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Space Shuttle Base Heating Tests were conducted using a 0.040-scale model in the Plum Brook Space Power Facility of The NASA Lewis Research Center. The tests measured heat transfer rates, pressure distributions, and gas recovery temperatures on the orbiter vehicle 2A base configuration resulting from engine plume impingement. One hundred and sixty-eight hydrogen-oxygen engine firings were made at simulated flight altitudes ranging from 120 000 to 360 000 feet.

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THE 0.040-SCALE SPACE SHUTTLE ORBITER BASE HEATING MODEL TESTS IN THE LEWIS RESEARCH CENTER SPACE POWER FACILITY

by Robert A. Dezelick

Lewis Research Center

SUMMARY

Space Shuttle Base Heating Tests Number OH64 were conducted using a 0.040-scale model in the Plum Brook Space Power Facility of The NASA Lewis Research Center from April through June 1975. The purpose of the tests was to measure heat transfer rates, pressure distributions, and gas recovery temperatures on the orbiter vehicle 2A base configuration resulting from engine plume recirculation and direct plume impingement. One hundred sixty-eight hydrogen-oxygen engine firings were made at simulated altitudes ranging from 120 000 to 360 000 feet. Steady-state data were achieved with the impulse type hot firings into the large volume vacuum chamber. Testing methods, an index of run conditions, and some typical results are presented.

INTRODUCTION

As part of the Space Shuttle Program, the aerothermodynamics group at Rockwell Space Division has the responsibility for defining the Space Shuttle ascent aeroheating design requirements. This task requires simulation of as much of the flight regimes as possible in evaluating the Space Shuttle integrated vehicle.

In previous tests at other space simulation chambers, the small size of the vacuum chamber has limited the data gathering period to 9 milliseconds due to shockwave return to the model and required three test runs per test setup to obtain 200 channels of data. When model firings are accomplished without engine throats plugged during the engine start transients, operating conditions may not be achieved for 25 milliseconds or longer.

The Plum Brook Space Power Facility was selected for follow-on tests since its size permitted run times in excess of those required to reach steady-state flow for acquisition of valid recovery temperature and pressure data at simulated altitudes above 120 000 feet. This report contains a detailed description of these tests.

TEST CONFIGURATION

General

The Plum Brook Space Power Facility of the NASA Lewis Research Center consists of a 100-feet diameter by 121-feet high aluminum, high-vacuum chamber enclosed in a low-vacuum concrete chamber 130-feet in diameter by 150-feet high. The interior volumes of the aluminum chamber and the annulus between the two chambers is approximately 800 000 cubic feet each. Vacuum capability of the inner chamber is 1×10^{-7} torr with the outer chamber at 25 torr.

The 0.040-scale model of the Space Shuttle orbiter vehicle was mounted in the center of the vacuum chamber at floor level with the engines firing vertically upward.

TEST HARDWARE

The impulse-type hot firing 0.040-scale model used for these tests simulates the model lines of the vehicle 2A Space Shuttle orbiter, aft of full-scale station 1400. The model base assembly simulating the external orbiter lines is seismically suspended from the structure housing the propulsion simulation system. The scale components included are the body flap, the orbital maneuvering system (OMS) pods, OMS engine nozzles, vertical tail, base heat shield, and the space shuttle main engine (SSME) nozzles. The engine nozzles (both SSME and OMS) throat diameters, internal contours, exit diameters, and lengths are scaled and are capable of gimbal angle changes. The vertical tail is accurate as to planform and location but simulates the undeflected rudder condition only. The body flap could be removed or positioned in the nominal zero degree position or deflected 20 degree (see fig. 1).

Within the propulsion simulation system, to which all other components attach, each propellant gas flows through a metering venturi which remains choked under normal operating conditions. Two sets of metering venturis were used for the tests, the full flow set for the three SSME firings and the three SSME plus OMS firings, while the two-thirds flow set was used for one SSME out plus OMS operation. For OMS alone operation, the venturis are unchoked and precise measurement of propellant gas flows is not possible.

The propellant gases are controlled within the propulsion simulation system through a bipropellant autovalve. The autovalve contains two propellant control valves which are yoked together to admit the hydrogen and oxygen at pressures up to 3000 psi. Energy for actuation of the control valves was supplied by a regulated source of gaseous nitrogen at 3000 psi through a solenoid-operated valve.

Downstream of the venturis, gas flows are divided; part of the gases flow through a mixing injector to a collector chamber while the remaining portion flows directly to the individual injectors for each of the three SSME combustion chambers. Ignition occurs in the collector which utilizes an automotive-type sparkplug. Internal passages connect the collector to each SSME combustion chamber and provide for diversion of a small percentage of the mass flow to the OMS engines when required.

FACILITY EQUIPMENT

The hydrogen and oxygen were loaded into type-304 stainless steel pipes called "charge tubes" which were flanged to the autovalve. The oxygen charge tube was fabricated from 1-inch schedule 80 pipe and the hydrogen charge tube from $1\frac{1}{4}$-inch schedule 80 pipe. The charge tubes were of welded construction and "folded" for rack-mounting to provide a package approximately 39-feet long by 2-feet wide by $3\frac{1}{4}$-feet high (see fig. 2). The charge tube lengths were sized for an expansion wave reflection time of at least 80 milliseconds. This wavetime was achieved for oxygen and hydrogen with 50 and 200 foot lengths, respectively. On site storage of gaseous oxygen utilized a 38-bottle, 50 000 standard cubic foot roadable trailer rated at 2400 psi working pressure (see fig. 3). Charge tube loading for oxygen was accomplished by cascading to available pressure and then pumping with a nitrogen-driven oxygen pressure intensifier to desired pressure. On-site storage of gaseous hydrogen was accomplished using 6000 psi cylinders charged to 5000 psi with 99.995 percent pure hydrogen gas. Cylinders of hydrogen being used were mounted in an eight-cylinder rack. Loading of the hydrogen charge tube was by cascading from the lowest pressure cylinders first and proceeding to desired pressure using the high pressure cylinders.

The helium used for ignition testing and leak-checking was stored on-site in a 50 000 standard cubic foot roadable trailer rated at 2400 psi working pressure.

The gaseous nitrogen required for autovalve operation and checkout runs was stored on-site in a 70 000 standard cubic foot roadable trailer rated at 2400 psi working pressure and 6000 psi cylinders charged to 5000 psi with 99.998 percent pure water-pumped nitrogen gas. The high pressure gaseous nitrogen cylinders were mounted in a four-cylinder rack and cascaded to achieve the desired pressures. Suitable valving was incorporated in the systems to allow loading the hydrogen charge tube with gaseous nitrogen, hydrogen or helium and the oxygen charge tube with gaseous oxygen or nitrogen. NASA requested, prior to delivery of the model, that the BUNA-N (nitrile) O-rings used throughout the model be replaced with Viton-A O-rings because of oxygen service to 3000 psi. The Viton-A O-rings were used for the entire test. The systems components were cleaned to meet or exceed the NASA Lewis Research Center Plum Brook Station specification RDL-003 for liquid oxygen and gaseous oxygen components.

All gases used for this test were stored outdoors. Transfer of gases from storage locations to the charge tubes or autovalve was accomplished manually from a panel with appropriate hand valves, check valves, pressure regulators, relief valves, etc., to prevent a temperature rise from rapid pressure buildup. All tubing and valves used were

1/4 inch. All lines entering the vacuum chamber were welded with a minimum amount of fittings used in any system to prevent leakage. All lines venting to atmosphere terminated with check valves and bug screens to prevent contamination of any system. Hydrogen vent lines were manifolded together to an elevated, nitrogen-purged, vent stack in a safe location.

All oxygen vents were evaluated to discharge in a safe location. Systems were pressure-checked prior to use to $1\frac{1}{2}$ times the working pressure if hydrostatic tests were preformed or $1\frac{1}{4}$ times the working pressure if pneumatic testing was performed. All systems were leak checked at their working pressures prior to use, using helium mass spectrometer techniques, and thereafter at any time an engine gimbal change was made or the model worked on. Initial requirements for leak-checking called for using pressure decay and bubble-check methods. The pressure decay and bubble-check methods were discarded as they proved inadequate in locating specific leak points. The soap solutions around the model would wet the gaging and model construction made pinpointing a leak virtually impossible.

Prior to initiation of the test program a detailed safety analysis of the proposed program was conducted. The maximum credible accident was determined to be simultaneous rupture and ignition of the oxygen and hydrogen charge tube gases. This failure would result in an increase of pressure in the chamber of 4.12 torr. If only the hydrogen charge tube ruptured, a rise of 0.345 torr in pressure would result and for the oxygen tube a rise of 0.048 torr. In case of the hydrogen charge tube rupturing without burning, the method of dilution would be to open the 20-inch equalizing valve between the chamber and annulus which would raise the pressure to 15 torr and provide a mixture below the lower limits for combustion of hydrogen in air.

A redundant closing signal and solenoid valve were incorporated in the model as a safety measure, to insure that engine damage would not result from a single failure mode in the closing sequence.

The hydrogen charge tube was inerted prior to the start of each pumpdown of the vacuum chamber for a series of runs. Inertion of the hydrogen system was accomplished by using a vacuum pump to lower the system pressure to about 25 torr and then backfilling with nitrogen to ambient pressure to reduce the oxygen content in the air. The system was then evacuated again to 25 torr and backfilled with hydrogen.

The design of the system, line sizes, pressures, and timing of events were important in providing uncontaminated hydrogen to the autovalve. The inertion procedure would leave the system with a slug of nitrogen at the autovalve backed up by hydrogen, this step was then followed by opening the autovalve to the vacuum chamber as evacuation of the chamber was started. Timing of events was important to prevent diffusion of the nitrogen into the hydrogen. At a chamber pressure of 200 torr, the autovalve was closed and the charge tubes loaded to the desired pressures with oxygen and hydrogen, respectively, and the system was ready for firing. At the conclusion of a day's testing, the high pressure oxygen and hydrogen were vented outdoors to atmospheric pressure and the autovalve opened to the vacuum chamber for 20 minutes. The autovalve was then closed and the hydrogen and oxygen charge tubes inerted with nitrogen.

Instrumentation leads from the model were brought to three connector terminal units (CTU's) mounted on the support structure for the model, to allow sensor connections to be made within 3 to 5 feet of the model. Approximately 200 separate channels of data were provided.

Three pressurizable containers were located in the vacuum chamber within 8 feet of the model to provide an atmospheric environment for the spark coil, autovalve sequencer, and the charge amplifiers for the pressure transducers.

Two additional pressurized containers were provided in the vacuum chamber for the high-speed motion picture cameras, used to record "plug" ejection from the nozzles, and engine plume shape. These cameras were run at 500 and 200 frames-per-second, respectively.

A special calibration stand was fabricated for calibration of the differential pressure transducers while installed on the model. The calibration stand consisted of a 48-inch inclined water manometer with 1000-scale divisions. Full-scale value was setup to equal 0. 1 psi negative pressure relative to atmospheric pressure or one division was equal to 0.0001 psi with an absolute accuracy of 0.4 percent. Negative pressure was obtained with a syringe bulb and micrometer valve.

TEST DESCRIPTION

Prior to any runday, an engineering work order would be issued defining any changes to be made to the model or facility systems and any leak check or pressure check necessary because of these changes. The body flap, engine gimbal angles, and vertical tail would be positioned to agree with the day's test plan configuration as called for in the engineering work order. After all items had been signed off on the engineering work order, checkout runs were made with nitrogen or helium gases in the charge tubes to determine charge tube pressures and sequencer timing settings for the required oxygen-to-fuel ratio at the desired engine chamber pressure. A test plan for each day's operations was completed defining the test objectives, part numbers for the model configuration, engine gimbal angles, body flap position, charge tube pressures, timer settings, autovalve opening, closing, and holding pressures, and the simulated altitudes to be used. The cameras were then loaded and focused, lights positioned, and checked. For some tests, wooden engine plugs were installed in the throats of the three SSME engines. These plugs were attached to lanyards of linearly increasing weight with length, so that when they were expelled from the engines they would travel in predetermined arcs and fall in defined areas. The wooden plugs were used to cause the engine chamber pressures to reach steady state values earlier and provide additional milliseconds of steady state data. Use of the plugs were limited to the first run of each day. The timers were then set and locked in position, the atmospheric containers closed and leak checked, and the vacuum chamber pumpdown sequence started.

The vacuum chamber was pumped down to the maximum altitude desired for that day's testing and held at altitude by matching the bleed rate of gaseous nitrogen into the chamber to the pumping speed of the chamber at the desired pressure. To decrease altitude for the follow on runs, the gaseous nitrogen bleed rate into the chamber would be increased. When all checksheets were complete and the chamber was at proper altitude, the autovalve closing, holding, opening, oxygen, and hydrogen pressures would be adjusted or verified and the tests were started.

To start a test all manual switches were placed in their proper positions. Calibrations were taken on the FM tapes, and the FM tapes started for run data. When the fire button was pushed, a timed controlled sequence was started. At T-2.5 seconds the camera lights and timing signals were turned on, at T-1 second the visicorder was started and at timeout the valve sequence was started. The valve sequence at timeout consisted of applying power to the relays in the circuits and a main timer set for nominally 0.5 second to allow contact closures to make following application of actuating voltage. When the main timer timed out, it activated the autovalve opening and redundant closing timers, and "froze" and displayed the exact time used to define T-0. At nominally 19 milliseconds from T-0 the opening timer started propellant gas flows. When the propellant valve spools, which were mechanically yoked together, reached the full open position (approximately 22 msec from the open signal) two limit switches were activated which started the normal autovalve closing timer and the spark timer.

The spark timer timed out at nominally 3 milliseconds and the normal closing timer at nominally 65 milliseconds. At one second after the opening signal, the number two camera and lights were turned off and the visicorder stopped. At $3\frac{1}{2}$ seconds after the opening signal, the number one camera and lights were turned off and the timing signals stopped, which ended the automatic sequence. The FM data tapes were then turned off manually and the frozen timing display recorded as the T-0 time for that run for data retrieval purposes. See figure 4 for a representative sequence of valve operations. Visicorder traces were then scrutinized for proper valve operation and verification that desired parameters had been met prior to proceeding to the next lower simulated altitude. Approximately 20 to 30 minutes were allowed after each test to allow the heat transfer gages to cool down after which a resistance check was made of each of the 144 channels to determine if any were malfunctioning.

A day's testing would consist of from two to nine simulated altitudes for a given configuration. The tests were run using three shifts of eight hours each on a five day basis. From the start of pumpdown until the vacuum chamber door was opened consumed approximately 12 hours of time with 12 hours of additional time required for model configuration changes, cold flow timing checks, and leak checks.

At the end of a series of runs or a test day, the vacuum chamber was returned to atmospheric pressure and selected data from the FM tapes for each run reduced to engineering units and tabulated each half-millisecond for approximately 100 milliseconds of run time. The data was then reviewed to insure that gages had not saturated or malfunctioned and that test conditions had been those selected. The model changes desired for the next test sequence were then started and the procedures repeated. A short run report was then prepared containing the tape reel numbers, run numbers, run description, T-0 time, vacuum chamber pressures, and any discrepancies that may have been encountered. The run report and instrument data flowsheet for that day were then filed for data retrieval purposes.

Table I is a detailed listing of all hot firing tests performed at the Space Power Facility for this model.

Table II is a listing of vacuum chamber pressures required at various engine chamber pressures, to simulate the requested altitudes.

Table III is the key code used for a test description number.

Table IV defines the SSME gimbal angle key.

All tests were conducted using detailed checksheet procedures, controlled by a Test Conductor, using a Master Checksheet.

MODEL PERFORMANCE OBSERVATIONS

During the first checkout runs, operation of the autovalve was inconsistent. To improve the closing characteristics, the closing pressure piping was replumbed and the existing nitrogen accumulator replaced with one of larger volume (see fig. 5). To eliminate spurious electrical signals on timers, the wiring was replaced with shielded wire.

The auto-valve position indicator (rotary potentiometer) and its associated linkage failed six times during 88 firings and on one occasion was the cause of failure of the valve to open on command. The rotary potentiometer and its associated linkage was replaced with an available linear potentiometer. The linear potentiometer failed three times during the next 30 runs (lost position trace) but did not affect valve performance. Since all of the valve dynamics were recorded the linear potentiometer was replaced with a proximity switch for full open position and used in this manner until the conclusion of testing.

After the first week's testing, motion picture film data were reviewed and indicated motion of the seismic mount during firing. While not affecting data, a decision was made to stiffen the thrust support mount with the addition of two vertical supports which in essence eliminated the need for the seismic mount.

After run number 34, data analysis indicated a problem in the autovalve (low chamber pressure). A subsequent leak check, followed by teardown, revealed a 1/4-inch-wide by 1/8-inch-deep-burnout of metal in the "O"-ring groove between the injector and chamber. A review of movie camera data revealed the burnout took place during run number 32. The parts were welded, machined, cleaned, reassembled, and operations resumed in 2 days.

After run number 70, model inspection revealed a blowout of solder from the lower side of SSME number 1. This instrumented nozzle was replaced with an uninstrumented nozzle until run number 103 at which time repairs had been made and the instrumented nozzle replaced. During the test program, "O"-rings were replaced when leakage was noted. All "O"-rings would be replaced in the section where the leak was detected as a matter of routine.

The automotive-type spark plug used for ignition was replaced in the autovalve for each pumpdown or series of runs; both the electrode and base of the plugs continually burned away.

Late auto-ignition occurred approximately four times during the test series. The exact cause was never pinpointed. No damage to the model or abnormal operation was experienced during these occurrences.

The nozzle plugs used during the tests were intended to increase data time by causing the combustion chamber, to fill more rapidly. The plugs used varied from 90 to 150 grams in weight. The use of the nozzle plugs reduced the time required to reach stabilized flow by about 10 percent (about 3.4 msec). The return of the reflected shock-wave to the model did not occur, or was not observed, during firing at the lower altitudes. At the higher altitudes or pressure in the 3×10^{-5} range when using plugs, a reflected wave was noticed which decreased the overall data window. This wave could have been a reflection from a wall or obstruction as the discrepancy occurred at the maximum pitch angle that was run. During this same period, arc-over in a camera connection may have contributed to the observed phenomena.

For runs numbered 53 through 86, additional instrumentation was installed and the runs collectively referred to as a gas recovery temperature probe survey. Five gas temperature probes were installed to prove the validity of calculation of the gas recovery temperature at the probe location, by analysis of the resistance changes of the two wires during the short steady-state operating time. Each probe consisted of a pair of hot-wire anemometer-type thermometers of platinum-10% rhodium wire supported on the tips of hollow steel needles. The wires were parallel to the model surface and 0.00254 millimeter in diameter. Their lengths differed by a factor of 2 (approximately 1 and 2 mm, respectively). Anticipated breakage or other problems in using the "fine" wires did not occur. The only problem occurred when "solder splatter" apparently hit the wires during the blowout of SSME nozzle number 1 during run number 70. The wires were placed approximately 1/2 inch from the instrumented surface. A series of runs were made with "long" probes which placed the wires either 3/4 or $1\frac{1}{4}$ inches from the surface.

The total heat transfer gage consists of a thin-film of platinum fused to a pyrex substrate and insulated by a thin dielectric coating of magnesium fluoride. Pressure levels less than 15 psia were measured with Hidyne variable reluctance transducers and those greater than 15 psia were measured with Kistler piezo-electric transducers. The Hidyne variable reluctance transducers were not acceleration compensated, making the seismic mount necessary. The quick-look visicorder data was the most reliable method of determining, after each run, whether or not problems were developing within the test article. If a problem was indicated, testing for the day would be terminated and the problem investigated before any major damage could occur. Television coverage of the runs was available and used during testing but because of the short time duration for a given test, could only show that the engines had fired.

The high-speed motion picture data could not be used immediately as film processing time was involved. The practice of verifying the integrity of all gages and transducers after each run eliminated the possibility of making a run and not recording critical parameters. By reducing the data to engineering units at the conclusion of a day's testing, trends could be established, noise eliminated, and gains revised for follow-on runs to avoid signal saturation, or insensitivity of a data channel, thus providing a "clean" data tape for computer reduction. Data reduction from the FM tape could be started at a precise millisecond from the defined time T-0. Firing of the engines at an exact pressure altitude was a simple problem in a vacuum chamber of this large a volume, but recording the pressure changes during a firing at the higher altitudes (3.0×10^{-5} pressure range) was questionable. The response of the vacuum gauging is not fast enough, nor was the instrumentation sufficient to show the pressure differentials throughout the vacuum chamber while the engines are causing the rapid pressure rise.

HEATING RATE TEST RESULTS

The data tapes, instrument flowsheets, and run report for each run were delivered to NASA Lewis Research Center, Cleveland, Ohio, for computer reduction and delivery to the Space Division/Rockwell International for analysis. The data that was reduced on a daily basis to engineering units, and the visicorder traces from each run were delivered to the Space Division/Rockwell International at the conclusion of the tests.

The data reduced at Lewis Cleveland and furnished to Rockwell International consisted of approximately 150 pages of calculated data and averages for 100 milliseconds of run data for each run, and microfilm of each of the graphical plots requested. A Dataman tape for the entire series of runs was also provided.

Figures 7 through 11 are typical plots of the data being provided. Figures 7 and 9 are typical plots showing the pressure raise ×1000 at the base of the model during an engine firing, against time in milliseconds. Figures 8, 10, and 11 are typical plots for various points at the base of the model and show (delta-T)/2 in degrees Farenheit and the variable and constant heating rates in Btu/ft^2-sec against time in milliseconds during an engine firing.

A total of 168 hot firings were made requiring 40 vacuum chamber pumpdowns during 44 working days. A total of 78 cold flow tests were accomplished with nitrogen and/or helium to establish valve timing and operational characteristics prior to and during these tests. The data from 154 of the 168 hot firing runs was reduced; the remainder of the runs being those that were repeated due to improper O/F ratio, or for some other nonsatisfactory condition.

CONCLUDING REMARKS

For any follow-on tests requiring updating of the existing model, the following recommendations are made:

1. Purge or inertion ports should be provided on the autovalve for the hydrogen and oxygen systems, to allow complete blowdown type purges from the hydrogen and oxygen sources through the autovalve and out to atmosphere, eliminating dead legs. This would eliminate the need for vacuum type inertions.

2. Replace the automotive type spark plug with one more compatible with the severe conditions encountered. Shield the inner electrode and porcelain and eliminate the base electrode so that the plug fires to the outer ring.

3. Replace the variable reluctance transducers used for these tests with acceleration compensated transducers and eliminate the seismic mount.

4. Minimize internal flow passage volumes in the model to reduce fill time and achieve steady state conditions more rapidly.

5. Provide a separate hydrogen and oxygen flow system and metering venturis for the OMS engines to enable precise flow measurements through these systems.

6. Eliminate the valve position rotary potentiometer and its' associated linkage and replace this system with proximity switches for fully open and fully closed indications.

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TABLE I. - SHUTTLE BASE HEATING TESTS
(Space Power Facility, Plumbrook Station, Sandusky, Ohio)

Date	Sequence run number	Test description	Test objective	Engine pressure P_c	Simulated altitude (K-ft)	Altitude pressure torr	Remarks
4-21-75	001	NHA 0500 +	Hot firing check run	750	Not critical	1.7×10^{-2}	Valve opening time slightly long.
	002	NHA 0500				1.2×10^{-2}	Repeat run # 001
4-22-75	003	NFA 0508 +	S.S.M.E. Gimbal survey	1500	240	1.27×10^{-2}	Valve failed to open.
	004						Valve failed to open, FM system not started.
	005						Valve failed to open.
	006						Valve failed to open.
	007	NHA 0508 +		750		8.3×10^{-3}	Valve opened, but position pot failed in the open position.
4-23-75	008	NHA 0500	Gimbal survey + Re. no.		Not critical	2.5×10^{-1}	Normal operation.
	009			1050	Not critical	4.0×10^{-2}	Normal operation .
	010			1275		2.3×10^{-2}	Normal operation.
	011			1500		1.8×10^{-2}	Normal operation.
	012	NFA 0508		1500	240	1.27×10^{-2}	Normal operation.
	013	NFA 0504			150	5.44×10^{-1}	Normal operation.
4-24-75	014	DFA 0508 +	Flap deflection	1500	240	1.27×10^{-2}	Normal operation.
	015	DFA 0508					Normal operation.
	016	DFA 0504			150	5.44×10^{-1}	Varian signal negative.
4-25-75	017	OFA 0508 +			240	1.27×10^{-2}	Normal operation.
	018	OFA 0508					Normal operation.
	019	OFA 0504			150	5.44×10^{-1}	Normal operation.
4-28-75	020	NFA 0208 +	S.S.M.E. Gimbal survey	1500	240	1.27×10^{-2}	Auto-ignition, after spark.

TABLE I. - Continued. SHUTTLE BASE HEATING TESTS
(Space Power Facility, Plumbrook Station, Sandusky, Ohio)

Date	Sequence run number	Test description	Test objective	Engine pressure P_c	Simulated altitude (K-ft)	Altitude pressure torr	Remarks
4-28-75	021	NFA 0208	S.S.M.E. Gimbal survey	1500	240	1.27×10^{-2}	I.R.I.G. stopped at 3 seconds - normal 4
	022	NFA 0204			150	5.44×10^{-1}	Normal operation.
4-29-75	023	NFA 0108 +			240	1.27×10^{-2}	Normal operation.
	024	NFA 0108					Normal operation.
	025	NFA 0104			150	5.44×10^{-1}	Normal operation.
4-30-75	026	NFA 0609 +			360	3.01×10^{-5}	A/V open too long, redundant signal closed.
	027	NFA 0609	A/V elect. check.	N/A	Not critical	3.0×10^{-5}	Charge tube pressure 100 psi. Checked good.
	028		S.S.M.E. Gimbal survey.	1500	360	3.01×10^{-5}	Arcing in vacuum chamber.
	029	NFA 0608			240	1.27×10^{-2}	Normal operation.
	030	NFA 0604			150	5.44×10^{-1}	Normal operation.
5-1-75	031	NFA 0A08 +	Thrust structure compliance	1500	240	1.27×10^{-2}	Normal operation.
	032	NFA 0A08					"O" Ring burnout.
	033	NFA 0A07			200	7.71×10^{-2}	Low engine P_c.
	034	NFA 0A05			160	3.72×10^{-1}	Low engine Pc.
5-5-75	035	NHA 0908 +	I.B.F.F. Comparison	750	240	6.14×10^{-3}	Normal operation.
	036	NHA 0908			240	6.4×10^{-3}	Normal operation.
5-6-75	037	NHA 0808 +		750	240	6.4×10^{-3}	Normal operation.
	038	NHA 0808					Normal operation.
	039	NHA 0804			150	2.72×10^{-1}	O/F off, lost FM 403
	040						Rerun of 039, O/F still off
	041	NHA 0803			140	4.07×10^{-1}	Position pot failed.
	042	NHA 0802			130	6.05×10^{-1}	No ignition - cold flow, early timing.

TABLE I. - Continued. SHUTTLE BASE HEATING TESTS
(Space Power Facility, Plumbrook Station, Sandusky, Ohio)

Date	Sequence run number	Test description	Test objective	Engine pressure P_c	Simulated altitude (K-ft)	Altitude pressure torr	Remarks
5-6-75	043	NHA 0802	I.B.F.F. Comparison	750	130	$6.05x10^{-1}$	O/F off.
	044	NHA 0801			120	$9.15x10^{-1}$	O/F off.
5-8-75	045	NHA 0808 +		750	240	$6.4x10^{-3}$	Non fire - cold flow, repeat of 5-6 run for O/F = 6
	046	NHA 0808					Normal operation.
	047	NHA 0804			150	$2.72x10^{-1}$	Normal operation.
	048	NHA 0803			140	$4.07x10^{-1}$	Normal operation.
	049	NHA 0802			130	$6.05x10^{-1}$	Normal operation.
	050	NHA 0801			120	$9.15x10^{-1}$	Normal operation.
5-9-75	051	NHA 0D08 +			240	$6.4x10^{-3}$	Normal operation.
	052	NHA 0D08			240	$6.4x10^{-3}$	Normal operation.
5-12-75	053	NFA 0508 X	Temperature probe survey	1500	240	$1.27x10^{-2}$	A/V failed to open.
	054	NFA 0508 X					Auto - ignition, no spark signal.
5-13-75	055	NFA 0508 X					Position pot failed.
	056	NFA 0508 X					Normal, repeat of 055.
	057	NFA 0504 X			150	$5.44x10^{-1}$	Normal operation.
	058	NFA 0504 X					Normal operation.
5-14-75	059	NFA 0608 X			240	$1.27x10^{-2}$	Lost visicorder trace.
	060	NFA 0604 X			150	$5.44x10^{-1}$	P_c-2 trace lost.
	061	NFA 0604 X					P_c-2 still out.
5-15-75	062	NFA 0009 X			360	$3.01x10^{-5}$	Normal operation.
	063	NFA 0008 X			240	$1.27x10^{-2}$	Normal operation.
	064	NFA 0007 X			200	$7.71x10^{-2}$	Normal operation.
	065	NFA 0006 X			180	$1.73x10^{-1}$	Normal operation.
	066	NFA 0005 X			160	$3.72x10^{-1}$	Normal operation.
	067	NFA 0004 X			150	$5.44x10^{-1}$	Normal operation.
	068	NFA 0003 X			140	$8.00x10^{-1}$	Normal operation.

TABLE I. - Continued. SHUTTLE BASE HEATING TESTS
(Space Power Facility, Plumbrook Station, Sandusky, Ohio)

Date	Sequence run number	Test description	Test objective	Engine pressure P_c	Simulated altitude (K-ft)	Altitude pressure torr	Remarks
5-15-75	069	NFA 0002 X	Temperature probe survey	1500	130	1.191×10^{0}	Normal operation.
	070	NFA 0001 X			120	1.796×10^{0}	Normal operation.
5-16-75	071	NFA 0008 XL	Temperature long probe survey	1500	240	1.27×10^{-2}	Normal operation.
	072	NFA 0007 XL			200	7.71×10^{-2}	Normal operation.
	073	NFA 0004 XL			150	5.44×10^{-1}	Normal operation.
	074	NFA 0003 XL			140	8.00×10^{-1}	Normal operation.
	075	NFA 0002 XL			130	1.191×10^{0}	Normal operation.
	076	NFA 0001 XL			120	1.796×10^{0}	Normal operation .
5-19-75	077	NFA 0008 X	Temperature probe survey	1500	240	$1,27 \times 10^{-2}$	Valve failed to open.
	078	NFA 0008 X			240	1.27×10^{-2}	Valve opened, increased opening press. (100psi):
	079	NFA 0007 X			200	7.71×10^{-2}	Normal operation.
	080	NFA 0006 X			180	1.73×10^{-1}	Normal operation.
	081	NFA 0005 X			160	3.72×10^{-1}	Normal operation.
	082	NFA 0004 X			150	5.44×10^{-1}	Normal operation.
	083	NFA 0003 X			140	8.00×10^{-1}	Normal operation.
	084	NFA 0002 X			130	1.19×10^{0}	Normal operation.
	085	NFA 0001 X			120	1.79×10^{0}	Normal operation.
5-20-75	086	OFA 0004 +	Flap effect	1500	150	5.44×10^{-1}	Lost position pot, auto-ignition, valve slow.
	087	OFA 0004				5.44×10^{-1}	Traces indicate trouble.
5-27-75	088	OFA 0008			240	1.27×10^{-2}	No ignition.
	089	OFA 0008					Normal operation.
	090	OFA 0004			150	5.44×10^{-1}	Normal operation.

TABLE I. - Continued. SHUTTLE BASE HEATING TESTS
(Space Power Facility, Plumbrook Station, Sandusky, Ohio)

Date	Sequence run number	Test description	Test objective	Engine pressure P_c	Simulated altitude (K-ft)	Altitude pressure torr	Remarks
5-28-75	091	DFA 0008	Body flap effect	1500	240	1.27×10^{-2}	Timer 2 fired prematurely.
	092	DFA 0008					Lost spark trace. Good run
	093	DFA 0004			150	5.44×10^{-1}	No spark trace, good data.
5-29-75	094	NFA 0009	Altitude survey	1500	360	3.01×10^{-5}	Normal operation.
	095	NFA 0008			240	1.27×10^{-2}	Normal operation.
	096	NFA 0007			200	7.7×10^{-2}	Normal operation.
	097	NFA 0006			180	1.73×10^{-1}	Normal operation.
	098	NFA 0005			160	3.72×10^{-1}	Normal operation.
	099	NFA 0004			150	5.44×10^{-1}	Normal operation.
	100	NFA 0003			140	8.00×10^{-1}	Normal operation.
	101	NFA 0002			130	1.19×10^{0}	Normal operation.
	102	NFA 0001			120	1.796×10^{0}	Normal operation.
5-30-75	103	NQA 0008	Reynolds no. effect	375	240	3.2×10^{-3}	Normal operation.
	104	NQA 0008					Repeat of run no. 103
	105	NHA 0008		750	240	3.2×10^{-3}	Normal operation.
	106	NQA 0004		375	150	1.36×10^{-1}	Normal operation.
	107	NHA 0004		750	150	2.72×10^{-1}	Normal operation.
6-2-75	108	NFA 0408	Gimbal survey	1500	240	1.27×10^{-2}	Normal operation.
	109	NFA 0404			150	5.44×10^{-1}	Normal operation.
6-3-75	110	NFA 0308			240	1.27×10^{-2}	Normal operation.
	111	NFA 0304			150	5.44×10^{-1}	Normal operation.
6-4-75	112	NFA 0708			240	1.27×10^{-2}	Normal operation.
	113	NFA 0704			150	5.44×10^{-1}	O_2 injector trace bad.
6-5-75	114	NFA 0F08	Combined gimbal	1500	240	1.27×10^{-2}	No spark trace, O/F high.
	115	NFA 0F08					No spark trace, O/F high.
	116	NFA 0F08					No spark trace, O/F high.

TABLE I. - Continued. SHUTTLE BASE HEATING TESTS
(Space Power Facility, Plumbrook Station, Sandusky, Ohio)

Date	Sequence run number	Test description	Test objective	Engine pressure P_c	Simulated altitude (K-ft)	Altitude pressure torr	Remarks
6-5-75	117	NFA OF08	Combined gimbal	1500	240	1.27×10^{-2}	No spark trace, H_2 venturi press. low.
	118	NFA OF04			150	5.44×10^{-1}	H_2 still low.
	119	NFA OE08			240	1.27×10^{-2}	O/F off.
	120	NFA OE04			150	5.44×10^{-1}	O/F off was visicorder calibration error.
6-9-75	121	NFA OA08	Structure compliance	1500	240	1.27×10^{-2}	Problem with visicorder.
	122	NFA OA08					Normal operation.
	123	NFA OA07			200	7.71×10^{-2}	Normal operation.
	124	NFA OA05			160	3.72×10^{-1}	Normal operation.
	125	NFA OA04			150	5.44×10^{-1}	Normal operation.
	126	NFA OA03			140	8.00×10^{-1}	Normal operation.
	127	NFA OA01			120	1.678×10^{0}	O_2 flow low.
	128	NFA OA01					Repeat of #127, Normal.
6-10-75	129	NFA OE08	Combined gimbal	1500	240	1.27×10^{-2}	Repeat of # 119 Normal.
	130	NFA OE04			150	5.44×10^{-1}	Repeat of # 120, Normal.
6-11-75	131	NFA OB08	Structure compliance	1500	240	1.27×10^{-2}	O/F Ratio off.
	132	NFA OB08					Repeat # 131, Normal.
	133	NFA OB07			200	7.7×10^{-2}	Normal operation.
	134	NFA OB05			160	3.72×10^{-1}	Normal operation.
	135	NFA OB04			150	5.44×10^{-1}	Normal operation.
	136	NFA OB03			140	8.00×10^{-1}	Normal operation.
	137	NFA OB01			120	1.676×10^{0}	Normal operation.
6-12-75	138	NHA 0808	I.B.F.F. Comparison	750	240	6.4×10^{-3}	Repeat of # 046.
	139	NHA 0808					Repeat of # 138.
	140	NHA 0806			180	8.65×10^{-2}	Data error.
	141	NHA 0806					Repeat of # 140, Normal.

TABLE I. - Continued. SHUTTLE BASE HEATING TESTS
(Space Power Facility, Plumbrook Station, Sandusky, Ohio)

Date	Sequence run number	Test description	Test objective	Engine pressure P_c	Simulated altitude (K-ft)	Altitude pressure torr	Remarks
6-12-75	142	NHA 0804	I.B.F.F. Comparison	750	150	2.72×10^{-1}	Repeat of # 047.
	143	NHA 0803			140	4.07×10^{-1}	Repeat of # 048.
	144	NHA 0802			130	6.05×10^{-1}	Repeat of # 049.FM Prob.
	145	NHA 0802			130	6.05×10^{-1}	Repeat of # 144, Normal.
	146	NHA 0801			120	9.15×10^{-1}	Repeat of # 050, Normal.
6-13-75	147	NFA 0508	Gimbal survey	1500	240	1.27×10^{-2}	Repeat of # 012, O/F hi.
	148	NFA 0508					Repeat of # 147, Normal.
	149	NFA 0504			150	5.44×10^{-1}	Normal operation.
6-16-75	150	NO4 F839	OHMS alone	125	360	6.01×10^{-5}	Normal operation.
	151	NO4 F838			240	2.53×10^{-1}	Wrong altitude pressure.
6-17-75	152	NO4 F839			360	6.01×10^{-5}	Repeat of # 150, Normal.
	153	NO4 F839					Repeat of # 152, Normal.
	154	NO4 F838			240	2.53×10^{-2}	Normal operation.
	155	NO4 F838					Repeat of # 154,with camera.
6-18-75	156	NO4 F819			360	6.01×10^{-5}	Normal operation.
	157	NO4 F819					Change spark timing.
	158	NO4 F818			240	2.53×10^{-2}	Normal pperation.
	159	NO4 F818					Repeat of # 158, with camera W/O lights.
	160	NO4 F818					Repeat of # 158, with camera with lights.
	161	NO4 F829			360	6.01×10^{-5}	Normal operation,
	162	NO4 F829					Spark changed to 3.5 from 4 on # 161.
	163	NO4 F828			240	2.53×10^{-2}	Camera on , no lights.
	164	NO4 F828					Camera on, with lights.
6-19-75	165	NF2 HC04	Abort # 2 with OHMS	1500 62.5	150	5.44×10^{-1}	Normal operation.

TABLE I. - Concluded. SHUTTLE BASE HEATING TESTS
(Space Power Facility, Plumbrook Station, Sandusky, Ohio)

Date	Sequence run number	Test description	Test objective	Engine pressure P_c	Simulated altitude (K-ft)	Altitude pressure torr	Remarks
6-20-75	166	NF2 HC09	Abort # 2 with OHMS	1500 62.5	360	3.01×10^{-5}	Normal operation.
	167	NF2 HC08			240	1.27×10^{-2}	Normal operation.
	168	NF2 HC04			150	5.44×10^{-1}	Normal operation.

Table 2. SIMULATED ALTITUDE VS. VACUUM CHAMBER PRESSURE

SSME ENGINE CHAMBER PRESSURE = 1500 psia

ALTITUDE FEET	VACUUM CHAMBER PRESSURE TORR
0	760
120,000	1.796
130,000	1.1909
140,000	8.0000×10^{-1}
150,000	5.4365×10^{-1}
160,000	3.7208×10^{-1}
180,000	1.7312×10^{-1}
200,000	7.7143×10^{-2}
240,000	1.2669×10^{-2}
360,000	3.0066×10^{-5}

SSME ENGINE CHAMBER PRESSURE = 750 psia

ALTITUDE FEET	VACUUM CHAMBER PRESSURE TORR
0	760
120,000	8.9773×10^{-1}
150,000	2.7182×10^{-1}
240,000	6.3345×10^{-3}

OMS ENGINE CHAMBER PRESSURE = 125 psia

ALTITUDE FEET	VACUUM CHAMBER PRESSURE TORR
0	760
240,000	2.5339×10^{-2}
360,000	6.0131×10^{-5}

Vacuum chamber pressure for a simulated altitude were derived from the following formulas to hold proper nozzle pressure ratio.

For SSME firings (with or without OMS):

$$P_{\text{vacuum chamber}} = \frac{P_{\text{engine chamber SSME}}}{3000} \times P_{\text{altitude}}$$

for OMS alone firings:

$$P_{\text{vacuum chamber}} = \frac{P_{\text{engine chamber OMS}}}{125} \times P_{\text{altitude}}$$

TEST DESCRIPTION KEY CODE

CHARACTER NUMBERS

1 2 3 4 5 6 7 8

BODY FLAP POSITION (character 1)

- Off — 0
- Neutral = 0° — N
- Deflected = 20° — D

SSME CHAMBER PRESSURE (character 2)

- Full=1500 psi — F
- Half= 750 psi — H
- Off — 0

SSME OPERATING (character 3)

- All Operating — A
- No. 1 Engine Out — 1
- No. 2 Engine Out — 2
- No. 3 Engine Out — 3
- No Engines Operating — 4

OMS CHAMBER PRESS (character 4)

- Double=250 psi — D
- Full = 125 psi — F
- Half = 63 psi — H
- Off — 0

SSME GIMBAL ANGLE (character 5)

- Parallel burn null — 0
- Parallel burn-11 Pitch — 1
- Parallel burn - 5pitch — 2
- Parallel burn-2 pitch — 3
- Parallel burn+2 pitch — 4
- Parallel burn+5 pitch — 5
- Parallel burn+11 pitch — 6
- Parallel burn-2 yaw — 7
- Static null — 8
- +4 pitch — 9
- A Thrust Structure Compliance
- B Thrust Structure Compliance
- C Abort
- D +8 Pitch
- E +Pitch - Yaw 2 (135°)
- F -Pitch - Yaw 2 (225°)

See Table 4 for actual gimbal angles

OMS GIMBAL ANGLES (character 6)

DEGREES

		PITCH	YAW
0	LH	0	0
	RH	0	0
1	LH	+4	-12°17'
	RH	+4	+12°17'
2	LH	-4	-12°17'
	RH	-4	+12°17'
3	LH	0	-12°17'
	RH	0	+12°17'

SIMULATED ALTITUDE (character 7)

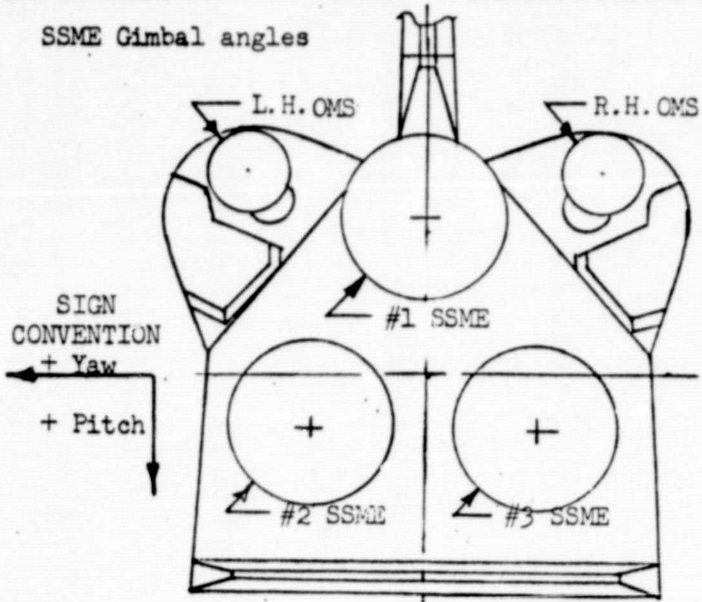
- 0 Atmospheric
- 1 120,000 feet
- 2 130,000 feet
- 3 140,000 feet
- 4 150,000 feet
- 5 160,000 feet
- 6 180,000 feet
- 7 200,000 feet
- 8 240,000 feet
- 9 360,000 feet

PLUG PROBE (character 8)

- \+ Engine plugs used
- X Gas probes installed
- XL Long probes installed

Table 3

SSME Gimbal angles



Character #5 "KEY"	Engine	Degrees Pitch	Yaw
0	#1	0	0
Parallel burn	#2	0	+3.5
"Null"	#3	0	+3.5
1			
Parallel burn	#1	-11	0
-11 Pitch	#2	-11	-3.5
	#3	-11	+3.5
2	#1	-5	0
Parallel burn	#2	-5	-3.5
-5 Pitch	#3	-5	+3.5
3	#1	-2	0
Parallel burn	#2	-2	-3.5
-2 Pitch	#3	-2	+3.5
4	#1	+2	0
Parallel burn	#2	+2	-3.5
+2 Pitch	#3	+2	+3.5
5	#1	+5	0
Parallel burn	#2	+5	-3.5
+5 Pitch	#3	+5	+3.5
6	#1	+11	0
Parallel burn	#2	+11	-3.5
+11 Pitch	#3	+11	+3.5
7	#1	0	-2
Parallel burn	#2	0	-5.5
-2 Yaw	#3	0	+1.5
8	#1	0	0
Static null	#2	0	0
	#3	0	0
9	#1	+4	0
+4 Pitch	#2	+4	0
	#3	+4	0

Character	Engine	Pitch	Yaw
A	#1	0	0
Thrust structure	#2	0	-3.5
compliance	#3	-2	+3.5
B	#1	+5	0
Thrust structre	#2	+5	-3.5
compliance	#3	+5	+3.5
C	#1	+1.41	-1.41
Abort	#2	0	0
	#3	+2	0
D	#1	+8	0
+8 Pitch	#2	+8	0
	#3	+8	0
E	#1	+1.41	-1.41
+ Pitch -Yaw	#2	+1.41	-4.91
2(135°)	#3	+1.41	+2.09
F	#1	-1.41	-1.41
- Pitch -Yaw	#2	-1.41	-4.91
2(225°)	#3	-1.41	+2.09

Table 4

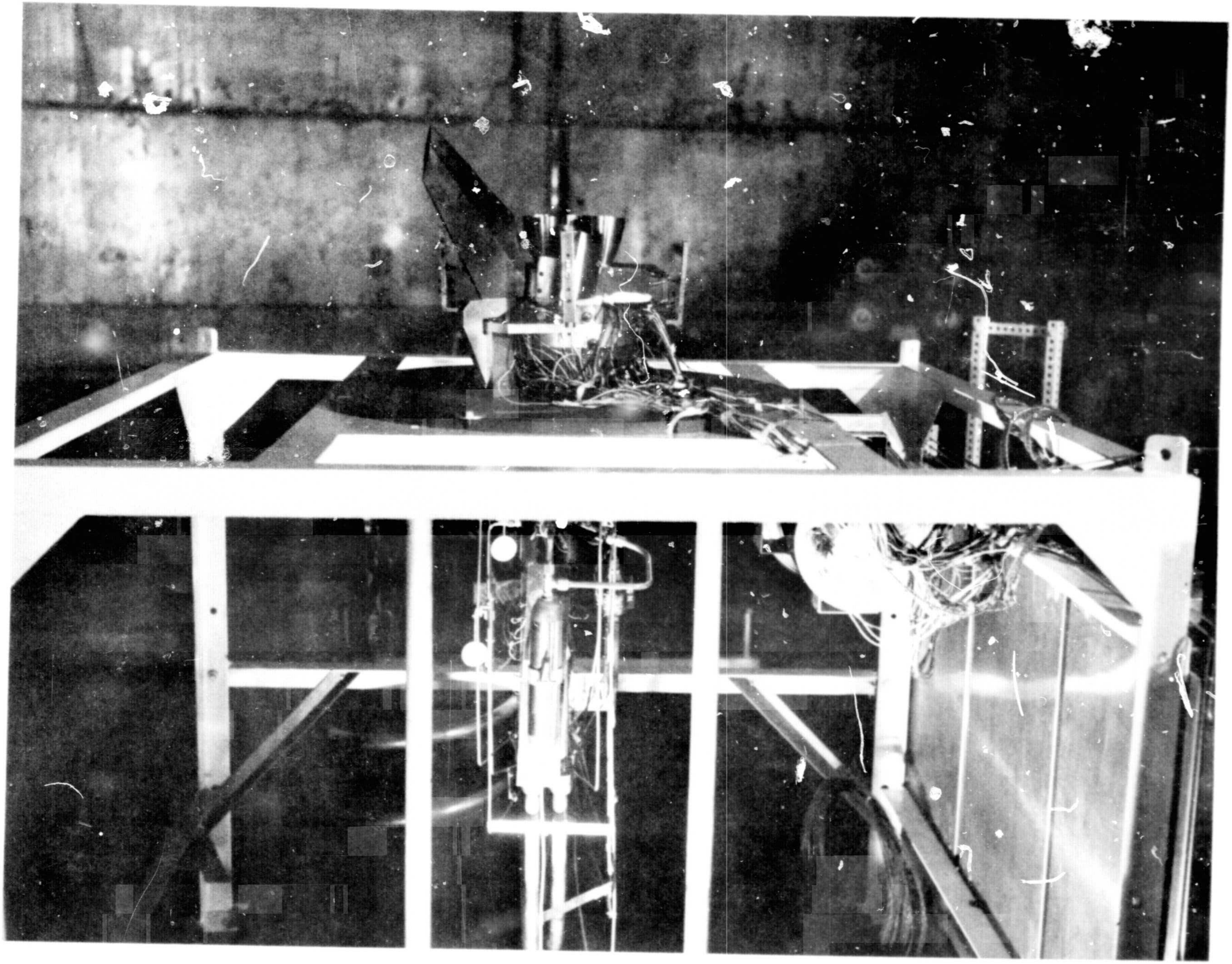


FIGURE 1

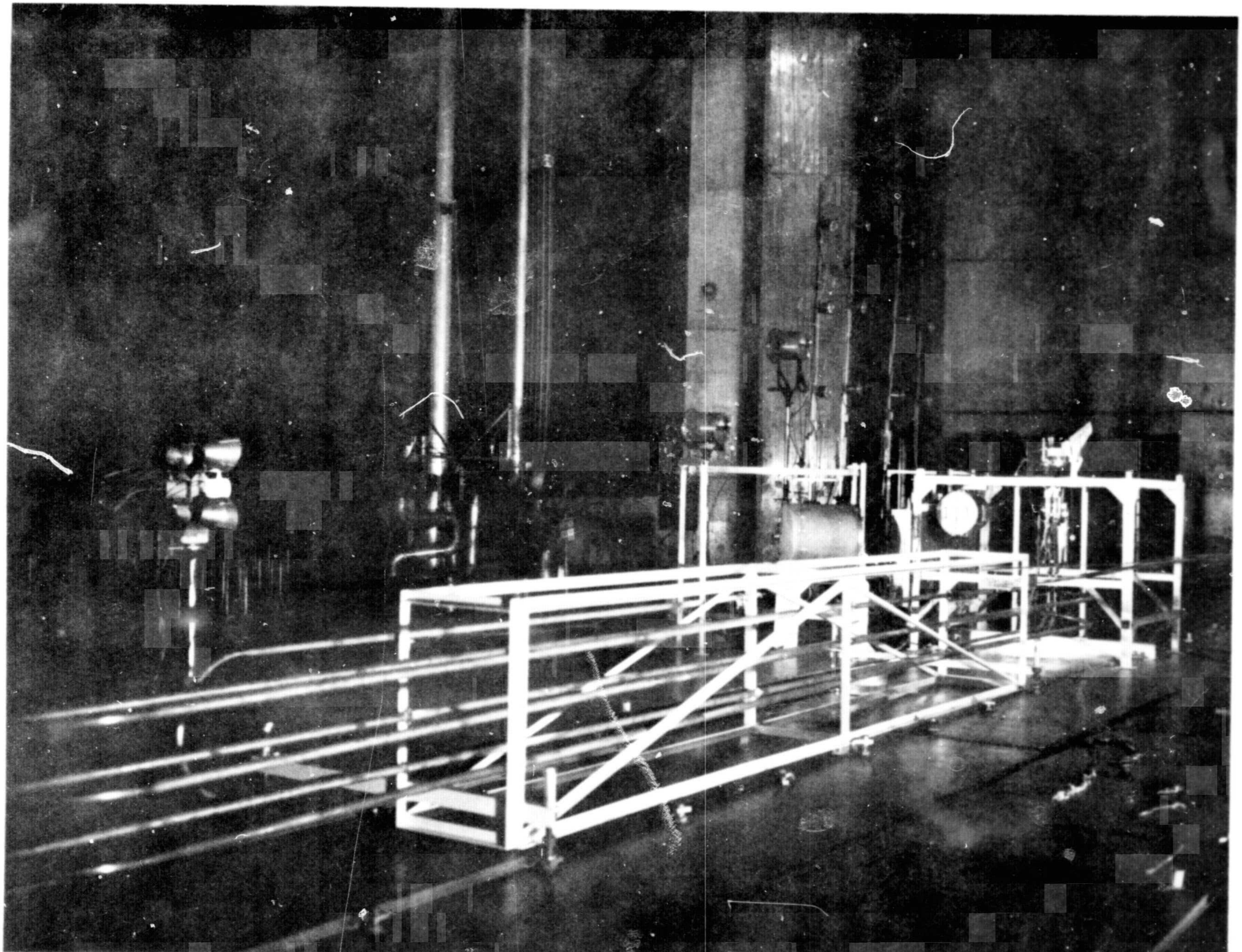


FIGURE 2

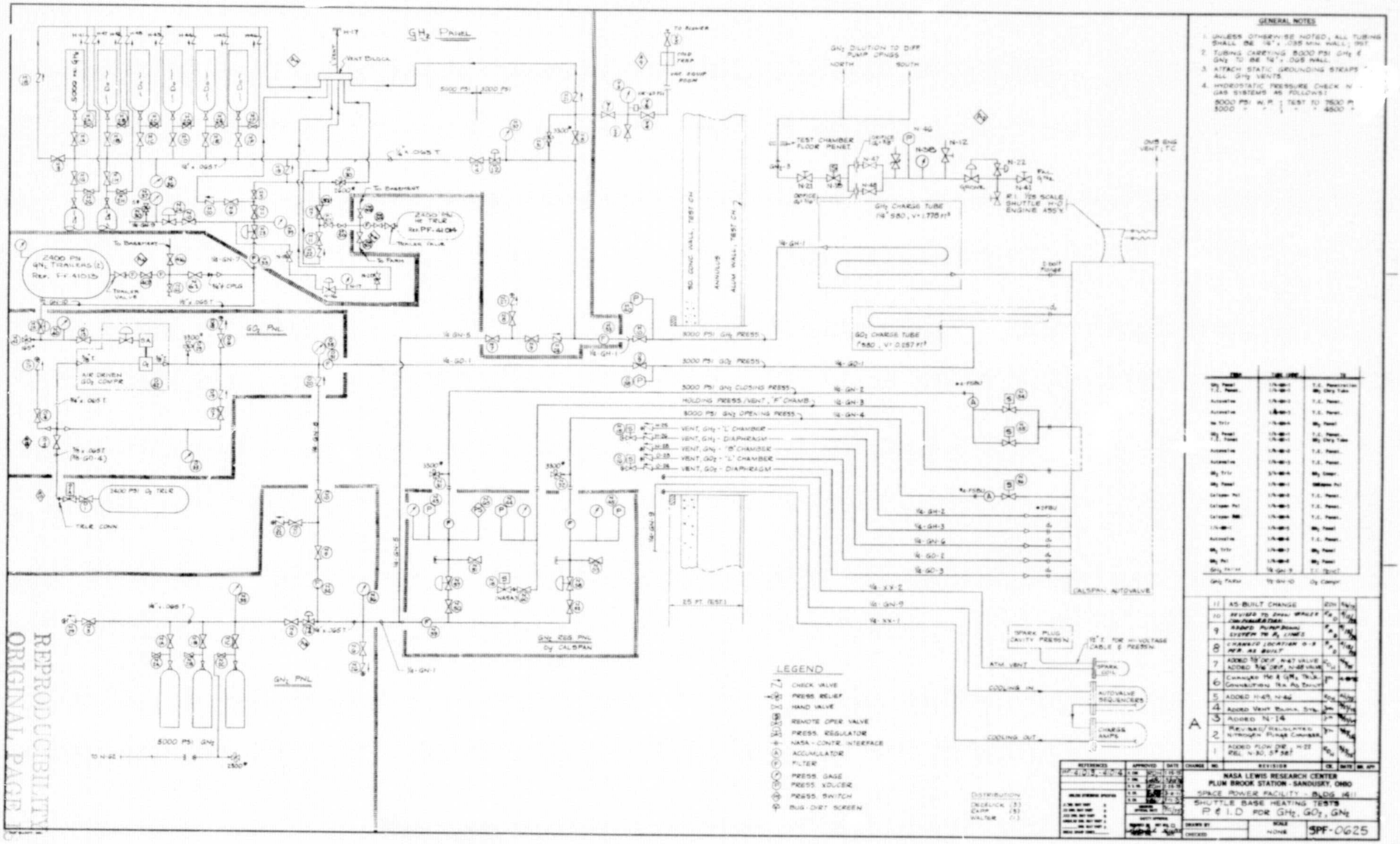
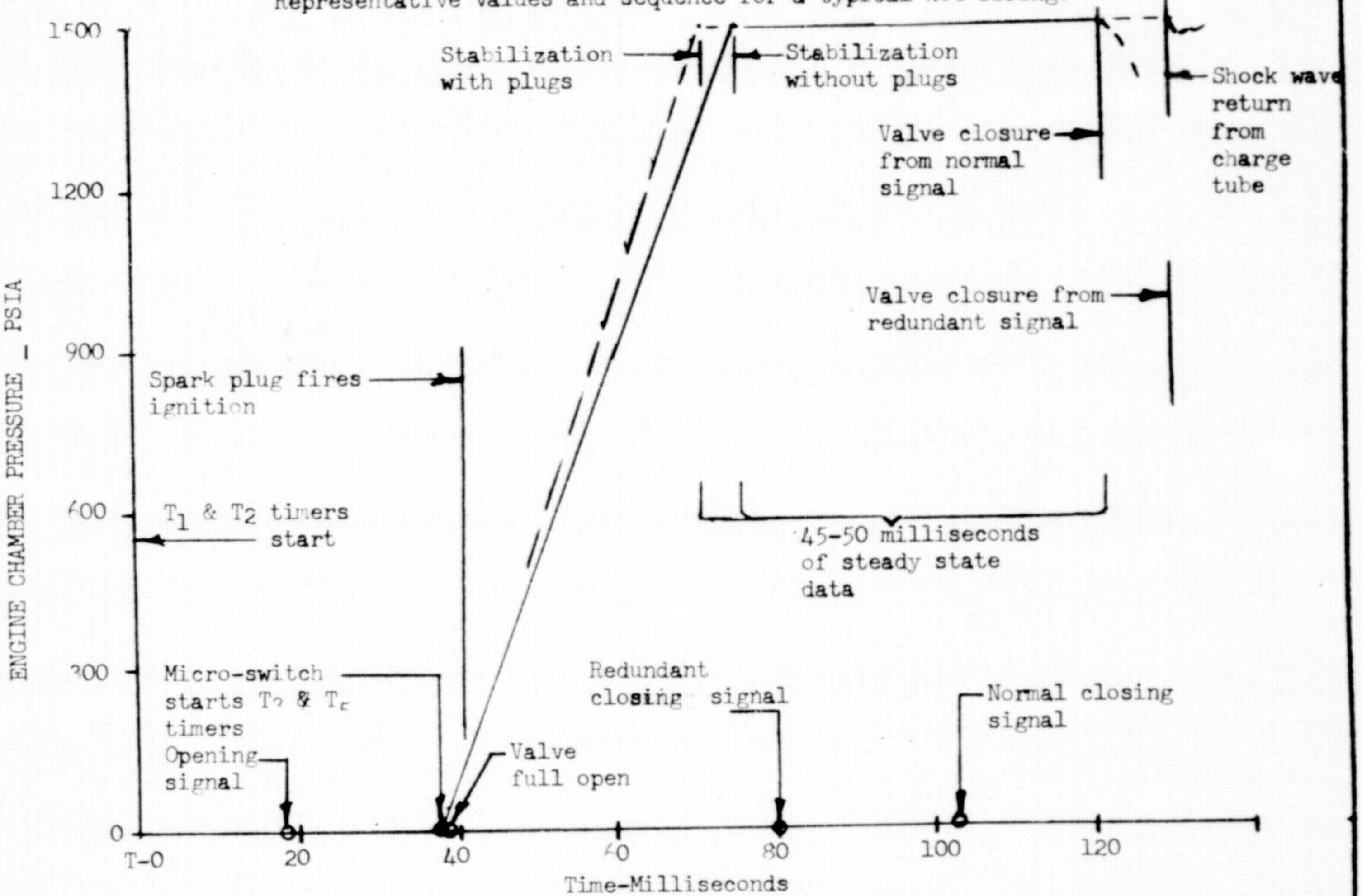
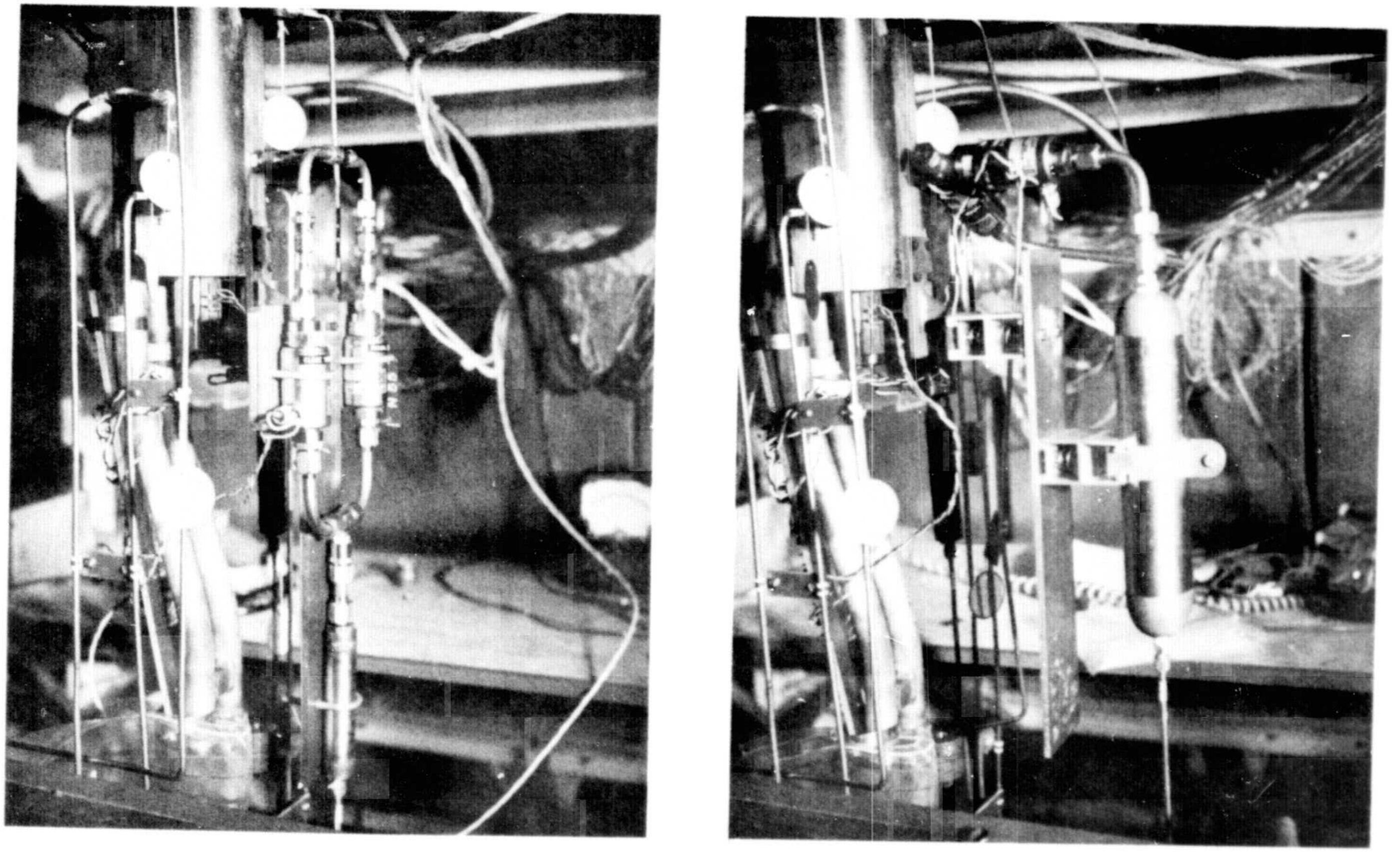

GENERAL NOTES
1. UNLESS OTHERWISE NOTED, ALL TUBING SHALL BE 1/4" x .035 MIN. WALL; SST
2. TUBING CARRYING 5000 PSI GH2 & GN2 TO BE 1/4" x .065 WALL.
3. ATTACH STATIC GROUNDING STRAPS ALL GH2 VENTS.
4. HYDROSTATIC PRESSURE CHECK GAS SYSTEMS AS FOLLOWS:
5000 PSI W.P. ; TEST TO 7500
3000 " " ; " " 4500 "
GH2 PANEL
GO2 PNL
GN2 PNL
GN2 REG PNL
GN2 CALSPAN
2400 PSI GN2 TRAILERS (2) REF. PF-41013
2400 PSI H2 TRLR REF. PF-41014
2400 PSI O2 TRLR
GH2 CHARGE TUBE
GO2 CHARGE TUBE
CALSPAN AUTOVALVE
3000 PSI GH2 PRESS
3000 PSI GO2 PRESS
3000 PSI GN2 CLOSING PRESS
HOLDING PRESS./VENT, "F" CHAMB.
3000 PSI GN2 OPENING PRESS
VENT, GH2 - "L" CHAMBER
VENT, GH2 - DIAPHRAGM
VENT, GN2 - "B" CHAMBER
VENT, GO2 - "L" CHAMBER
VENT, GO2 - DIAPHRAGM
SPARK PLUG CAVITY PRESS'N
ATM VENT
COOLING IN
COOLING OUT
AUTOVALVE SEQUENCERS
CHARGE AMPS
5000 PSI GN2
LEGEND
CHECK VALVE
PRESS. RELIEF
HAND VALVE
REMOTE OPER VALVE
PRESS. REGULATOR
NASA - CONTR. INTERFACE
ACCUMULATOR
FILTER
PRESS. GAGE
PRESS. XDUCER
PRESS. SWITCH
BUG-DIRT SCREEN
DISTRIBUTION
11 AS-BUILT CHANGE
9 ADDED PUMPDOWN SYSTEM TO B2 LINES
8 CHANGED LOCATION OF N-3 PER AS BUILT
6 CHANGED PIE & GN2 TRLR CONNECTION
5 ADDED N-45, N-46
4 ADDED VENT BLDG. STR.
3 ADDED N-14
2 REVISED/RELOCATED NITROGEN PURGE CONNECTION
1 ADDED FLOW DIR., N-22 REL N-30, 5th SET
A
REFERENCES
PF-41013, -41014
APPROVED
DATE
CHANGE
NO.
REVISION
NASA LEWIS RESEARCH CENTER
PLUM BROOK STATION - SANDUSKY, OHIO
SPACE POWER FACILITY - BLDG 1411
SHUTTLE BASE HEATING TESTS
P & I.D FOR GH2, GO2, GN2
DRAWN BY
CHECKED
SCALE
NONE
SPF-0625

Figure 4. SHUTTLE BASE HEATING TESTS
Representative values and sequence for a typical hot firing.



T_1 timer = Valve opening signal set for 18-19 milliseconds.
T_2 timer = Redundant closing signal set for 80 milliseconds
T_3 timer = Normal closing signal set for 65 milliseconds.
~~T_5 timer = Spark signal set for 3 milliseconds.~~

PLUMBING MODIFICATIONS



BEFORE

AFTER

FIGURE 5

SSME # 1 BLOWOUT

SOLDER SPLATTER

FIGURE 6

E-8568

PLUMBROOK SPACE POWER FACILITY RUN DATE 6/12/75 RUN 130 TEST 0H44 MODEL 26-0

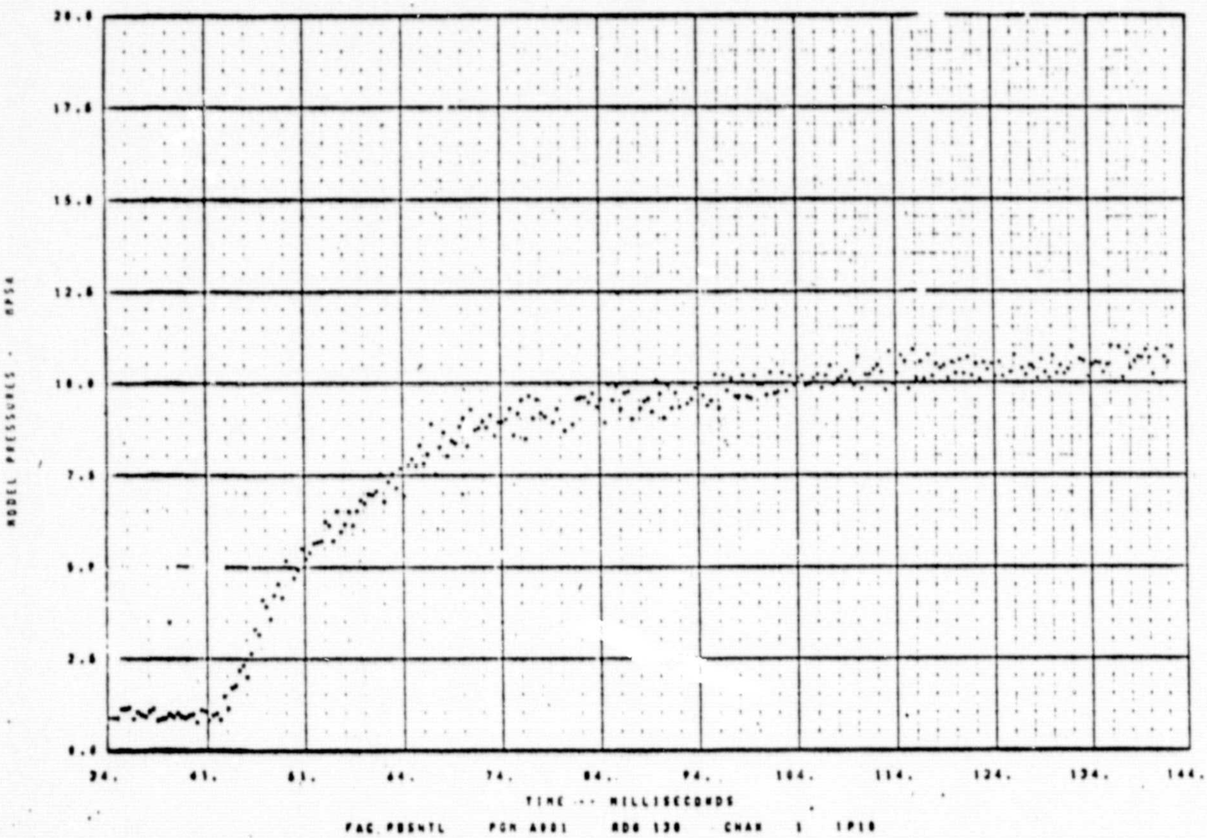


FIGURE 7

PLUMBROOK SPACE POWER FACILITY RUN DATE 6/12/75 RUN 130 TEST 0444 MODEL 28-9

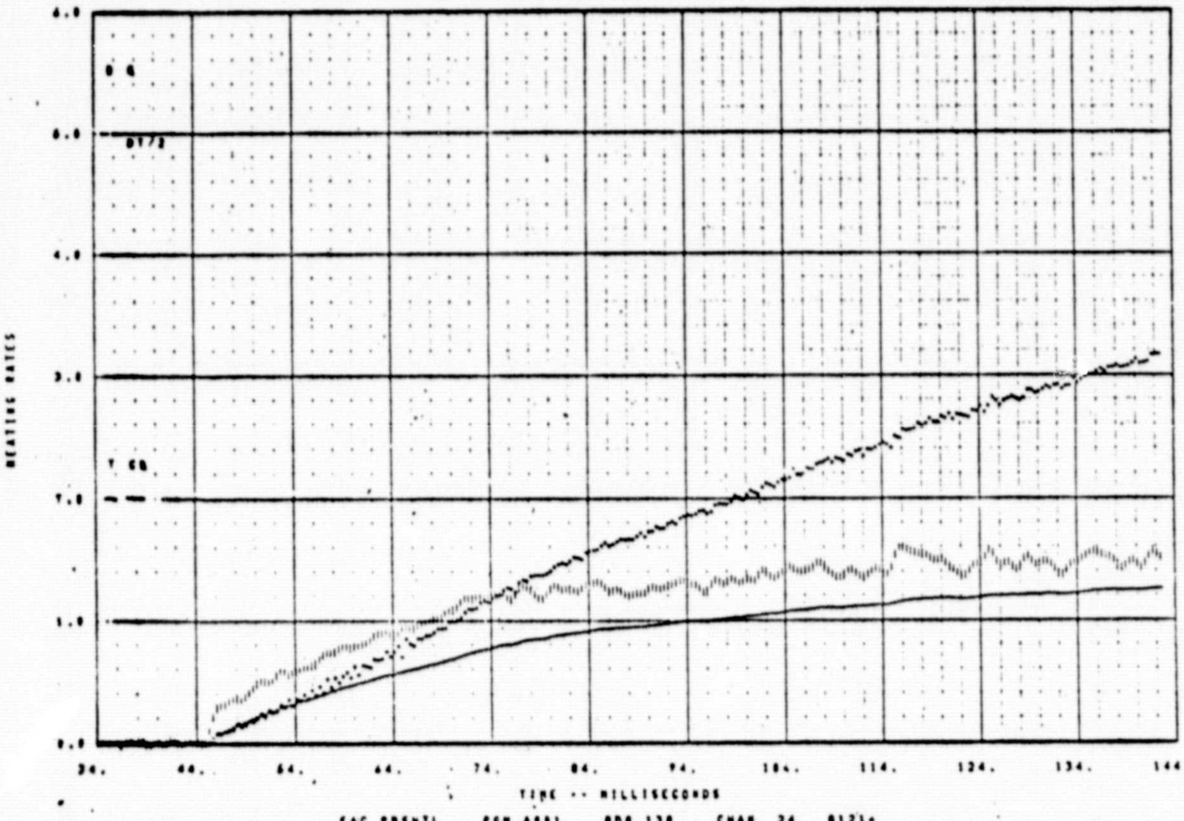
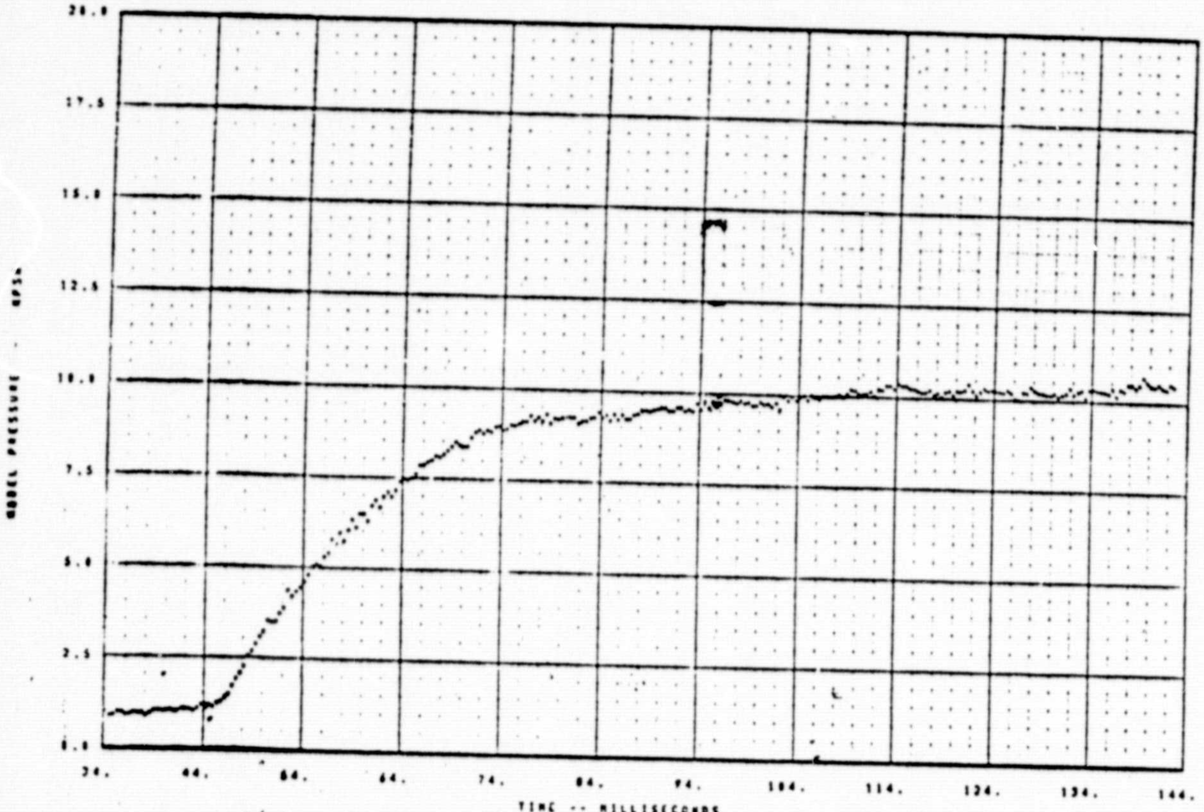


FIGURE 8

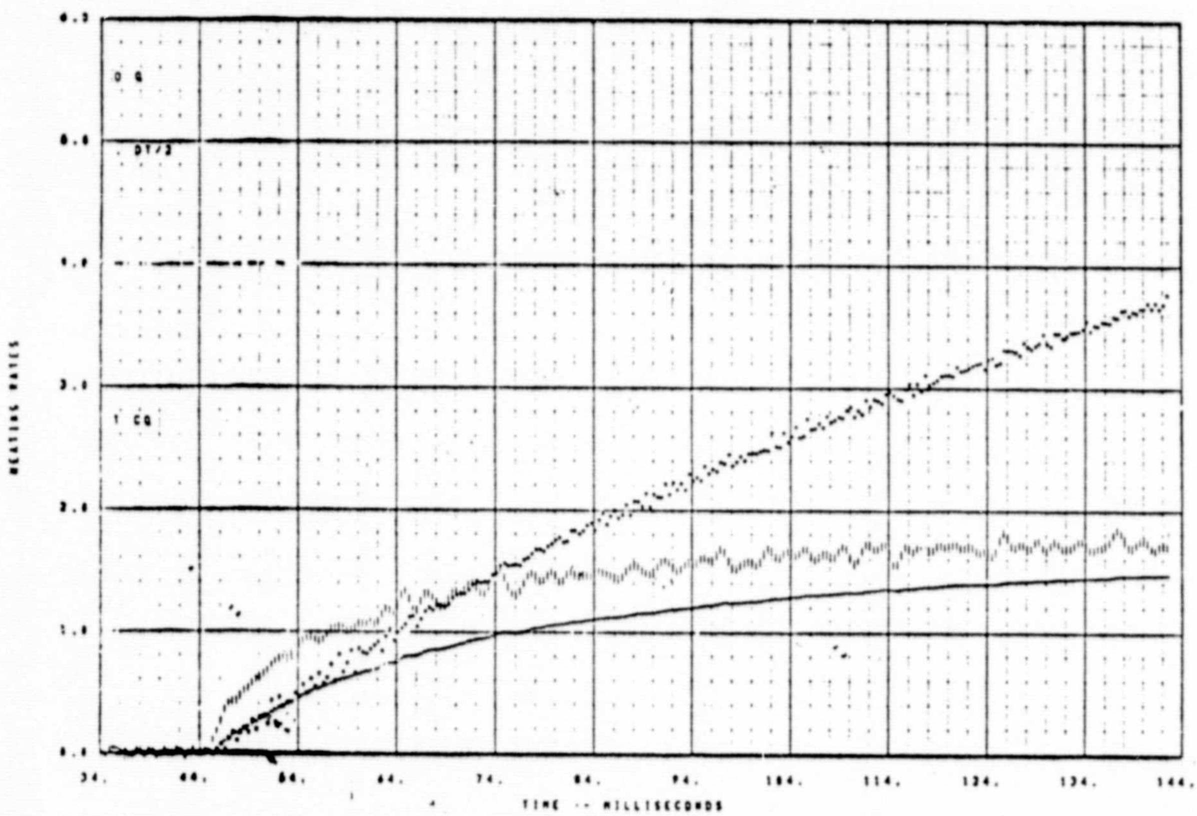
PLUMBROOK SPACE POWER FACILITY RUN DATE 6/12/75 RUN 130 TEST 0H64 MODEL 26-0



FAC PBSHTL PGN A001 RDG 130 CHAN 47 LP07

FIGURE 9

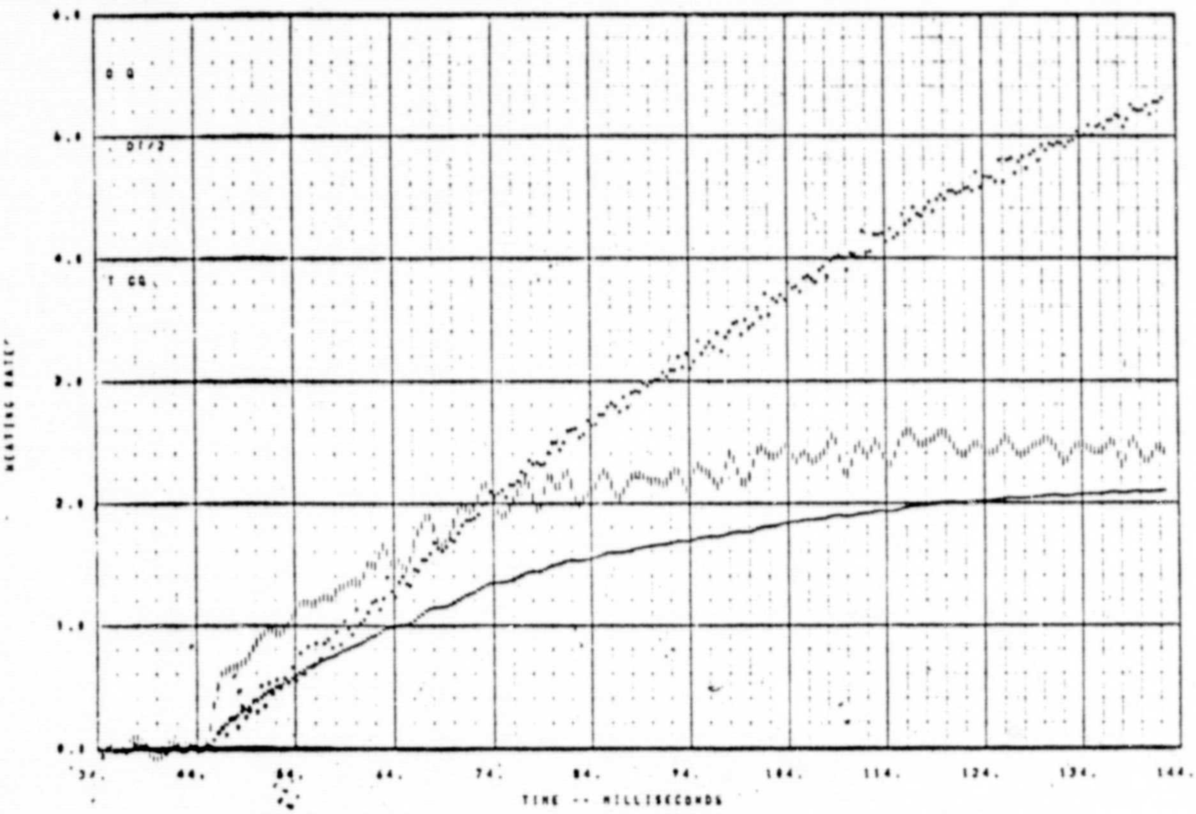
PLUMBROOK SPACE POWER FACILITY RUN DATE 4/12/76 RUN 130 TEST 0H44 MODEL 26-0



FAC PBSHTL PGM A001 RDG 130 CHAN 81 Q1??

FIGURE 10

PLUMBROOK SPACE POWER FACILITY RUN DATE 4/12/76 RUN 138 TEST OH44 MODEL 26-8



FAC PBSNTL PGM A661 RDG 138 CHAN 54 Q118

FIGURE 11