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(NASA-CR-170881) SRB THERMAL PROTECTION SYSTEMS MATERIALS TEST RESULTS IN AN ARC-HEATED NITROGEN ENVIRONMENT (Lockheed Missiles and Space Co.) 62 p HC A04/MF A01 CSCL 11D G3/24

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FOREWORD

This report documents the results of a materials test of Solid Rocket Booster thermal protection systems conducted at Acurex Corporation in their 1 Megawatt Arc Plasma Generator Facility. The purpose of the test was to verify the thermal protection systems materials performance in a high heating and high enthalpy environment similar to Space Shuttle Solid Rocket Booster staging environment. Acurex personnel conducted the tests, and Lockheed-Huntsville provided a test monitor.

Lockheed-Huntsville support for the tests is provided under Contract NAS8-32982, "Solid Rocket Booster Thermal Protection System Material Development." The NASA-MSFC Contracting Officer's Representative for this contract is Mr. William Baker, EP44. Mr. Baker was also the COR on the Acurex test support contract. The Acurex test engineers were Mr. L. Arnold and Mr. E. Fretter; the Lockheed-Huntsville test engineer was Mr. C. J. Wojciechowski.

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NOMENCLATURE

English	Description
H	total enthalpy, Btu/lbm
h	static enthalpy, Btu/lbm
M	Mach number
P	pressure, lb/in^2
$\dot{q}$	heating rate, Btu/ft^2-sec
$\dot{R}$	recession rate, mils/sec
T	temperature, R

Greek

τ	shear stress, lb/in^2

Subscripts

cw	cold wall defined at 460 R
e	boundary layer edge condition
L	local condition
o	stagnation point conditions
OL	local stagnation condition
r	recovery value

1. INTRODUCTION AND SUMMARY

The external surface of the Solid Rocket Booster (SRB) will experience imposed thermal and shear environments due to aerodynamic heating and radiation heating during launch, staging and reentry. The thermal protection system (TPS) is an insulation system applied to the external surfaces of the SRB for maintaining the structural and component temperatures within their design limits. This report is concerned with the performance of the various TPS materials during the staging maneuver. During staging, the wash from the Space Shuttle Main Engine (SSME) exhaust plumes impose severe, short duration, thermal environments on the SRB. Five different SRB TPS materials were tested in the 1 MW Arc Plasma Generator (APG) facility of Acurex/Aerotherm. This facility allowed simulation of the SSME aerodynamic heating and aerodynamic shear environments over most of the SRB surface. Some local hot spots on the SRB with predicted SSME plume wash heating rates spikes of 360 Btu/ft^2-sec were not simulated. The maximum simulated heating rate obtained in the APG facility was 248 Btu/ft^2-sec, however, the test duration was such that the total heat was more than simulated. Similarly, some local high shear stress levels of 0.04 psia were not simulated. Most of the SSME plume impingement area on the SRB experiences shear stress levels of 0.02 psia and lower. The shear stress levels on the test specimens were between 0.021 and 0.008 psia. The SSME plume stagnation conditions (in the SRB impingement region) of 5260 R temperature, 6000 Btu/lbm enthalpy and 3 psia pressure were simulated using arc heated nitrogen with stagnation conditions of 9700 R temperature, 4800 Btu/lbm enthalpy and 2.7 psia stagnation pressure.

The TPS material samples held up as expected or better than expected in terms of material recession rates under the simulated SSME plume wash environments. In terms of virgin material recession rates, the five TPS materials ranking from highest to lowest are: MSA-2, MTA-2, P50 and phenolic glass (both ranked same), and finally B-Stage cork. The thickness of the TPS materials was a nominal 0.30 in. The test data indicates that this thickness is more than sufficient to protect against the SSME plume wash thermal environments as simulated.

2. TECHNICAL DISCUSSION

Discussed in the first part of this section are the features of the TPS test facility, calibration methods, TPS specimen descriptions, data measurements and data reduction. The second part discusses the flight simulation criteria and the test data analysis. The main objective of the test program was to obtain SRB TPS material ablation characteristics (virgin material recession rates and surface temperatures) in a short duration, high heating and enthalpy environment representative of the SSME plume wash conditions. On the SRB, the highest heating rates occur on the SRB structural protuberances which use phenolic glass TPS. In addition, it was also desired to simulate the heating rates on the acreage areas where other TPS materials are used. To simulate this range of heating rates two test configurations were employed. The probe configuration was used for the higher heating rate simulation and a panel configuration was used to simulate the acreage area heating. The materials that were tested were P50 sheet cork, B-Stage cork, phenolic glass manufactured by Edler Industries, Inc., MTA-2 and MSA-2 both of which were developed by NASA-MSFC. All the materials were tested on both model configurations in order to obtain a good variation of virgin material recession rate as a function of cold wall heating rate and shear stress level.

2.1 TEST DESCRIPTION

The tests were conducted at Acurex Corporation in their 1 Megawatt Arc Plasma Generator (APG) facility. A complete description of this facility, as well as the Acurex final data report is included in this report in the Appendix. The test gas used was nitrogen. Nitrogen was selected because it provided an oxygen-free high enthalpy environment similar to the SSME plume wash. The SSME plume wash consists mainly of 75% water vapor and 25% hydrogen gas. The reaction of the water vapor with the carbon char layer was not simulated.

However, estimates of the reaction rates for this reaction under the low pressure environment indicates that this reaction would not be dominant. Because of differences in the specific heats of the SSME plume wash and the arc heated nitrogen gas, the temperature-enthalpy relationship could not be simulated, i.e., stagnation temperatures of 9950 R at an enthalpy of 4781 Btu/lbm for the arc heated nitrogen as compared with SSME plume wash stagnation temperatures of 5260 R at an enthalpy of 6000 Btu/lbm. Since enthalpy potential is the main driving force in convective heat transfer, it was desired to simulate as close as possible the enthalpy potential as this would better simulate the hot wall convective heating rates. The nozzle size was selected to yield a Mach number of 3.53 approach flow which would simulate the local SSME plume and Mach number.

With the test gas selected, the next phase was to run a series of calibration tests to determine the thermal environment about the models. Since a 2 in. exit diameter nozzle was used the TPS models were small in order to have as uniform a flow field as possible over the model surface. The probe model was a 1 in. diameter flat disc and the panel model was 1.25 in. by 3 in. as shown in Figs. 2 and 3 on page 4 of the Appendix. For the calibration runs, the standard Acurex flat face slug calorimeter calibration probe and separate pitot probe were used for the probe models. For the flat panel models, a flat panel calibration model was built by the Lockheed-Huntsville model shop. The panel calibration model is shown in Fig. 5, page 8, of the Appendix. The calibration model featured 3 thin skin (0.030 in. nominal) heat transfer sensing areas, one Gardon gage calorimeter, and three local pressure measurement locations. The thin skin area thicknesses were accurately measured using a micrometer, prior to placing the 30 gage wire chromel alumel thermocouple junctions. The calibration test procedures are given on page 11 of the Appendix.

The TPS test specimens were all a nominal 0.30 in. thick mounted on individual 0.125 in. thick aluminum backup plates. The backface thermocouples were mounted on the backside of the aluminum substrate plate.

The probe and panel test specimens are shown in Figs. 2 and 3 in the Appendix. Figures 1 and 4 in the Appendix show how the test specimens were mounted in their respective holders for testing. The procedure used when testing the TPS specimens is listed on page 14 of the Appendix. A list of all the TPS specimens which were tested are given in Table 1. The models were prepared by NASA-MSFC Materials Laboratory with help from Lockheed-Huntsville. The models were photographed prior to the test at Acurex. Pre-test thicknesses and weights were made by NASA-MSFC Materials Lab as well as placement of the thermocouples. Post-test virgin material thicknesses were made at Lockheed-Huntsville. All the models were first tested at the lower exposure time and then inspected by the Lockheed-Huntsville onsite test monitor. If the models looked good with plenty of virgin material remaining and the backface temperature rise was low, the next similar TPS specimen was tested at the longer exposure time. A complete description of the test instrumentation is given in Section 3, pages 6 through 11 of the Appendix. All of the Visicorder data reduction and analysis was done on site by the Lockheed-Huntsville monitor, after instruction from Acurex personnel. This included both the calibration runs and the TPS specimen runs. In this way there were no delays in setup time and communication and the next APG run could be prepared by the Acurex test engineer while data from the previous run were being reduced and analyzed. Upon test completion, copies of the reduced Visicorder and surface temperature data were made for verification and comparison with the Vidor DDAS data for inclusion in the Acurex final data report. Figure 6 on page 15 in the Appendix shows the probe model TPS test configuration, and Fig. 7 on page 16 (Appendix) shows the TPS panel model test configuration. During testing, the models were viewed through the quartz windows.

2.2 DATA ANALYSIS

A detailed listing of the test instrumentation and data reduction methods is given on pages 6 through 11 of the Appendix. The discussion here is concerned with determining the APG facility flow field, the model flow field, extrapolation to flight conditions, and TPS specimen recession measurements.

Table 1

LIST OF TPS TEST SPECIMENS

Run No.	Configuration	Model No.	TPS Material
1	Panel	C-1	P50 Sheet Cork
2	Probe	PC-1	P50 Sheet Cork
3		PC-2	P50 Sheet Cork
4		PA-3	Edler S-Glass Phenolic
5		PA-4	Edler S-Glass Phenolic
6		PA-5	Edler S-Glass Phenolic
7		PA-6	Edler S-Glass Phenolic
8		PB-1	B-Stage Sheet Cork
9		PB-2	B-Stage Sheet Cork
10		PD-1	MSA-2
11		PE-1	MTA-2
12		PE-2	MTA-2
13		PD-2	MSA-2
14	Panel	C-2	P50 Sheet Cork
15		A-1	Edler S-Glass Phenolic
16		A-2	Edler S-Glass Phenolic
17		B-1	B-Stage Sheet Cork
18		E-1	MTA-2
19		D-1	MSA-2
20		E-2	MTA-2
21		D-2	MSA-2
22		C-3	P50 Sheet Cork
23		B-2	B-Stage Sheet Cork

2.2.1 APG Facility Flow Field

During the calibration phase of the program, the arc chamber pressure and model pitot pressure and heating rates were measured. Using these data and the thermal properties of high temperature nitrogen, the Mach number of the plasma jet centerline was determined to be approximately [illegible].53 using an effective gamma (ratio of specific heats) of 1.30. The nitrogen gas gamma varies from 1.17 in the chamber to 1.38 in the highly expanded regions of the flow field.

2.2.2 Model Aerothermodynamic Environments

During the model TPS tests only the arc chamber pressure and stagnation heating rate were measured. This presented no problem for the probe TPS tests, but for the panel TPS tests, the local heating rates had to be derived from the stagnation point heating rate. During the calibration phase, both the probe and the panel calibration model were immersed sequentia' at the same stabilized arc condition. From this data ratios of local-to-stagnation point heating rate were established for the three instrumented locations on the panel as shown in Table 2.

The model local shear stress calculation was calculated using the same general form of equation that was used in the preflight predictions for the SSME plume wash, (Refs. 2 and 3). The equation used was

$$\tau = \frac{0.008372\, \dot{q}\, M_L \sqrt{T_e}}{(H_r - h_w)} \quad \text{psia,}$$

where

$\dot{q}$ = local heating rate, Btu/ft^2-sec
M_L = local Mach number
T_e = boundary layer edge temperature, R
H_r = recovery enthalpy, Btu/lbm
h_w = wall enthalpy at 460 R, Btu/lbm

Table 2

PANEL LOCAL-TO-STAGNATION POINT HEATING RATE RATIO*

Test No.	Location 1**	Location 2	Location 3
3150-02	.320	.253	.115
3150-03	.354	.238	.104
3151-01	.392	.262	.106
Test Averages	.355	.251	.108

*Defined as q_{cw}/q_o

**See Fig. 5 of Appendix for locations.

For the panel tests the local Mach number was obtained from the ratio of the local pressure to the pitot pressure. Then using the local Mach number, the boundary layer edge temperature and enthalpy were determined using ideal gas relationships and a gamma of 1.3. The panel results for the three locations are shown in Table 3. A boundary layer recovery factor of 0.9 was used. Figure 1 presents the heating rate-shear stress variation for both the probe and panel configurations. The shear stress level on the probe configuration was calculated at the junction between the TPS specimen and the graphite collar. The flowfield properties at this junction were evaluated with the assistance of the data presented in Ref. 4. Figures 2 and 3 show the SSME plume wash shear stress levels at two time points from Ref. 2. Shown in Figs. 4 and 5 are the corresponding SSME plume wash heating rate levels from Ref. 2. The values shown in Figs. 2 through 5 are "clean" body values. Protuberance heating is presented in Ref. 3 but no corresponding shear stress levels are presented. Comparison of Fig. 1 with Figs. 2 through 5 indicate that the heating rate and shear stress levels were well simulated in this test for most of the SRB impingement area.

2.2.3 Data Extrapolation to Flight

Due to differences in the heat capacities of the SSME plume wash and the APG nitrogen, the relationships between the ratio of cold wall to hot wall convective heating are different for the two gases. Figure 6 depicts the temperature-enthalpy relationships for the two gases. Figure 7 shows the ratio of cold wall to hot wall convective heating rate versus wall temperature for the SSME plume wash and one recovery enthalpy value for the APG. Also shown is the ratio of flight cold wall to test cold wall heating rate as a function of wall temperature for these two particular recovery enthalpy values. Basically for each TPS test, the flight cold wall simulated heating rate was calculated using the following procedure:

1. The local cold wall heating rate was calculated from the measured stagnation point heating rate and the appropriate local factor for the panel from Table 3. Using the appropriate factor from Table 3, the recovery enthalpy was determined.

Table 3

PANEL LOCAL AEROTHERMODYNAMIC RELATIONSHIPS FOR THE THREE TEST LOCATIONS

Panel Location	q_{cw}/q_o	H_r/H_o	T_e/T_o	M_L	τ (psi)	P_e/P_{OL}
1	.355	.962	.661	1.85	.021	.473
2	.251	.941	.478	2.70	.018	.116
3	.108	.930	.376	3.33	.008	.027

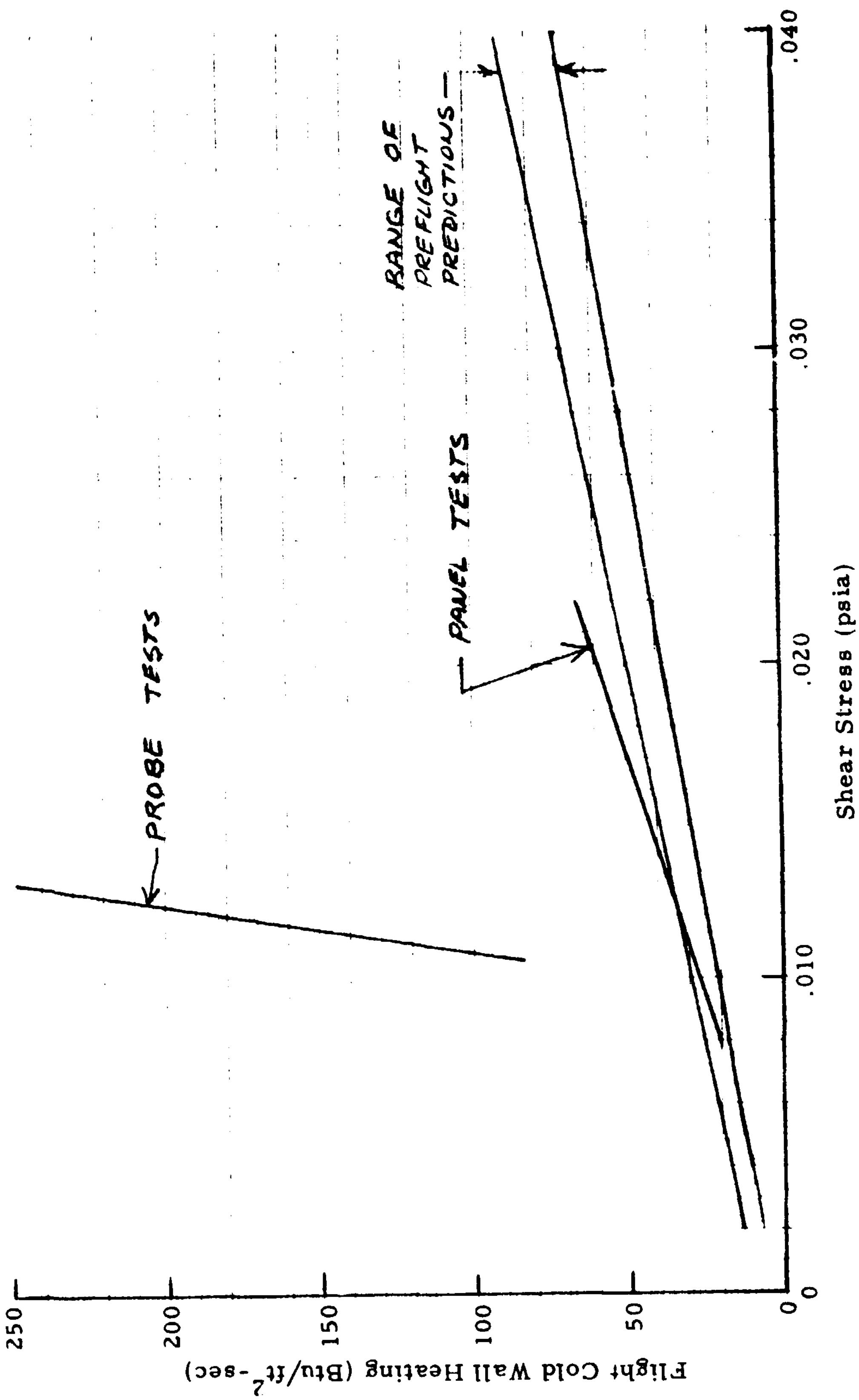

Fig. 1 - Heating Rate-Shear Stress Relationship for Test and Flight

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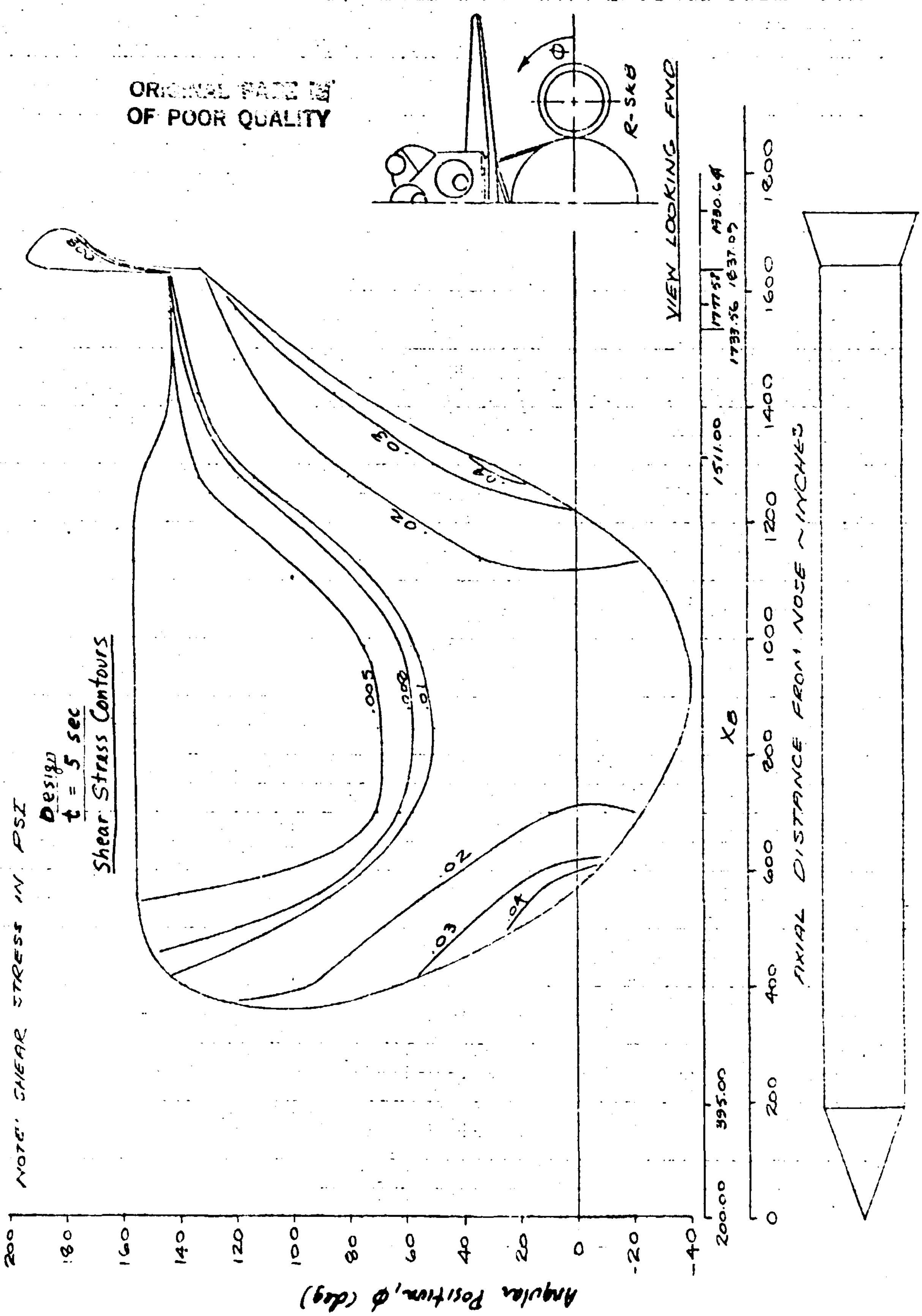

Fig. 2 - Constant Plume Impingement Shear Stress Contours at t = 5 sec

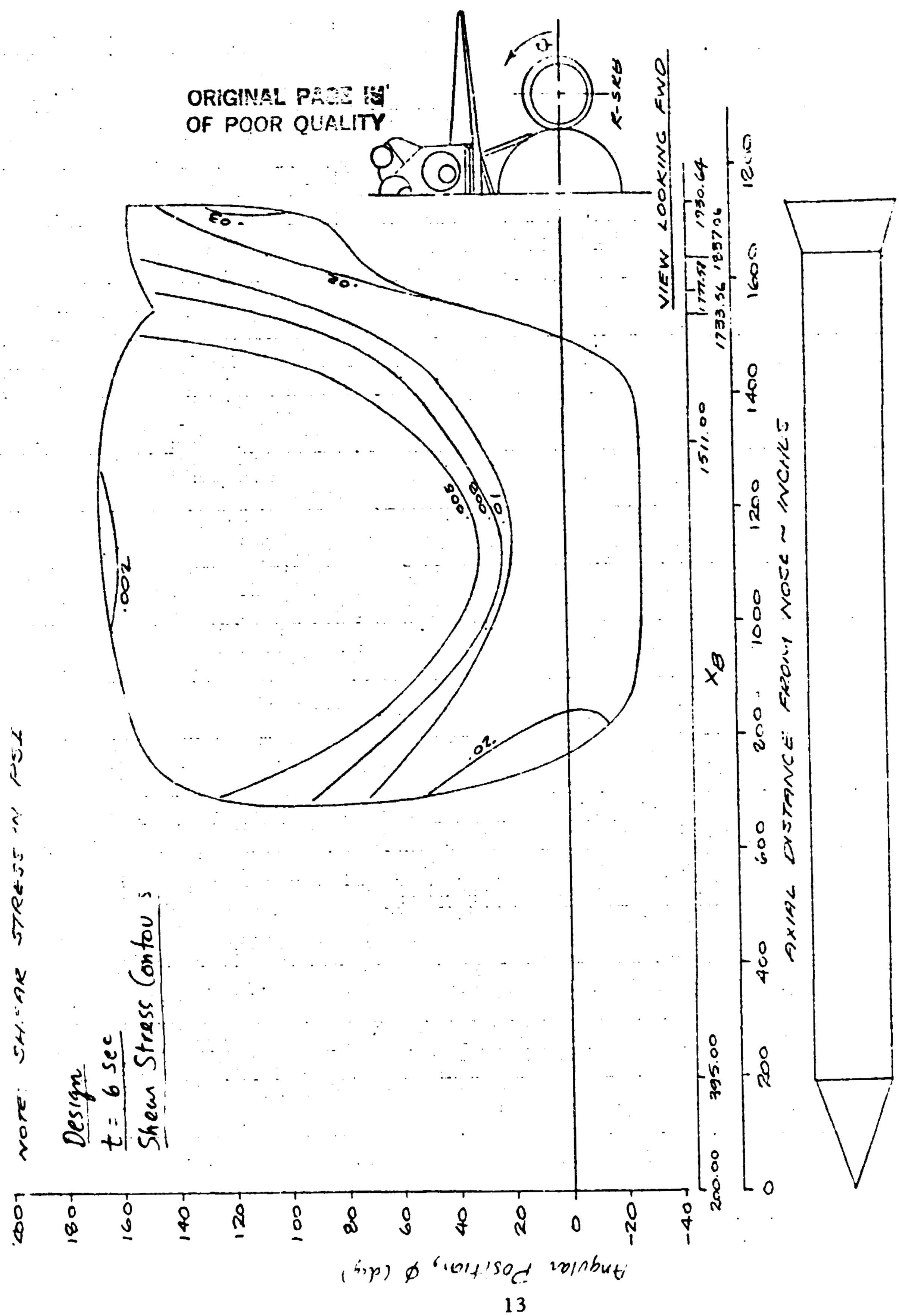

Fig. 3 - Constant Plume Impingement Shear Stress Contours at t = 6 sec

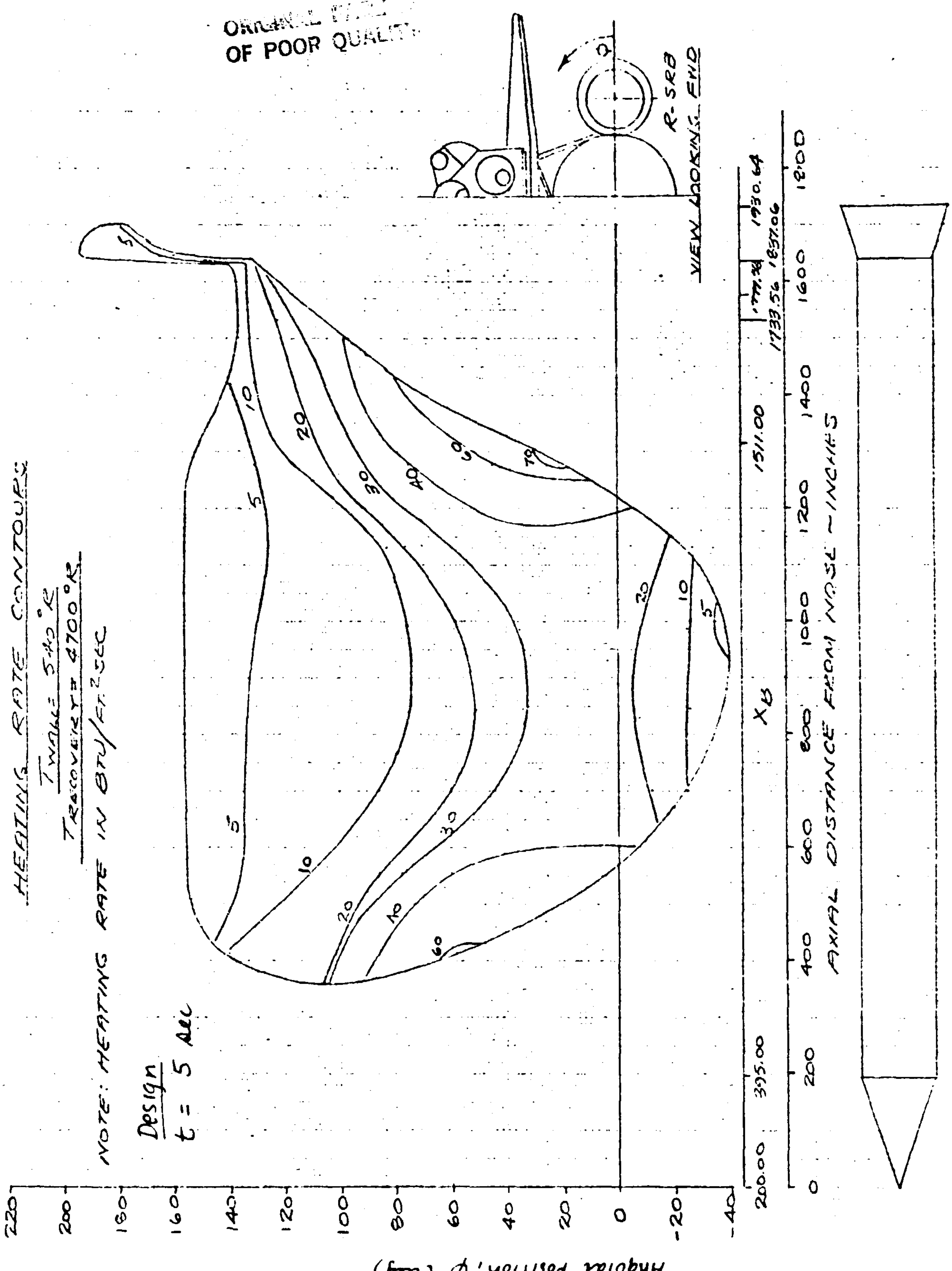

Fig. 4 - Constant Plume Impingement Heating Rate Contours at t = 5 sec

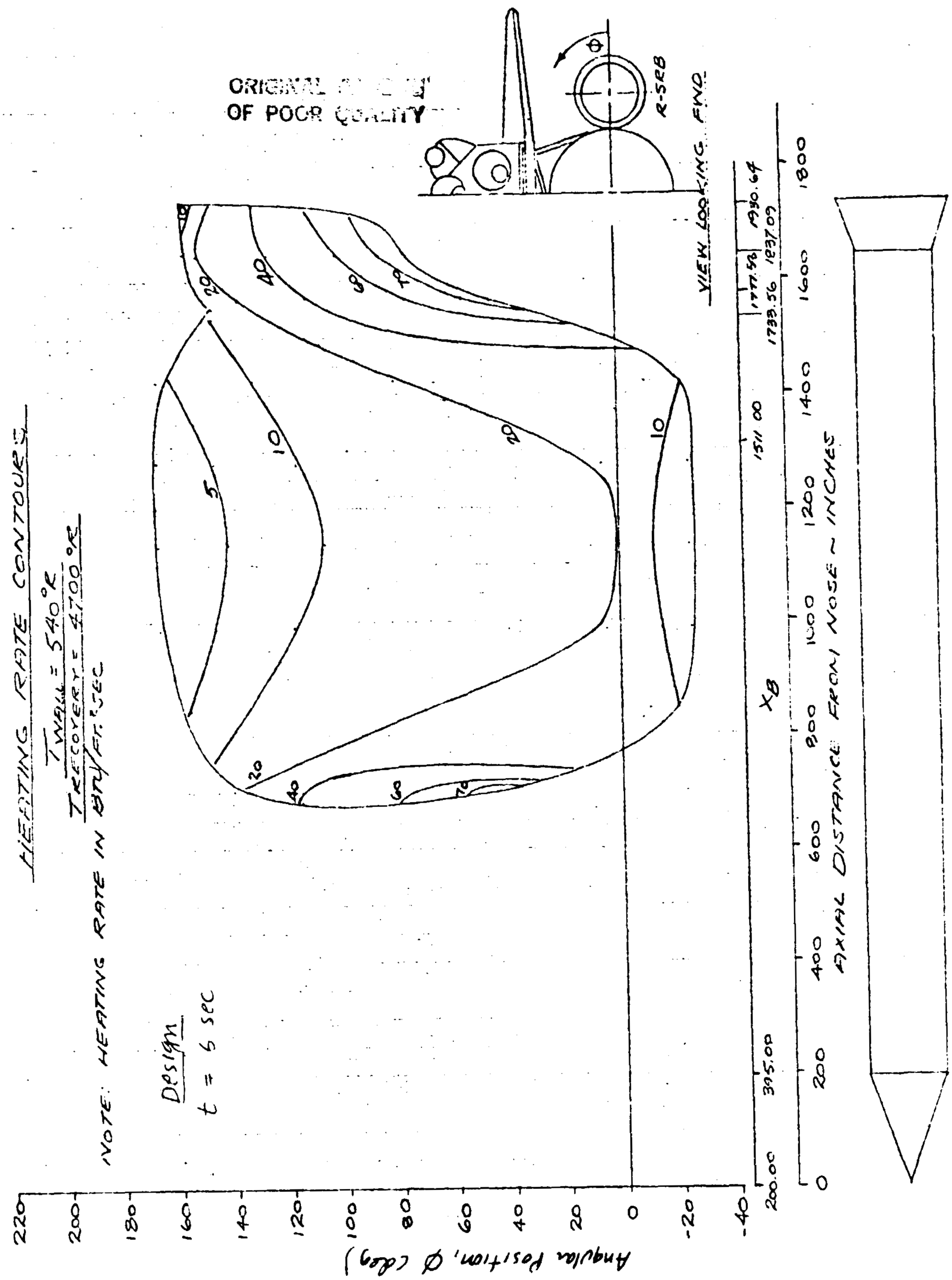

Fig. 5 - Constant Plume Impingement Heating Rate Contours at t = 6 sec

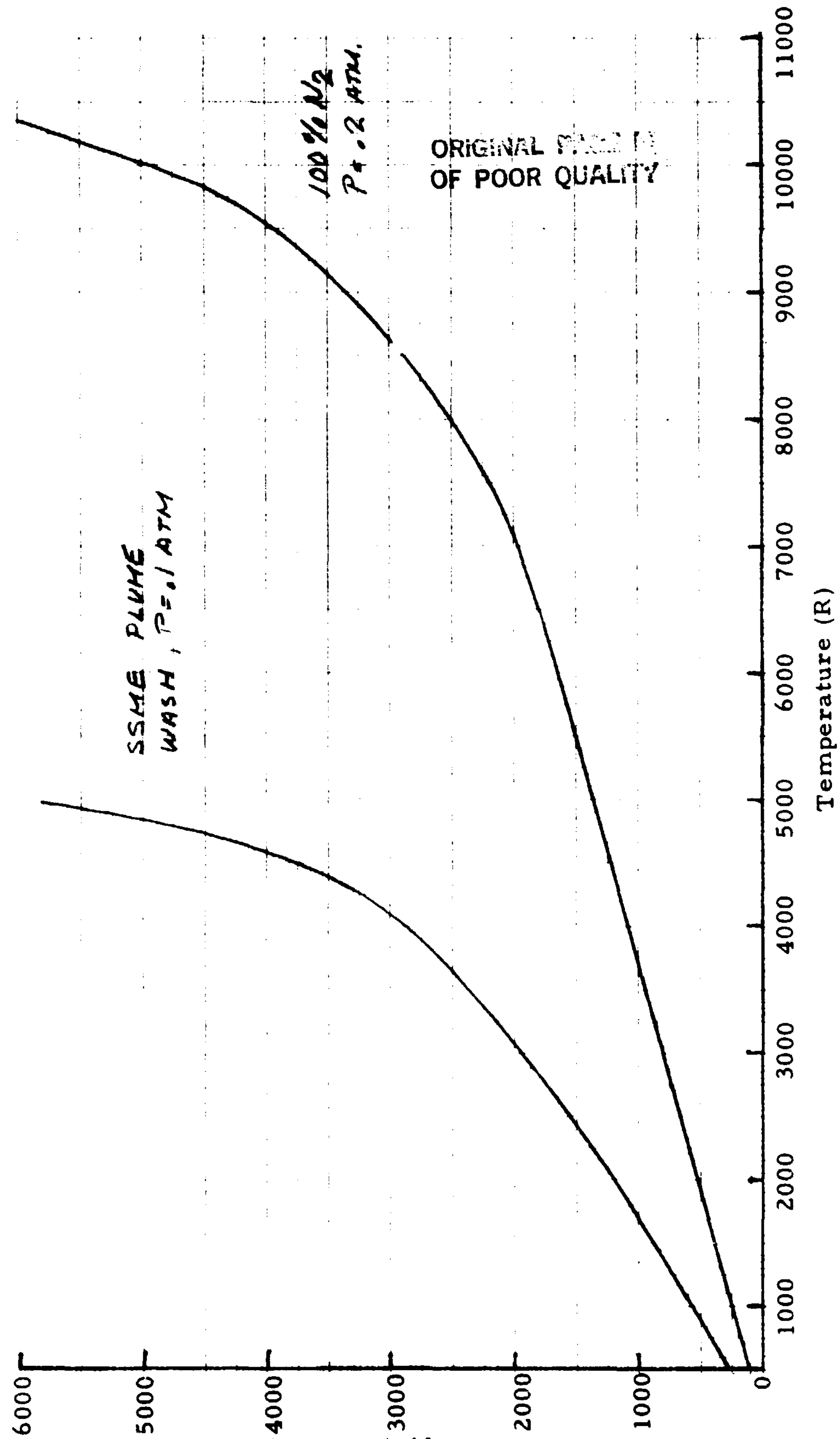

Fig. 6 - Temperature-Enthalpy Relationship for Nitrogen and SSME Plume Wash

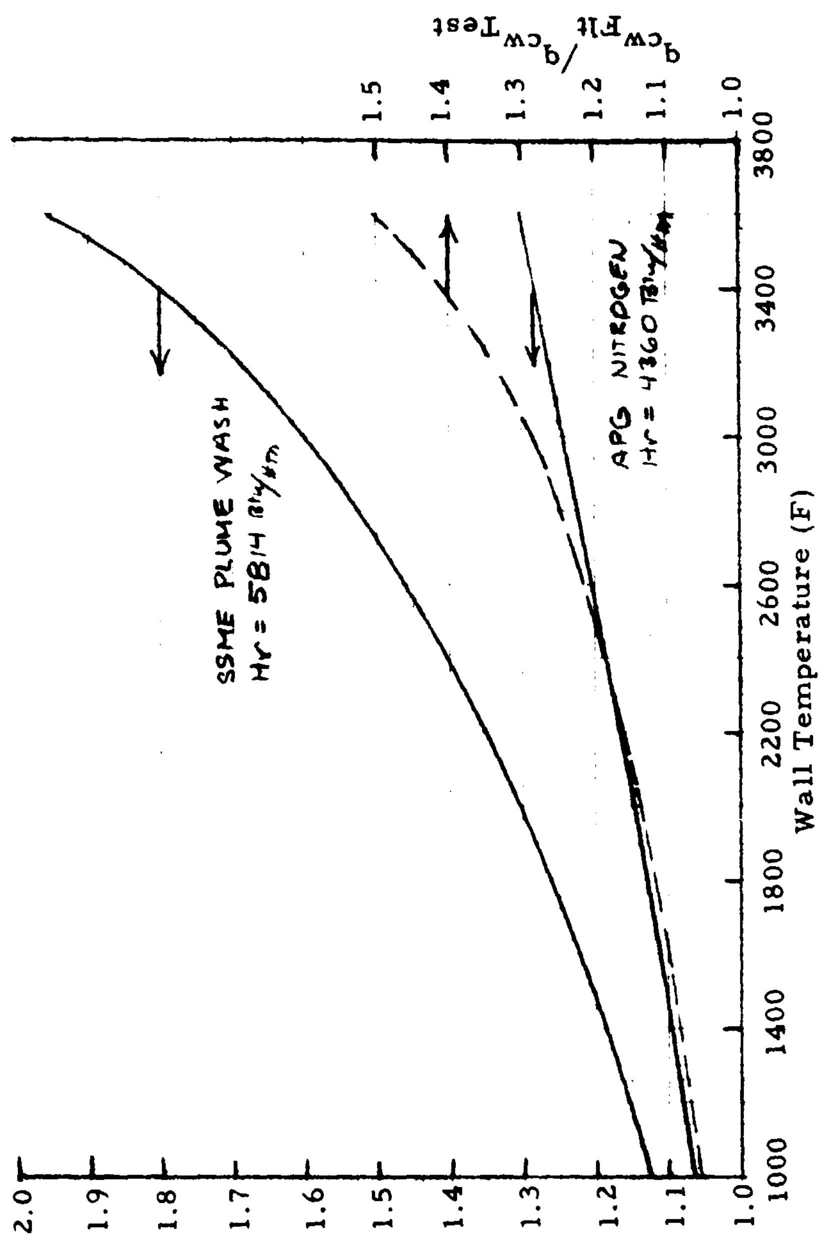

Fig. 7 - Wall Temperature Effects on Convective Heating Rate for Nitrogen and SSME Plume Wash

2. Using the measured wall temperature and Fig. 6 , the test hot wall heating rate was calculated using:

$$\dot{q}_{hw_{test}} = \dot{q}_{cw_{test}} \times \frac{(H_{r_{test}} - h_{hw_{test}})}{(H_{r_{test}} - h_{cw_{test}})} .$$

Then by definition the test hot wall heating rate was assumed to be equal to the flight hot wall heating rate.

3. Using the measured wall temperature and Fig. 6, the flight hot wall enthalpy was determined. The flight recovery enthalpy used was 5814 Btu/lbm. The flight cold wall heating rate was then calculated using

$$\dot{q}_{cw_{flt}} = \dot{q}_{hw_{flt}} \times \frac{(H_{r_{flt}} - h_{cw_{flt}})}{(H_{r_{flt}} - h_{hw_{flt}})} .$$

where the h_{cw} is defined at 460 R.

2.2.4 Model Recession Measurements

Each model was weighed immediately after test. Post-test photographs were taken at MSFC. The amount of virgin material remaining was measured after the char layer was carefully machined away until the virgin material was exposed. Thickness measurements were taken at the center of the probe models and at the three measurement locations on the flat panels.

3. TEST RESULTS

The preliminary TPS materials test results are presented in Table 3 of the Appendix. Table 4 in the Appendix presents the APG run conditions for each materials test. The TPS test sample pretest and post-test weights and thicknesses with and without the post-test char are given in Table 4. The post-test weights shown in Table 4 are sometimes greater than the pretest weights. The probable reason for this is that the pretest weights were made at MSFC and the post-test weights made at Acurex by different personnel and a different scale. In observing the post-test material thicknesses with the char retained, it is evident that the only materials that exhibited any char removal were the MTA-2 material and to a lesser extent the MSA-2 material. The cork materials exhibited swelling during the test. The only correlations that were made in this report was with the pretest thickness and post-test thickness measured with the char removed.

The probe TPS test results are presented in Table 5. The recession rates presented in Table 5 are based on the post-test char removed thicknesses and the exposure time. The panel TPS test results are presented in Table 6. The recession rates were calculated the same as for the probe tests and are given for the three instrumented locations on the panel. A composite plot of the TPS recession rate versus cold wall heating rate is presented in Fig. 8. Also presented in Fig. 8 are the current TPS material recession rate design curves for the various TPS materials.

All of the TPS materials samples tested held up as expected or much better than expected under the simulated SSME plume impingement environment. The various materials tested and their results are discussed next on an individual basis.

Table 4

AEROTHERM TPS TEST SAMPLES WEIGHTS AND THICKNESS MEASUREMENTS

Model No.	Config.	TPS Mat'l	Pretest Wt (gm)	Post-Test Wt (gm)	With .125 in. Al Plate 1 Pretest Thick (in.)	With .125 in. Al Plate 2 Pretest Thick (in.)	With .125 in. Al Plate 3 Pretest Thick (in.)	With Char 1 Post Test Thick (in.)	With Char 2 Post-Test Thick (in.)	With Char 3 Post-Test Thick (in.)	Without Char 1 Post-Test Thick (in.)	Without Char 2 Post-Test Thick (in.)	Without Char 3 Post-Test Thick (in.)
PC-1	Probe	P50	10.8	10.710	.428	N/A	N/A	.455	N/A	N/A	.399	N/A	N/A
PC-2		P50	10.7	10.733	.428			.460			.400		
PA-3		Phenolic	14.7	14.716	.385			.398			.325		
PA-[illegible]		Phenolic	14.5	14.401	.385			.425			.307		
PA-5		Phenolic	14.6	14.756	.385			.390			.349		
PA-6		Phenolic	14.7	14.685	.387			.4[illegible]8			.342		
PB-1		B Cork	10.806	10.502	.428			.470			.402		
PB-2		B Cork	10.935	10.689	.429			.502			.405		
PE-2		MTA-2	11.045	—	.431			.372			.356		
PE-2		MTA-2	11.063	—	.430			.325			.320		
PD-1		MSA-2	10.218	10.078	.431			.417			.325		
PD-2	Probe	MSA-2	10.239	—	.432			.413			.294		
C-1	Panel	P50	38.0	37.624	.427	.427	.427	.442	.445	.438	.407	.410	.421
C-2		P50	38.424	37.070	.426	.426	.426	.453	.458	.454	.381	.392	.408
C-3		P50	38.20	35.148	.428	.428	.428	.446	.464	.457	.350	.374	.398
A-1		Phenolic	57.015	56.092	.390	.390	.390	.400	.396	.394	.343	.344	.389
A-2		Phenolic	36.4	55.141	.385	.385	.385	.405	.390	.387	.314	.321	.359
B-1		B Cork	37.4	36.102	.429	.429	.429	.483	.485	.482	.384	.401	.423
B-2		B Cork	37.5	35.691	.429	.429	.429	.511	.515	.507	.387	.400	.429
E-1		MTA-2	38.9	35.976	.430	.430	.430	.347	.351	.398	.326	.332	.379
E-2		MTA-2	38.8	34.175	.429	.429	.429	.375	.323	.390	.317	.311	.370
D-1		MSA-2	34.8	34.063	.429	.429	.429	.401	.411	.420	.244	.260	.316
D-2	Panel	MSA-2	34.9	32.409	.426	.426	.426	.380	.395	.404	.215	.262	.304

Table 5

AEROTHERM PROBE TPS TEST RESULTS

Model No.	TPS Material	Flight Sim., $\dot{q}_{cw}$ (Btu/ft^2-sec)	Exposure Time (sec)	Flight Load q_{cw} (Btu/ft^2)	Shear τ (psi)	$\dot{R}$ (mils/sec)	T_o (R)	T_{surf} (F)	ΔT_{back} (F)
PC-1	P50	141	4.4	622	.012	6.60	8735	2826	62
PC-2	P50	141	5.1	717	.012	5.49	8635	3101	90
PA-3	Phenolic	227	5.45	1237	.013	11.0	9640	2912	119
PA-4	Phenolic	231	9.1	2101	.013	8.57	9680	2902	>296
PA-5	Phenolic	84	8.8	736	.011	4.09	7500	2202	141
PA-6	Phenolic	248	5.75	1423	.013	7.83	8770	2988	134
PB-1	B-Cork	166	5.0	832	.012	5.20	9050	2978	45
PB-2	B-Cork	146	8.8	1280	.012	2.73	8700	3047	208
PE-1	MTA-2	138	5.9	818	.012	12.7	8820	2870/1885	65
PE-2	MTA-2	136	9.4	1274	.012	11.7	8750	2897/1885	233
PD-1	MSA-2	122	5.6	676	.011	18.	340	2991	63
PD-2	MSA-2	127	8.6	1095	.011	16.[illegible]	8440	3041	161

Table 6

AEROTHERM PANEL TPS TEST RESULTS

Model No.	TPS Material	Flight Sim., $\dot{q}_{cw}$ (Btu/ft^2-sec)			Exposure Time (sec)	Heat Load (Btu/ft^2)			Recession Rate (mils/sec)			T_o (R)	Loc. 1 T_w (F)
		Loc. 1	Loc. 2	Loc. 3		Loc. 1	Loc. 2	Loc. 3	Loc. 1	Loc. 2	Loc. 3		
A-1	Phenolic	71.0	50.3	21.6	16.3	1157	820	352	2.88	2.82	.061	9545	2424
A-2	Phenolic	73.0	51.6	22.2	26.1	1905	1347	579	2.72	2.45	.996	9585	2267
B-1	P Cork	75.0	53.0	22.8	15.7	1178	832	358	2.87	1.78	[illegible]82	96[illegible]5	2370
B-2	B Cork	70.3	49.5	21.3	25.7	1807	1272	547	1.63	1.13	0.000	9470	2338
C-1	P50 Cork	39.1	62.9	27.0	4.3	383	270	116	4.65	3.95	1.40	9950	2395
C-2	P50 Cork	78.0	55.1	23.7	15.9	1240	876	377	2.83	2.14	1.13	9730	2273
C-3	P50 Cork	80.0	56.6	24.4	26.1	2088	1477	637	2.99	2.07	1.15	9740	2400
D-1	MSA-2	74.0	52.3	22.5	15.7	1162	821	353	11.8	10.8	7.20	9600	2374
D-2	MSA-2	80.0	56.6	24.4	26.0	2080	1472	634	8.12	6.3	4.69	9760	2345
E-1	MTA-2	72.0	50.9	21.9	16.0	1152	814	350	6.50	6.13	3.19	9600	2320
E-2	MTA-2	77.0	54.5	23.4	21.1	1625	1150	494	5.31	5.59	2.80	9740	2350

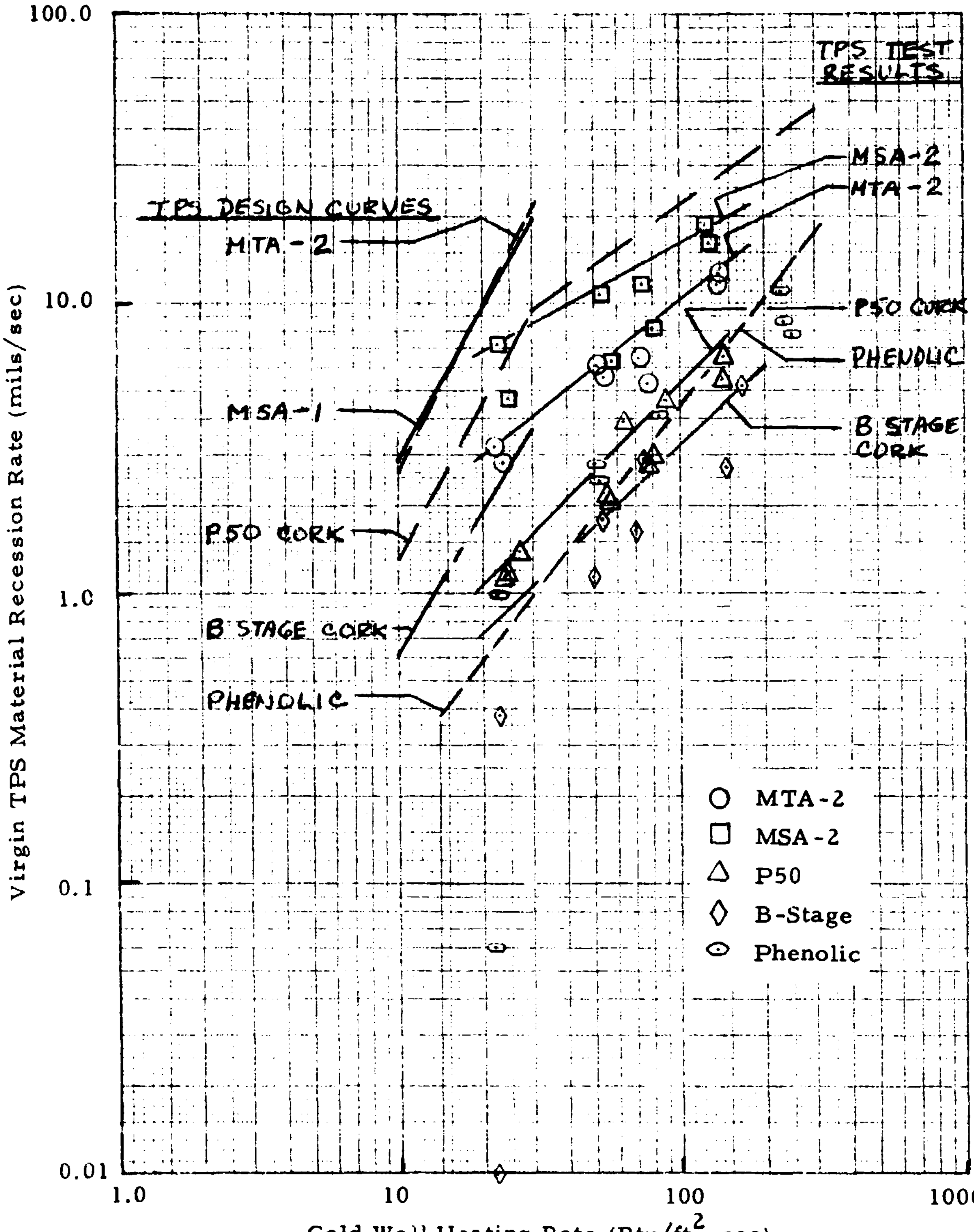

Fig. 8 - Recession Rate vs Heating Rate Design Curves and TPS Test Results

- Edler S-Glass Laminated Phenolic

This material was tested in the simulated flight cold wall heat rate range between 20 and 248 Btu/ft^2-sec. The virgin material recession rate matched the flight design curve of $\dot{R} = 0.01377\ (\dot{q}_{cw})^{1.257131}$. At the higher heat rate levels, the glass reinforcement melted and flowed, and tiny bubbles appeared under the outer plies. The material formed a very stable char with no visible evidence of char recession. All of the test samples were bonded with epoxy to a 0.125 in. aluminum substrate using EA 934 adhesive. Some of the models showed evidence of bondline failure and on one probe model the phenolic specimen fell off after test completion. On the flight vehicle, the phenolic will be mechanically attached so this should not be a problem. Measured surface temperatures varied from 2230 to 3000 F depending on the test conditions. These temperatures are representative of predicted flight values.

- P50 Sheet Cork

This material was tested in the simulated flight cold wall heat rate range between 23 and 142 Btu/ft^2-sec. The virgin material recession rate was well below the 2000 R design values by about a factor of 4. The material recession rate was similar to the phenolic recession rate. The recession rate equation which describes the data fairing shown in Fig. 8 is $\dot{R} = 0.05279\ \dot{q}_{cw}^{0.99895}$. The material formed a very stable crazed char with no visible char recession, in fact, the material swelled a bit. This stable char was probably the main reason for the low recession rates. Measured surface temperatures varied from 2273 to 3100 F depending on the heat rate level.

- B-Stage Cork

This material was tested in the simulated flight cold wall heat rate range between 21 and 166 Btu/ft^2-sec. The virgin material recession rate was the lowest of all the materials tested. The recession rate design values shown in Fig. 8 were obtained from Ref. 5. In this test, the virgin material recession rate was approximately 62% that of the P50 sheet cork. The B-stage cork recession rate equation which best describes the data fairing in Fig. 8 is $\dot{R} = 0.0447\ \dot{q}_{cw}^{0.928}$. The B-Stage cork reacted to the thermal environment very similar to the P50 sheet cork with possibly slightly more swelling occurring. Measured surface temperatures varied from 2338 to 3047 F depending onthe heat rate level.

- MTA-2 Marshall Trowelable Ablator-2

This material was tested in the simulated flight cold wall heat rate range between 21 and 138 Btu/ft^2-sec. This material was developed as a closeout material for either MSA-1 or cork. As such, its recession rate is expected to be similar for a good closeout material. The virgin material recession rate was well below the MSA-1 and MTA-2 (Ref. 6) design values, and about one-half the P50 cork design values. In this test, it receeded about twice as fast as the P50 cork. The recession rate equation which describes the data fairing in Fig. 8 is $\dot{R} = 0.3037\ \dot{q}_{cw}^{0.76455}$. This material did not exhibit a stable char formation during the test. The char continually spalled off as evidenced by a pulsating surface temperature history and hot sparks coming off the model. At a simulated flight cold wall heating rate of 77 Btu/ft^2-sec the surface temperature varied between 1940 and 2350 F, and at 136 Btu/ft^2-sec the surface temperature varied between 1885 and 2900 F, averaging about 2260 F under the last condition.

- MSA-2 — Marshall Spray-On Ablator-2

This material is one of several types being developed by MSFC to replace MSA-1 and cork TPS materials. This material could be developed into a sprayable material which would eliminate the laborious task of bonding cork in the areas that MSA-1 will not stand up to the exposed thermal environments. In these tests, the material demonstrated that it could be a direct replacement for P50 cork and MSA-1. The material exhibited virgin material recession rates slightly lower than the P50 cork design values. The recession rate equation which describes the data fairing shown in Fig. 8 is $\dot{R} = 1.3931\ \dot{q}_{cw}^{0.52922}$ during test. The material formed a stable char. Surface temperatures varied from 2374 F at a heating rate of 74 Btu/ft^2-sec to 3041 at a heating rate of 127 Btu/ft^2-sec.

4. CONCLUSIONS

For the range of test conditions investigated in this study, the TPS material samples performed as expected or much better than expected. The range of heating rates investigated were from 20 to 240 Btu/ft^2-sec and shear stress levels from 0.008 to 0.021 psia. The aerotherm APG facility provided valuable data for this investigation, and extended the range of applicability of the design recession curves for the various TPS materials. However, higher shear stresses and heating rates are still required to cover the complete plume wash range on the SRB vehicle. Future investigations should attempt to cover this range as well as simulate the SSME plume wash chemical species. The Acurex APG facility is a likely candidate facility in which such a future experimental program can be conducted.

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APPENDIX

SRB THERMAL PROTECTION SYSTEMS MATERIALS TEST RESULTS IN AN ARC-HEATED NITROGEN ENVIRONMENT

Acurex Project 6945

TESTING OF SRB-TPS MATERIALS IN AN ARC HEATED NITROGEN ENVIRONMENT

L. Arnold

Acurex Corporation/Aerotherm
Aerospace Systems Division
485 Clyde Avenue
Mountain View, California 94042

May 1979

ACUREX FINAL DATA REPORT 79-355

Prepared for
George C. Marshall Space Flight Center
Code: EP44
Marshall Space Flight Center, Alabama 35812

NASA Contract NAS8-33401

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1. INTRODUCTION

This report presents the results of testing 23 SRB-TPS material specimens for Marshall Space Flight Center under NASA contract number NAS8-33401 and Acurex/Aerotherm contract number 6945. The contract monitor was Mr. William Baker of NASA, and the onsite technical monitor was Mr. Carl Wojciechowski of Lockheed Missiles & Space Company, Inc. The tests were conducted in the 1 MW Arc Plasma Generator (APG) facility of Acurex/Aerotherm from 16 April 1979 to 27 April 1979.

1.1 Objective

The objective of the program was to test the SRB-TPS material specimens in a high heating and high enthalpy environment under two configurations. The probe configuration simulated the heating on the upper forward corner lip of the TPS where the TPS interfaces with the top of the attach ring or kick ring of the SRB. The panel configuration simulated the flight heating effects on the self-supporting TPS areas on the forward web of the SRB kick ring and attach ring.

2. TEST DESCRIPTION

The materials that were tested in this program were P50 cork, glass phenolic, "B" cork, MTA-2, and MSA-2. All of the materials were tested under both model configurations.

2.1 Facility Descriptions

This test program was conducted in the vacuum chamber of the Acurex/Aerotherm 1 MW Arc Plasma Generator (APG) facility located in Mountain View, California. Briefly, the VAC-APG produces a high enthalpy, low pressure stream using a subatmospheric pressure test section. The vacuum is provided by a five-stage steam ejector. The APG input power is supplied by a 600 kW continuous rated, saturable core reactor, DC rectifier power supply. This power supply uses a rectifier transformer which transforms 460 VAC, 60 HZ input voltage into a usable DC output voltage. The power supply can provide 1.25 MW for short periods of time.

A 1-inch diameter constricted arc heater, consisting of two segmented constrictor packs 13.5 inches long, was used for this test program. The test nozzle had a 0.75-inch throat diameter with a 8.5° half angle leading to the exit diameter of 2 inches. The models, pitot probe, and calorimeters were moved in and out of the test stream using one of the three water-cooled, pneumatically controlled stings.

2.2 Test Models

A total of 23 specimens were tested in two different model configurations. The probe test specimens supplied by NASA were mounted into a graphite model holder, as shown in Figure 1, and attached to the sting. The sting was adjusted perpendicular to the centerline flow of the test stream with a standoff distance 1 inch from the nozzle exit. The probe specimen in Figure 2 shows the shape and size of the specimens being tested.

The panel specimen shape and size are illustrated in Figure 3. The panel test specimens supplied by NASA were mounted into a copper model holder with the leading and trailing edges protected by graphite sections as shown in Figure 4. The sting was positioned so that the centerline test stream flow came into contact with the specimen 5/8 inch back of the leading edge with a standoff distance 1 inch from the nozzle exit. The specimen/holder was inclined 30° to the flow centerline.

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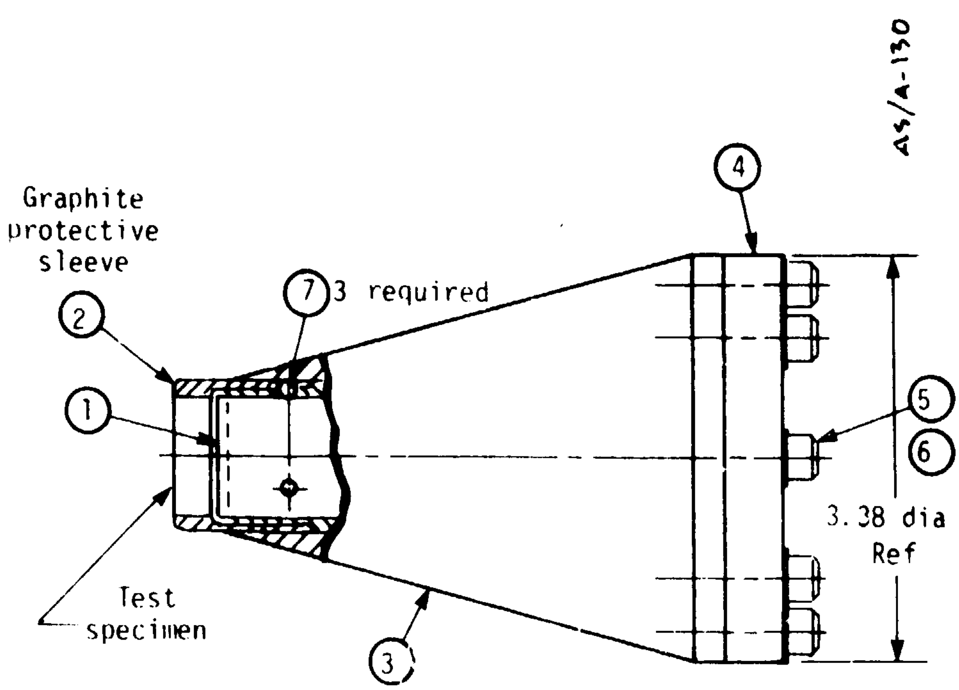

Figure 1. The SRB-TPS model holder assembly for the probe configuration.

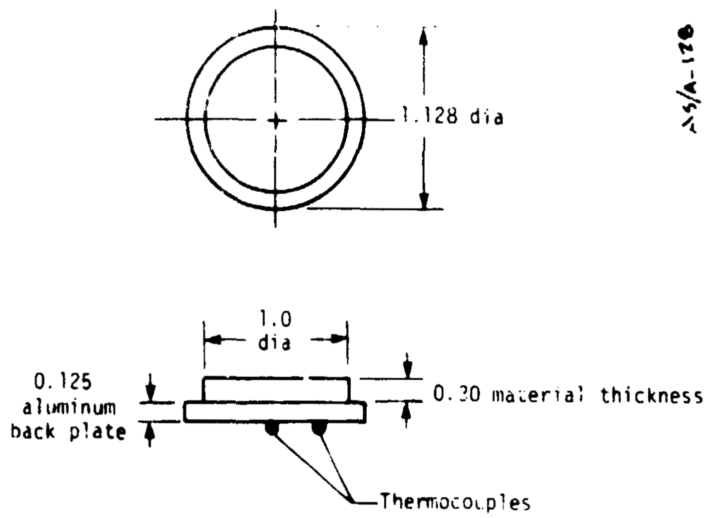

Figure 2. The probe specimen dimensions.

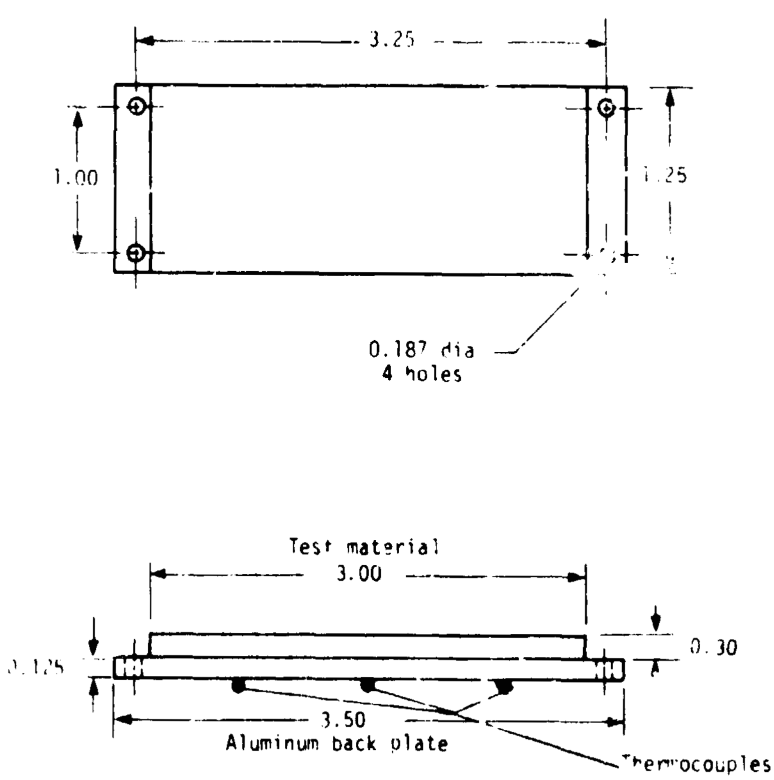

Figure 3. The panel specimen dimensions.

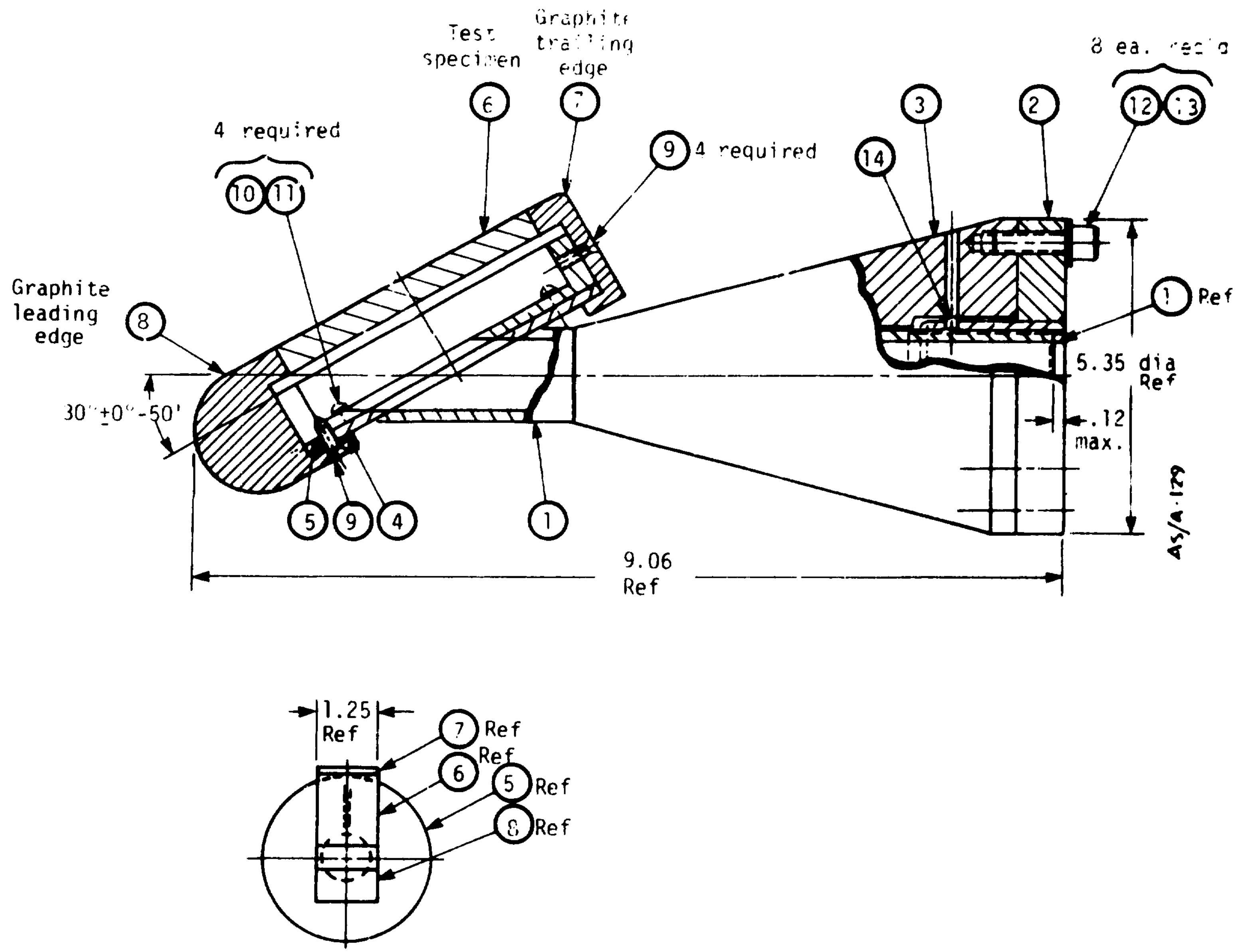

Figure 4. The SRB-TPS model holder assembly for the panel configuratio.

3. INSTRUMENTATION

The following instrumentation was used to collect the data referred to later in this report.

3.1 Data Acquisition and Analysis

All data was collected by the Vidar high-speed 80-channel digital data acquisition system with a magnetic tape recording. The data includes arc current and voltage, arc heater cooling water mass flow and temperature rise, arc chamber pressure, pitot pressure, pyrometer output, calorimeter values, and thermocouple signals. The tape was processed through an Acurex computer program to give power outputs, arc losses, bulk enthalpies, pressures, and temperatures.

In addition to the magnetic tape, a Honeywell 1858 Visicorder was used to record certain test data for immediate analysis. Some of the parameters recorded on the visicorder were pressure, thermocouple responses, arc current, and pyrometer and calorimeter outputs.

3.2 Arc Chamber Pressure

A Bell and Howell 0-25 psia pressure transducer, type 4-326-0003, was used to measure the nozzle stagnation pressure in the plenum upstream of the 0.75-inch diameter throat. The pressure transducer output signal was amplified by a Bell and Howell 8-114 signal conditioning unit before it went to the Vidar for recording.

3.3 Heating Rate

A slug calorimeter, simulating the probe specimen shape, was used to measure the heating rate of the probe configuration. The calorimeter was a 1.25-inch flat faced slug with a 0.06-inch corner radius. The calorimeter was inserted into the arc stream and withdrawn after 1 to 2 seconds had elapsed at the centerline of the arc flow.

A thin-skin calorimeter, provided by NASA to simulate the size and shape of the panel specimen, was used to collect the heating rate of the panel configuration. The thin-skin calorimeter had three type K thermocouples spaced evenly across the panel back face and offset on both sides from the centerline by 3/16 inch. Three pressure taps were also spaced evenly across the thin-skin calorimeter opposite each of the thermocouples and offset from the centerline. A Gardon gage calorimeter was used on the trailing edge of the thin-skin calorimeter to provide a secondary measurement of the heating rate. This was a Model C-1117-GX-60-120, serial number 44118. The thin-skin calorimeter, shown in Figure 5, was inserted into the arc flow and held for 3 seconds at the centerline before being withdrawn.

3.4 Backwall Temperature

Both the probe and the panel specimens were instrumented with 20-mill, type K (chromel-alumel) thermocouples. The probe configuration had one thermocouple attached at the center of the specimen and another offset about 1/4 inch to one side as shown in Figure 2. The panel configuration had three thermocouples evenly spaced from the leading edge of the specimen to the trailing edge on the specimen's centerline as shown in Figure 3.

3.5 Model Surface Temperature

For the probe configuration, a fiber optic pyrometer was used to record the surface temperature. The pyrometer was a Vanzetti Model 1317-1185-8-0H2, serial number 101719, with a 3-inch focal length and an effective spot diameter of 0.035 inch. The sensitive range is 0.7 to 0.97 microns. The pyrometer was mounted on the nozzle and positioned 3 inches from the center of the probe specimen. The temperature range was 1400°F to 4500°F.

For the panel configuration, a Thermodot Model TD-9F was used to measure the surface temperature. This pyrometer has an effective spot

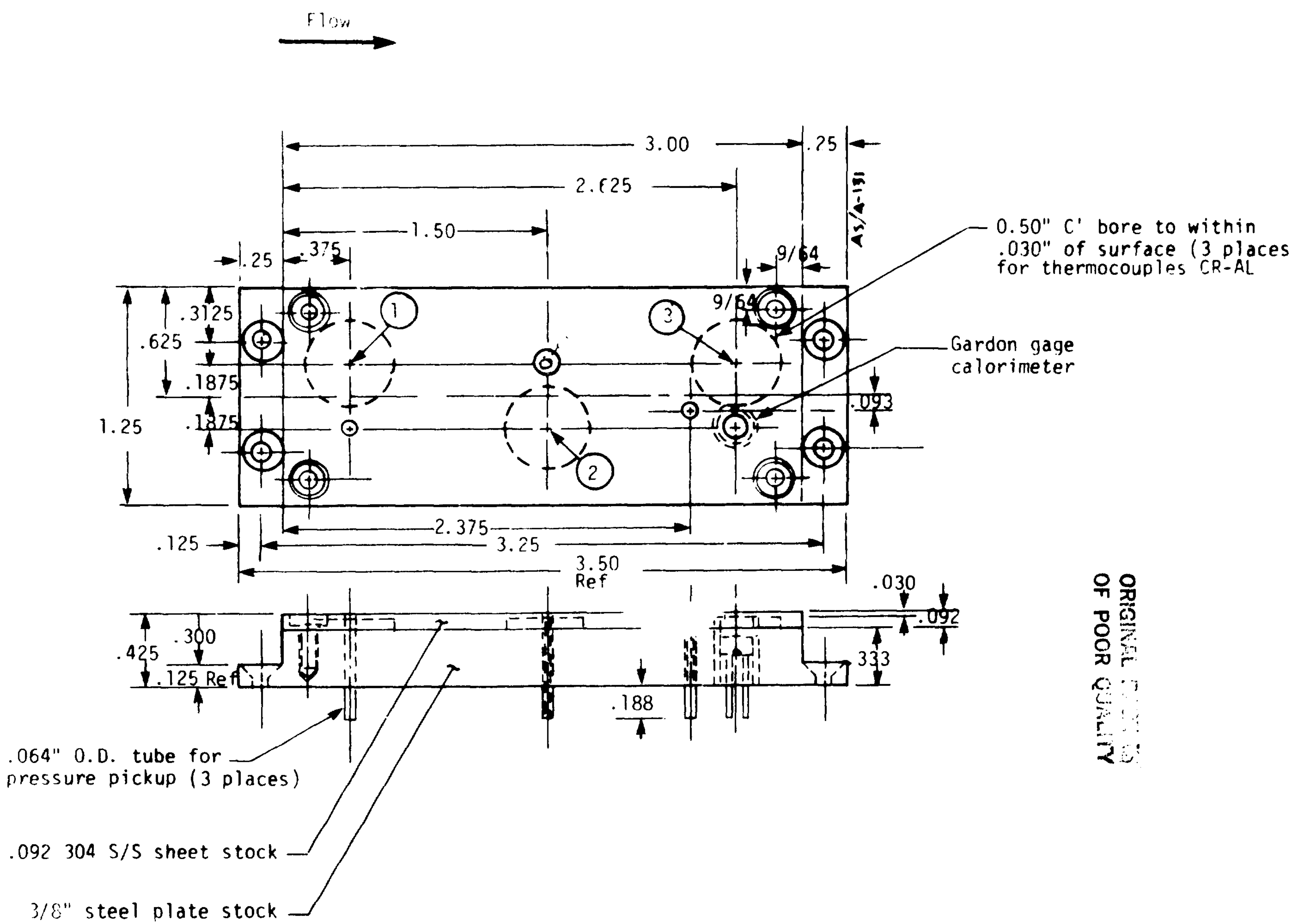

Figure 5. Thin-skin calorimeter provided by NASA.

diameter of 0.076 inch with a sensitive range of 0.75 to 0.90 microns. The pyrometer was positioned on the outside of the vacuum chamber looking through a quartz window, with the effective spot placed where the test stream centerline flow hit the panel specimen. The range of the pyrometer was 1750°F to 2600°F.

3.6 Bulk Enthalpy

The enthalpy of the gas was determined by an energy balance of the APG system, including the arc column from the cathode to the anode, plenum, and nozzle. Bulk enthalpy is defined as:

$$h_B \text{ (Btu/lb)} = \frac{0.9484 \times 10^{-3} \text{ (IV)} - \dot{m}_{H_2O} \, C_p \, (\Delta T_{H_2O})}{\dot{m}_{t_{gas}}}$$

where

I = Arc current (amps)

V = Voltage dropped from cathode to anode (volts)

$\dot{m}_{H_2O}$ = Mass flowrate of the cooling water through the arc, plenum, and nozzle (lb/sec)

ΔT_{H_2O} = Difference in the temperature between the inlet and the outlet cooling water for the arc, plenum, and nozzle (°F)

$\dot{m}_{t_{gas}}$ = Total mass flow of arc heated gas (lb/sec)

Water flowrates were measured with an ASME sharp edge orifice and a differential pressure transducer. Temperatures were measured with a differential thermopile. Gas flow was measured on two flowmeters calibrated for a fixed pressure, temperature, and flow range.

3.7 Model Surface Pressure

Three Statham 0-5.15 psia pressure transducers, type PA 732 TC-5.15-350, were used to measure the model surface pressure. The 1/16-inch diameter pressure ports were located on the thin-skin calorimeter, offset 3/16 inch from the centerline and placed alternately on each side of the centerline. A small tube was run from the pressure ports to the pressure transducers. The surface pressures were then taken during the calibration runs for the panel configuration.

3.8 Model Stagnation Pressure

A pitot tube was used to measure the stagnation pressure on the centerline. The 3/8-inch diameter pitot probe had a 1/16-inch opening. The pitot probe was connected to a Statham 0-15 psia pressure transducer, type P68-15A-300, which obtained the pressure reading. Visicorder records of the pressure response were used to ensure that a steady-state condition had been reached before removal from the gas stream.

3.9 Centerline Enthalpy

The centerline enthalpy was calculated using the measured quantities of model stagnation pressure, the coldwall heating rate, and the following Zoby equation for N_2 (Reference 1):

$$h_{\mathrm{c\!\!L}} \text{ (Btu/lb)} = \frac{\dot{q}_{CW} \sqrt{R_{eff}}}{0.0431 \sqrt{P_{t_2}}}$$

where

$\dot{q}_{CW}$ = Coldwall heat flux from the 1.25-inch flat faced calorimeter (Btu/ft^2 sec)

P_{t_2} = Model stagnation pressure (atm)

$\sqrt{R_{eff}}$ = 0.421 for the calorimeter configuration (ft$^{1/2}$)

3.10 Camera

The camera used to record the models under test conditions was a Locam camera with a 50 mm lens. The speed was set at 100 frames a second. The f stop was either 16 or 22, depending on the type of film being used.

Three different kinds of film were used. The first was the Kodak Plus-X Reversal Film 7276 with an ASA of 50. The second film was Eastman Ektachrome Video News Film 7240-Tungsten with an ASA of 125. The last type of film used was Eastman Ektachrome Video News Film, High Speed, 7250-Tungsten with an ASA 400.

4. TESTING

4.1 Test Matrix

Table 1 lists the test sequence for the models, test duration, test heating conditions, and model configuration.

The coldwall heating rate did not simulate the surface temperature and the heat load as closely to actual flight conditions as had been expected. The hotwall heating rate, however, was determined to closely simulate actual flight conditions. By taking the hotwall heating rate, both the flight surface temperature and the flight heat load could be simulated using the arc heater. The simulated conditions were obtained with an N_2 test gas in a supersonic stream having a minimum Mach number of 2.5.

4.2 Test Procedures

Calibration runs were made at each test configuration before the model runs were made. The calibration sequence was as follows:

1. Hook up all instrumentation to the slug or thin-skin calorimeter.

TABLE 1. TEST MATRIX OF SRB-TPS MATERIALS

Run No.	Configuration	Model No.	Heating Condition	Time (sec)
1	Panel	C-1	Hi	4
2	Probe	PC-1	Lo	4
3		PC-2	Lo	4
4		PA-3	Hi	4
5		PA-4	Hi	8
6		PA-5	Lo	8
7		PA-6	Hi	5
8		PB-1	Lo	4
9		PB-2	Lo	8
10		PD-1	Lo	5
11		PE-1	Lo	5
12		PE-2	Lo	8
13		PD-2	Lo	8
14	Panel	C-2	Hi	15
15		A-1	Hi	15
16		A-2	Hi	25
17		B-1	Hi	15
18		E-1	Hi	15
19		D-1	Hi	15
20		E-2	Hi	20
21		D-2	Hi	25
22		C-3	Hi	25
23		B-2	Hi	25

2. Calibrate all the modules on the 1858 Visicorder with a known voltage.
3. Pump down the arc vacuum chamber.
4. When chamber is pumped down to desired pressure, zero the transducers.
5. Check vacuum chamber and all instrumentation lines for leakage.
6. Set gas line pressure.
7. Cold flow gases to ensure proper mass flowrate.
8. Start arc on argon, turn magnetic tape on, and switch nitrogen on when the arc current is 100 amperes above the desired test point.
9. After switching to nitrogen, lower the arc current to the test point.
10. Insert the pitot probe (P_{t_2}) into the arc flow, stationary at the centerline of the flow for 2 seconds with 1858 Visicorder running at 1 ips, and then withdraw it.
11. With the 1858 Visicorder running at 10 ips, insert the thin-skin calorimeter into the arc flow and leave it at the flow centerline for 3 seconds before withdrawal.
12. With the 1858 Visicorder running at 10 ips, insert the slug calorimeter into the arc stream for 1 to 2 seconds before withdrawal.
13. Using the information on the magnetic tape, run a computer program to yield the data for the arc conditions; analyze the data from the 1858 Visicorder, and record the results.

14. Repeat this process several times to ensure operation at the desired test point is obtained.

The procedure used when testing the models was as follows:

1. Take pretest photograph.
2. Record pretest weight.
3. Record pretest thickness.
4. Connect model thermocouples to the recording system.
5. Securely mount model to the sting with the probe center on the centerline of the arc, 1 inch away from the nozzle exit, or the panel inclined 30° to the arc flow, with the arc flow centerline hitting the model 5/8 inch from the leading edge of the specimen; the panel stagnation point had a 1-inch standoff distance from the nozzle exit.
6. Check all instrumentation to ensure that it is working properly.
7. Lower the vacuum chamber pressure to the desired level.
8. Cold flow the gases to ensure proper mass flowrate.
9. Start the arc and switch over to nitrogen at 100 amperes over the desired current.
10. Lower the arc current to the test setting.
11. With the 1858 Visicorder turned on at 10 ips, insert the slug calorimeter into the arc stream for 1 to 2 seconds and then withdraw it.
12. With the Locam camera and the 1858 Visicorder turned on, insert the probe or panel model into the arc stream with the duration of the test starting when the model reaches the arc flow centerline as shown in Figures 6 and 7.

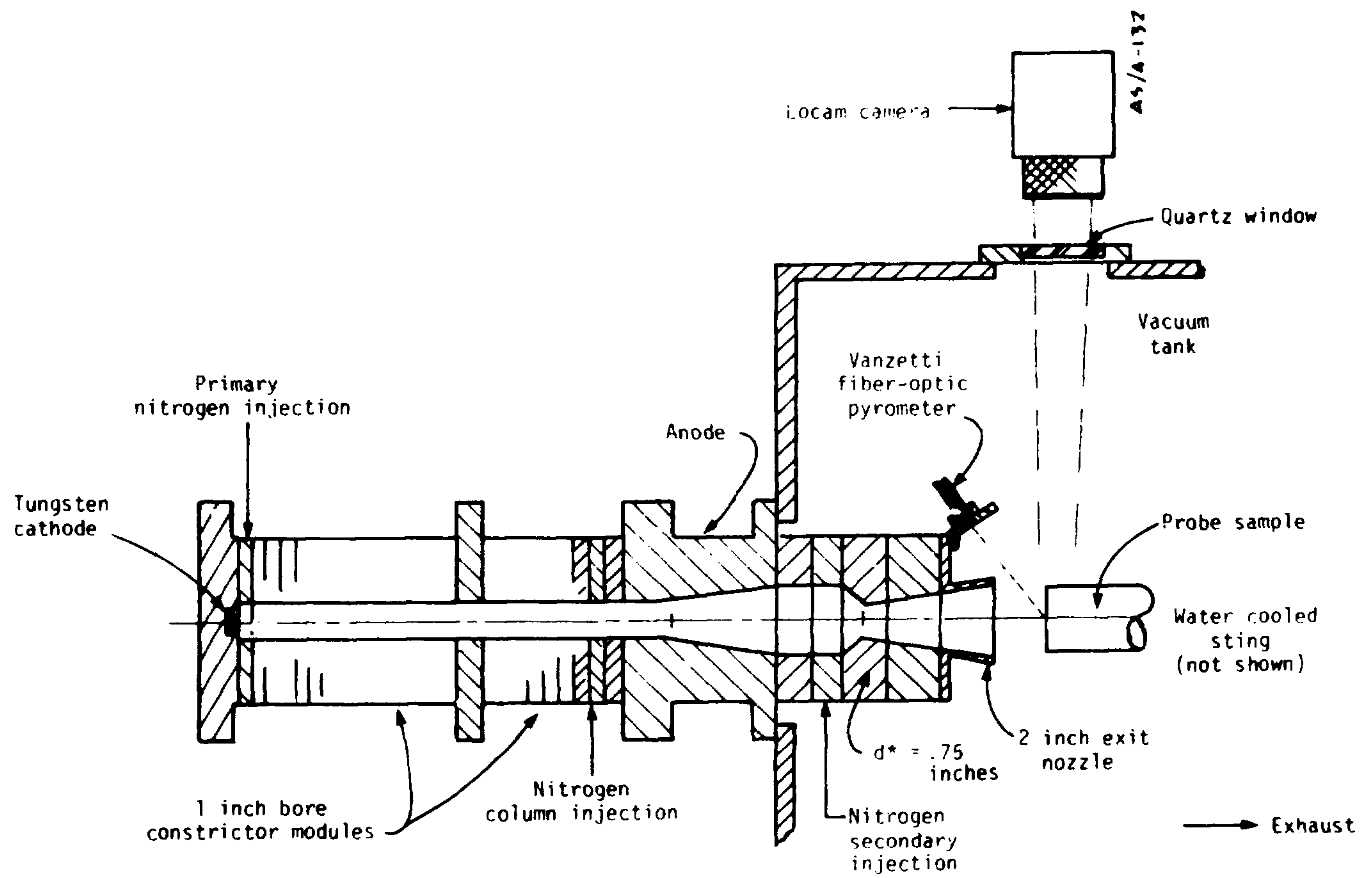

Figure 6. Testing of the SRB-TPS models in the probe configuration.

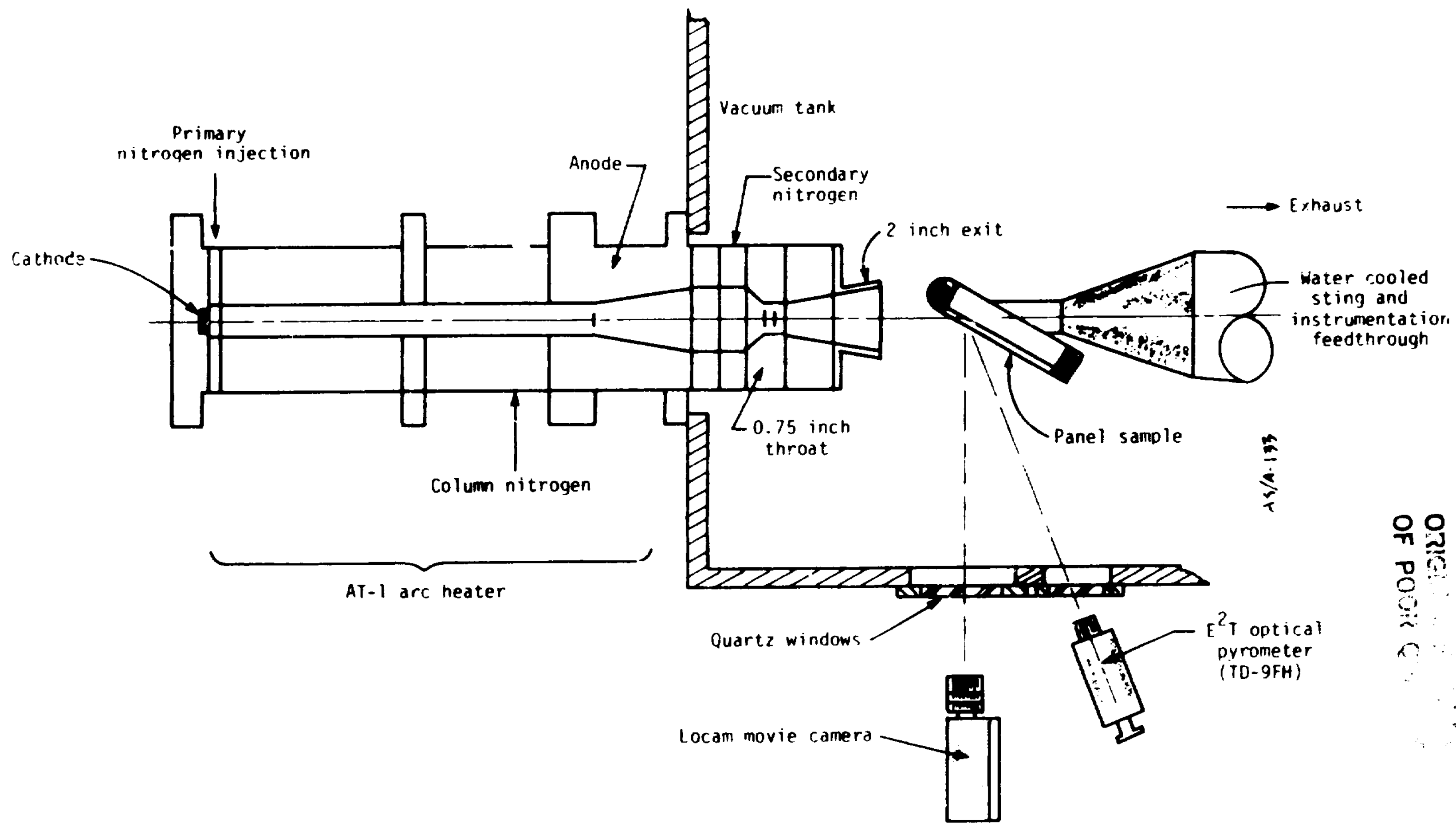

Figure 7. Testing of the SRB-TPS models in the panel configuration.

13. After running the test, bring the vacuum chamber up to atmospheric condition and remove the model from the sting.

14. Give the model to the onsite technical representative for observations of the charring and spalling (the post-test photographs, post-test thickness, and post-test weight will be taken at NASA).

15. Repeat steps 1-14 for each test model.

5. RESULTS

Table 2 presents the ten calibration runs taken for both the panel and the probe configurations. Seven calibration runs were made for the probe configuration to determin the stagnation pressure, coldwall heating rate, arc current, and chamber pressure. From this information, the centerline enthalpy, centerline temperature, and hotwall heating rate were calculated. The hotwall/coldwall correction was made using the equation,

$$\dot{q}_{HW} = \dot{q}_{CW} \left[\frac{H_{\mathrm{CL}} - H_{HW}}{H_{\mathrm{CL}} - H_{CW}}\right]$$

Based on the actual flight data, a surface temperature of 3500°F was assumed for the hotwall, corresponding to an enthalpy of 830 Btu/lb.

Three calibration runs were made for the panel configuration. The calibration runs provided information on the coldwall heating rate, centerline enthalpy, centerline temperature, arc current, chamber pressure, and surface pressure across the panel. From the thin-skin calorimeter, the coldwall heating rate and the hotwall heating rate at two temperatures, 3500°F and 2000°F, were found by calculations.

A total of 23 specimens supplied by NASA were tested during the program. Twelve specimens were tested in the probe configuration. Of

TABLE 2. CALIBRATION RUNS FOR THE PROBE AND PANEL CONFIGURATIONS OF THE SRB-TPS TEST PROGRAM

Run No.	I (Amps)	Voltage (Volts)	Probe $\dot{q}_{CW}$ (Btu/ft^2-sec)	H_{ℓ} (Btu/lb)	T_o (°R)	Pt_2 (atm)	P_{cham} (atm)	Probe $\dot{q}_{HW}$ (Btu/ft^2-sec)	$\dot{q}_{CW1}$ (Btu/ft^2-sec)	$\dot{q}_{CW2}$ (Btu/ft^2-sec)	$\dot{q}_{CW3}$ (Btu/ft^2-
3148-02	321	509	143	3520	9160	.1593	0.978	113			
3149-01	522	481	200	4[illegible]73	9810	.1828	1.136	168			
3150-01	224	514	95	2447	8019	.1438	0.888	65			
-02	520	482	174	3982	9491	.184	1.133	142			
-02	520	482	23	3982	9491	-	1.133	-	55	44	16.[illegible]
-03	525	484	190	4335	9695	.184	1.142	158			
-03	525	484	19	4335	9695	-	1.142	-	67	45	19.[illegible]
-04	224	514	87	2244	7657	.1453	0.886	58			
3151-01	520	481	180	4069	9509	.1875	1.136	147			
-01	520	481	19	4069	9509	-	1.136	-	70	47	11.[illegible]

FOLDOUT FRAME

$\dot{q}_{CW2}$ (Btu/ft^2-sec)	$\dot{q}_{CW3}$ (Btu/ft^2-sec)	$\dot{q}_{HW1}$ (Btu/ft^2-sec)		$\dot{q}_{HW2}$ (Btu/ft^2-sec)		$\dot{q}_{HW3}$ (Btu/ft^2-sec)		$P_{surface}$			Config.
		3500	2000	3500	2000	3500	2000	1 (atm)	2 (atm)	3 (atm)	
											Probe
											Probe
											Probe
											Probe
44	16.5	45	51	35	41	13	15	0.087		0.005	Panel
											Probe
45	19.5	56	63	[illegible]	42	16	18	0.088		0.005	Panel
											Probe
											Probe
47	11.9	58	66	39	44	10	11	0.0791	0.0213	0.0099	Panel

those 12, three specimens were tested at the low heat load simulating plume conditions. The remaining nine specimens were tested at the high heat load simulating flight conditions. The results are shown in Tables 3 and 4.

The other 11 specimens were tested in the panel configuration. They were all tested at the high heat load to simulate flight conditions. The results from the panel configuration tests are also shown in Tables 3 and 4.

In Table 3, the exposure time started when the test model entered into the test stream and ended when the model was withdrawn from the test stream. The centerline temperature is the actual time the test model was at the centerline of the test stream.

The hotwall heating rate in Table 2 and the test hotwall heating rate in Table 3 were from the probe calorimeter. Also the coldwall heating rate in Table 2 was from the probe calorimeter.

All of the backwall temperatures in Table 3 were taken from the Visicorder traces made during the exposure time of the test model.

The post-test photographs of all specimens, certain post-test weights, and all the post-test thicknesses will be taken at NASA. The pretest photographs and the Visicorder traces of the test runs were taken to NASA by the technical onsite monitor to be analyzed.

TABLE 3. RESULTS FROM THE TESTING OF THE SRB-TPS MATERIALS IN THE ARC PLASMA GENERATOR

Run No.	Model No.	Config.	Material	$T_{surface}$ (°F)	T_{BW1} (°F)	T_{BW2} (°F)	T_{BW3} (°F)	Time on ℄ (sec)	Exposure Time (sec)	T_{BW1_i} (°F)	T_{BW2_i} (°F)	T_{BW3_i} (°F)	Probe $\dot{q}_{HW_{test}}$ (Btu/ft^2-sec)
3152-01+	C-1	Panel	P50	2395	93	82	82	3.20	4.25	75	75	75	64
3153-01	PC-1	Probe	P50	2836	130	120	-	4.25	4.4	68	68	-	85
-02	PC-2		P50	3101	159	165	-	4.30	5.1	69	69	-	80
-03	PA-3		Phenolic	2912	187	194	-	4.20	5.45	68	68	-	139
-04	PA-4		Phenolic	2902	>365	>365		8.2	9.1	68	69	-	142
3154-01	PA-5		Phenolic	2220	216	204	-	8.2	8.8	76	76	-	57
3155-01+	PA-6		Phenolic	2988	207	205	-	6.0	5.75	73	73	-	149
-02+	PB-1		"B" cork	2978	122	116	-	4.3	5.0	77	76	-	107
-03+	PB-2		"B" cork	3047	283	267	-	8.3	8.8	75	76	-	84
-04	PD-1		MSA-2	2991	138	128	-	5.5	5.56	76	76	-	71
3156-01	PE-1		MTA-2	2870	139	128	-	5.3	5.91	74	74	-	100
-02	PE-2		MTA-2	2897	307	270	-	8.2	9.4	74	73	-	95
-03	PD-2		MSA-2	3041	238	224	-	8.4	8.6	78	78	-	74
3157-01+	C-2	Panel	P50	2273	163	106	89	15.5	15.9	67	66	66	55
-02+	A-1		Phenolic	2424	254	123	101	15.4	16.27	68	68	69	50
-03+	A-2		Phenolic	2267	241	154	167	25.5	26.1	77	77	77	53
-04+	B-1		"B" cork	2370	165	X	110	15.4	15.7	74	X	74	52
3158-01+	E-1		MTA-2	2320	284	144	105	15.4	16.0	76	76	76	54
-02+	D-1		MSA-2	2374	166	X	X	15.4	15.65	76	X	X	53
-03+	E-2		MTA-2	2350	216	X	X	20.7	21.1	83	X	X	58
-04+	D-2		MSA-2	2345	264	X	X	25.6	26.0	84	X	X	58
3159-01+	C-3		P50	2400	273	X	X	25.5	26.1	94	X	X	54
-02+	B-2		"B" cork	2338	268	X	X	25.5	25.7	97	X	X	48

\- There were no number 3 thermocouples on the probe configuration
X The thermocouple was not hooked up
% To be measured or weighted at NASA
+ Movies taken

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Probe $\dot{q}_{HW_{test}}$ (Btu/ft^2-sec)	Weight Pre (g)	Weight Post (g)	Thickness Pre (in)	Thickness Post (in)	Remarks
64	38.0	37.624	.427	*	Barely scorched
85	10.8	10.710	.428	*	Good char buildup; 1/32 in char depth
80	10.7	10.733	.428	*	Good char buildup; 3/64 in char depth
139	14.7	14.716	.385	*	Glass flow and outer ply bubbled; 1/16 in char depth
142	14.5	14.401	.385	*	Glass flowed and bubbles occurred; model debonded after test; 3/32-in char depth
57	14.6	14.756	.385	*	No glass flow or bubbles; model looked good; 3/64 in char depth
149	14.7	14.685	.387	*	Model looked good; glass melted; 1/16 in char depth
107	10.806	10.504	.428	*	Model looked good; good char; 1/16 in char depth; no recess
84	10.935	10.689	.429	*	Model looked good; model swelled 1/32 in; good c[illegible]; 3/32-in char depth
71	10.218	10.078	.431	*	Model looked good; 3/64-in char depth; recess 1/32 in
100	10.045	*	.431	*	Char spalled off; $T_{surface}$ varied; measurable recess
95	11.063	*	.430	*	Saw hot char spall; $T_{surface}$ avg. 2255°F; slight surface dimple
74	10.239	*	.432	*	Model debonded after shutdown; good model (no spalling); recess = .04 in; char = .06 in
55	38.424	37.070	.426	*	Good char buildup; final ~ .32 thick; minimum char erosion in spots; .10 in char depth
50	57.015	56.092	.390	*	Slight glass melt; debonded after test; good model; no recess; .05 in char depth
53	56.4	55.141	.385	*	Slight glass melt; debonded after test; good model; no recess; .08 in char depth
52	37.4	36.102	.429	*	Good char; $T_{surface}$ ~ 2330 to 2370°F
54	38.9	35.976	.430	*	Char spalled off
53	34.8	34.063	.429	*	Good model; stable char; T_2 and T_3 were eliminated to save time; $T_{surface}$ 2370°F; minor char erosion; crazing
58	38.8	34.175	.429	*	T_2 and T_3 deleted to save time; char spalled off; major surface erosion; $T_{surface}$ 2642°F
58	34.9	32.409	.426	*	Good stable char almost to aluminum back; minor surface erosion; charred surface crazed
54	38.2	35.148	.428	*	Good char buildup; surface crazed; T_B = 320°F in 3.5 sec after shutdown
48	37.5	35.691	.429	*	Model almost all charred; T_B = 387°F after shutdown

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TABLE 4. CONDITIONS OF THE ARC PLASMA GENERATOR DURING THE TESTING OF THE SRB-TPS MODELS

Run No.	Model No.	Config.	Material	P_{cham} (atm)	$\dot{q}_{CW}$ (Probe) (Btu/ft^2-sec)	I (Amps)	Volts (V)	H_{bulk} (Btu/lb)	$H_{℄}$ (Btu/lb)	$\dot{m}_{t_{gas}}$ (lb/sec)	T_o (°R)
3152-01	C-1	Panel	P-50	1.137	202	520	484	3307	4781	0.0415	9950
3153-01	PC-1	Probe	P-50	0.986	118	317	504	2480	3084		8735
-02	PC-2		P-50	0.996	115	322	504	2488	2999		8635
-03	PA-3		Phenolic	1.129	174	519	479	3170	4164		9640
-04	PA-4		Phenolic	1.124	177	519	481	3217	4229		9680
3154-01	PA-5		Phenolic	0.881	80	222	512	1922	2065		7250
3155-01	PA-6		Phenolic	1.133	185	521	481	3232	4395		9770
-02	PB-1		"B" cork	0.991	132	316	505	2434	3416		9050
-03	PB-2		"B" cork	0.983	118	319	501	2414	3088		8700
-04	PD-1		MSA-2	0.978	104	318	501	2414	2754		8340
3156-01	PE-1		MTA-2	0.979	122	320	501	2459	3179		8820
-02	PE-2		MTA-2	0.987	120	325	501	2480	3116		8750
-03	PD-2		MSA-2	0.984	108	325	499	2458	2831		8440
3157-01	C-2	Panel	P-50	1.123	181	518	480	3158	4320		9730
-02	A-1		Phenolic	1.126	167	511	475	3070	4010		9545
-03	A-2		Phenolic	1.136	172	514	481	3186	4095		9585
-04	B-1		"B" cork	1.128	174	519	480	3156	4159		9635
3158-01	E-1		MTA-2	1.131	172	515	484	3192	4103		9600
-02	D-1		MSA-2	1.132	172	514	482	3150	4101		9600
-03	E-2		MTA-2	1.138	183	513	486	3190	4344		9740
-04	D-2		MSA-2	1.141	185	516	486	3209	4389		9760
3159-01	C-3		P-50	1.140	183	516	485	3168	4340		9740
-02	B-2		"B" cork	1.145	165	515	486	3134	3928		9470

REFERENCE

1. Zoby, E. V., "Empirical Stagnation-Point Heat-Transfer Relation in Several Gas Mixtures at High Enthalpy Levels," National Aeronautics and Space Administration, June 24, 1968.