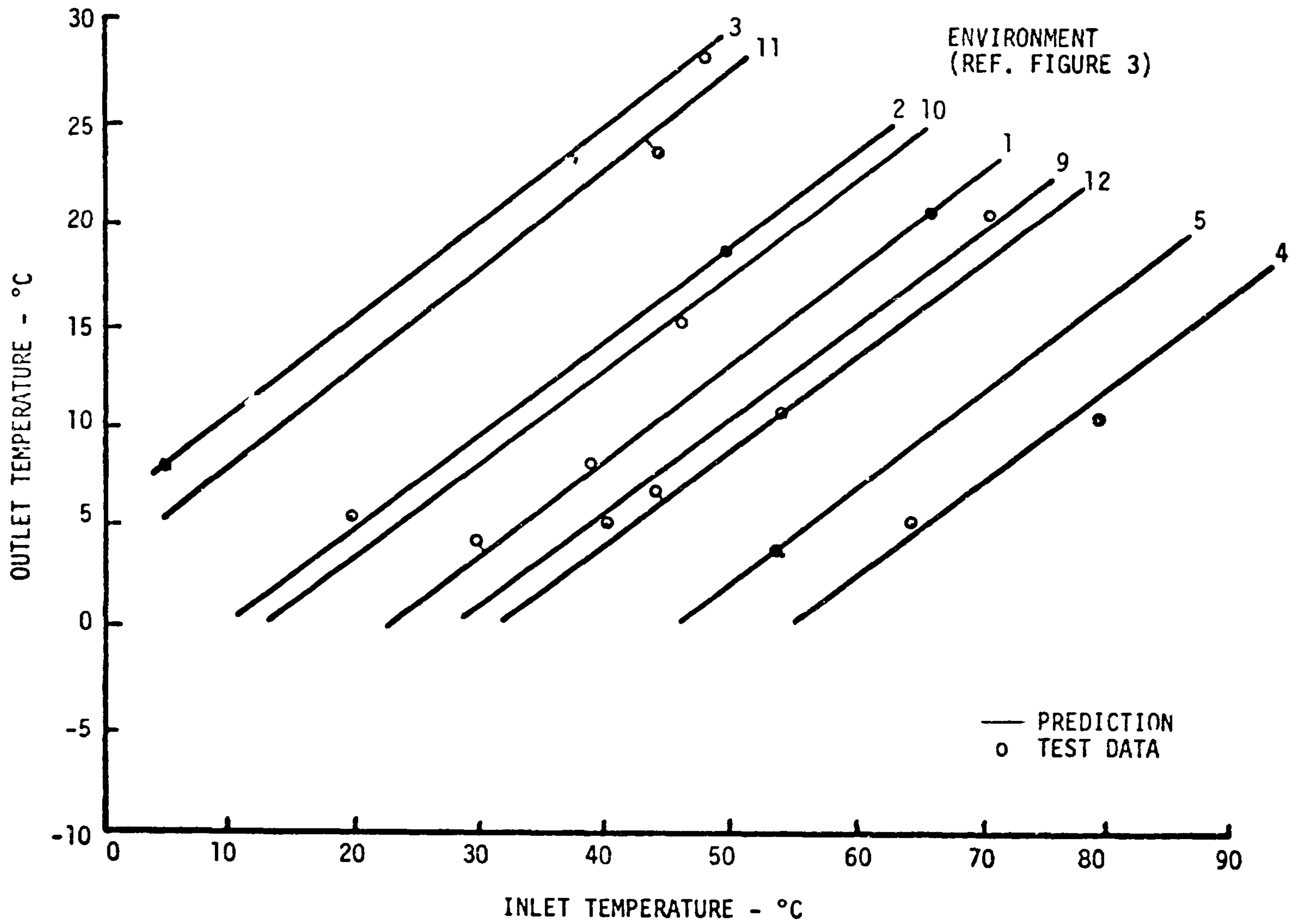

FIGURE 5. COMPARISON OF ANALYSIS AND TEST DATA - 4 PANELS