D3/ N81-14169

HEATSHIELD MATERIAL SELECTION FOR ADVANCED BALLISTIC REENTRY VEHICLES

P. J. Legendre,* T. Holtz* and J. C. Sikra**

ABSTRACT

This paper presents a review of the available ground test data obtained in support of the Air Force Systems Command Space and Missile Systems Organization (presently Ballistic Missile Office) efforts to evaluate the roll torque and thermodynamic performance of recently flown, tape-wrapped carbon phenolic heatshield materials in order to select a material for future flight tests. These efforts evaluated the performance of staple rayon fiber and AVTEX continuous rayon fiber as precursor materials for heatshields. The materials studied were referenced to the IRC FM5055A heatshield materials flown during the past decade. Three different arc jet facilities were used to simulate portions of the reentry environment in this study.

The paper specifically addresses the comparison of the IRC FM5055A and the AVTEX FM5055G, both continuous rayon fiber woven materials having the phenolic impregnant filled with carbon particles. The AVTEX continuous fiber, unfilled material FM5822A was also examined to a limited extent. Test results showed that the AVTEX FM5055G material provided a close substitute for the IRC FM5055A material both in terms of thermal protection and roll torque performance.

INTRODUCTION

During the past few years, a number of heatshield materials were developed to replace the International Rayon Corporation (IRC) rayon-based FM5055A carbon phenolic heatshield material for reentry vehicles. This replacement was necessitated when IRC stopped the production of continuous fiber rayon. The carbon phenolic heatshields based on this material have performed satisfactorily with respect to roll torque and thermal protection. Currently, the continuous fiber rayon cloth is being produced by AVTEX, Inc. For a while, however, the supply of continuous fiber rayon cloth was non-existent or in doubt, so that the Air Force Space and Missile Systems Organization (SAMSO) developed carbon phenolic heatshield materials manufactured from rayon cloth woven from staple rayon fibers.

In the discussions to follow, the flight heatshields and ground test heatshield specimens using the continuous fiber cloth manufactured by IRC will be referred to as IRC. This cloth is impregnated with phenolic resin filled with carbon particles and is designated FM5055A. Similarly, the same items manufactured from the AVTEX continuous rayon fiber cloth will be referred to as AVTEX. The AVTEX carbon phenolic heatshields come in two variations. In one, the phenolic with which the rayon cloth is impregnated is loaded with carbon particles. This combination is called AVTEX filled [AVTEX(F)] with the

*The Aerospace Corporation, El Segundo, CA.
**USAF Ballistic Missile Office, Norton AFB, CA.

designation FM5055G. The other is AVTEX rayon cloth impregnated with phenolic resin without carbon particles. This is called AVTEX unfilled [AVTEX(U)] with the designation FM5822A. Similarly, heatshields fabricated from staple rayon cloth and impregnated with resin with and without carbon particles are known as filled staple, FM5829A, and unfilled staple, FM5832A, respectively.

Finally, there are three manufacturers who are qualified to manufacture reentry heatshields to Air Force specifications: HITCO, Haveg-Reinhold, Inc., and Kaiser Industries. Table I summarizes the known differences in the manufacturing techniques of the three heatshield manufacturers. If, for example, a test specimen is referred to as an AVTEX(F)/HITCO, then the heatshield is made from continuous rayon cloth produced by AVTEX, the impregnating phenolic is loaded with carbon particles, and the heatshield was processed per the HITCO process outlined in Table I.

A number of the heatshields flown during the past two years were produced from new heatshield materials. Unfortunately, some vehicles with heatshield mid-sections fabricated from the unfilled staple rayon cloth and manufactured by the HITCO process (FM5832A, Process A) exhibited unacceptable levels of roll torque on recent flight tests. Vehicles with mid-sections fabricated from the unfilled staple rayon cloth and manufactured by the Kaiser process (FM5832A, Process B) exhibited satisfactory roll torque characteristics. Finally, a vehicle with a filled staple heatshield manufactured by the HITCO process (FM5829A, Process A) also exhibited unsatisfactory roll torque characteristics.

In a continuation of the program described here, the Air Force Systems Command Ballistic Missile Office is currently evaluating heatshield material and fabrication options to make a heatshield which will produce more desirable vehicle roll behavior. The leading candidate is a carbon phenolic made from the AVTEX continuous rayon fiber carbonized cloth and impregnated with the carbon filled resin (FM5055G). The process selection in this evaluation was open.

It was the prime objective of the study reported herein to review the available ground test data and based on these results make an interim recommendation for a candidate material and process for future heatshields. The present study thus encompasses principally the comparison of IRC FM5055A material to the AVTEX(F) FM5055G and the processes by which both have been manufactured.

NOMENCLATURE

M_e	Edge Mach Number
H_e	Edge Enthalpy, Btu/lb
P_e	Edge Pressure, atm
$\dot{q}_{cw}$	Cold Wall Heat Flux at the edge, Btu/sq ft sec
τ_w	Boundary Layer Shear at the wall, lbs/sq ft (psf)
QA	Quality Assurance

HT Height

1 inch = 2.54 cm

1 mil = 0.00254 cm

1 foot = 30.5 cm

1 pound (lb) = 0.454 kg

1 atm = 760 mm Hg

3413 Btu = 1 kw-hr

1 Btu = 1054 joules

°R = 0.555°K

DESCRIPTION OF TESTS

A general test matrix of all of the ground tests reported in this paper is presented in Table II. Note in this table that heatshield specimens were tested other than those made from FM5055A, FM5055G and FM5822A. These other specimens, from material designated FM5832A, were made from staple rayon cloth which was found to contribute to unsatisfactory heatshield roll torque performance in these and previous tests. Therefore, this study focused on (1) comparing the performance of FM5055G and FM5822A materials with the old FM5055A, and (2) investigating the reasons for the poor performance of the FM5832A materials.

As shown in Table II, three different arc jet facilities were used to obtain the ground test data: the Air Force Flight Dynamics Laboratory (AFFDL) 50-megawatt arc jet, the General Electric Company (GE) Hy-Arc facility, and the Avco Corporation 10-megawatt arc jet. Each facility accommodated a different test specimen configuration, had different instrumentation, and provided a somewhat different test environment. Thus the tests supplemented each other in the information obtained. Table III summarizes the test environments.

AFFDL 50 MW Tests

SAMSO sponsored a series of roll torque manufacturing comparison tests in the AFFDL arc jet facility. Prototype Development Associates (PDA), Inc. was the test conductor. Of a total of 25 heatshield specimens tested, five were AVTEX(F) FM5055G models, three fabricated with right-hand (RH) splices and two fabricated with left-hand (LH) splices. There were eight IRC FM5055A models, five with right-hand splices and three with left-hand splices. Haveg was the fabricator of all 25 models and simulated the constructions of the other manufacturers, as required. A detailed test matrix is presented in Table IV (Reference 1), and the test technique is described in References 2 and 3.

The results from these tests were very interesting. As own in Figure 1, all of FM5055G LH and RH spliced models rolled in the same . (negative) direction. This indicated that the rawwrap helix angle, which was left-handed for all the models, was a significant parameter in producing roll torque and, in fact, dominated here over the splice direction. The rate of change of roll rate for the RH splice model, AF-4, was greater than either (AL-1 and AL-2) LH splice models. Two of the RH splice models, AF-1 and AF-5, did not start rolling for 3 and 4 seconds, respectively.

A review of the test films showed that models AL-1 and -2 spun smoothly in the predicted direction.

When AF-4 was reviewed, it was noted that minor lands formed on the heat-shield along with minor pock marks. Cross hatching was not noted until later in the test. On the other hand, AF-5 exhibited minute pits at first. No lands were observed. The surface was noted as being mottled in appearance with a uniform distribution of pocks. It is not known if the delay in the spin for AF-5 was due to a bearing problem or to the absence of lands on the model early in the test.

All three of the AVTEX(U) FM5822A RH splice models (AU-1, -3 and -4) hardly rotated. Their surfaces in the 50 MW tests tended to degrade late in the tests with some char peeling noted.

Several of the SAMSO IRC FM5055A baseline models exhibited a somewhat random roll behavior (Figure 1), with even some roll reversals experienced by the FB-3 and FB-1 models.

In conclusion, the two FM5055G LH splice models produced the most consistent roll torque performance. The FM5055G RH splice models were consistent in roll direction only, and the reasons for the delayed roll onset of AF-1 and -5 are not known. The observations from the test films indicate that development of local surface features, such as lands, during the ablation process may be related to the roll torque performance.

Prior to these roll torque manufacturing comparison tests, SAMSO sponsored a development roll torque screening test series in October 1978. Over 30 models were tested and some of the test results are applicable to this study. A summary of results is presented in Table V.

A total of 12 data points were obtained from the screening tests and the roll torque manufacturing comparison tests for the IRC FM5055A model, with a left-hand helix, left-hand splice, and externally cured. It has been designated B-, SB- and RB- in the two test series. Eleven of the 12 FM5055A models gave regular, repeatable roll performance. (The fabrication of the twelfth, Model B-2, is in question.)

In the October 1978 test series (Table V), three FM5055A models (FM-1, -2 and -3) were fabricated similarly to the RB Reference models listed in Table IV, except for the cure. These three models were cured in a female mold (internal bag). As shown in Table V, these internally bagged models (FM serial nos.) performed comparably to the externally bagged models (B serial nos.). Thus, type of cure did not appear to be a principal variable affecting performance.

GE HY-ARC Tests

From Table II, 35 models were tested in the GE HY-ARC facility. Of these, five were fabricated of AVTEX(F) FM5055G and six of IRC FM5055A. Many of these models were instrumented with thermocouples, and as indicated by Table II, several had other special thermal and ablation instrumentation.

Both the FM5055A and the FM5055G materials exhibited similar recession rates, 0.0085 and 0.0089 inch per second, respectively. As shown by Figure 2, their temperature histories follow the prediction identically. The thermocouple response times for the materials are tabulated in Table VI. The foregoing data are taken from Reference 4.

The post-test examinations showed considerable differences between the char profiles for the FM5055A and FM5055G materials. A sample of FM5055A exhibited a narrow, densified region near the model surface with large interior voids. This interior structure has heretofore not been modeled in thermal analyses. The FM5055G maximum surface roughness was much smaller than the FM5055A (Table VII, Reference 4). In fact, the FM5055G material had a 0.70 mil maximum roughness height whereas the FM5055A and the FM5822A had maximum roughness heights of 1.10 and 1.30 mils, respectively. Since the mean or nominal roughness data are all comparable (Table VII), the differences in maxima indicate that FM5055G has the most uniform surface characteristics.

The problem was noted that thermal expansion of carbon phenolics is not adequately predicted. This expansion could be facility or material peculiar, or could be a real phenomenon; further study is required. In either or both cases, this expansion will have to be factored into the reentry vehicle charring ablator computer programs.

Sufficient testing was not performed in this series to differentiate between most of the process variables, e.g., bagging effects, splice effects, etc.

Avco 10 MW Tests

A series of tests was performed in the Avco 10 MW arc jet facility (Table II) to obtain a detailed evaluation of the ablative response of candidate staple-fiber materials. Twenty-nine models were tested in this series, including three AVTEX(F) FM5055G specimens.

The ablative performance of the heatshield materials is summarized in Table VIII, taken from Reference 5. The recession rates for the three FM5055G models varied from 0.00209 to 0.00252 inch per second, whereas the FM5055A recession rates varied from 0.00211 to 0.00624 inch per second. The thermodynamic test conditions were within 2.5% for all parameters for the five valid FM5055G and FM5055A test runs.

The 10 MW arc jet test conductor, Avco, presented a very detailed post-test description of the models. Two of the FM5055A models exhibited hard black charred surfaces, with stepped regions of material removal and interlaminar separation. Surface char appeared to be susceptible to fabric layer separation. From the movies, it was noted that a small surface anomaly was present at the beginning of the high heat pulse with little effect on total ablation. Erosion patterns started near the leading edge. Interlaminar separations began about 11.1 sec into the test. Material progressive delamination was evident. One FM5055A test was compromised due to overexposure of the film. However, surface expansion of 0.029 inch was noted in one area of the test sample.

The three FM5055G models exhibited a hard black charred surface with a stepped transition region 0.8 inch from the leading edge. The film review showed some small surface "spots" at the start of the high heat flux cycle, and the surface had some brightness variations over its entirety. An ablation/erosion pattern developed near the leading edge and progressed slowly downstream. Limited ply delamination occurred. The FM5055G material had a lesser tendency to delaminate than FM5055A.

The FM5055A and FM5055G centerline surface recession profiles are presented in Figures 3 and 4, respectively (Reference 5). As these figures show, the profiles for both materials are fairly consistent.

The 10 MW temperature history data for FM5055A, FM5055G, FM5832A and FM5822A were approximately equivalent. This means that all of the candidate heatshield materials may give equal thermal protection, including the staple fiber materials.

Some overall general observations noted in Reference 5 follow:

1. All models except the FM5832A material manufactured by Kaiser exhibited poor interlaminar integrity, resulting in ply lifting and loss of material en masse when exposed to a high heating environment. The FM5055G rated the best of the materials with respect to interlaminar integrity except, of course, the FM5832A Kaiser staple fiber. This material exhibited relatively smooth ablation for all three test models.

2. The FM5832A Kaiser staple material temperature gradient was different from the other materials tested, but the reason is not known at this time. This material exhibited a pure linear temperature distribution through the test sample.

3. Reversal of the cloth lay-up angle to the flow had no obvious effect in suppressing the ply separation.

4. Again, as in the 50 MW tests, no clear correlation with bagging effects was noted. An additional data point relative to bagging effects on FM5055A was obtained from detailed photographic time histories of two specimens cut from heatshields made by the standard HITCO process. However, one was internally bagged and the other externally bagged. No clear performance difference were observed here.

Results

The results of this study show:

1. The FM5055A and the AVTEX FM5055G materials have comparable thermodynamic performance in the three facilities utilized by SAMSO for testing. Mass loss and recession rates are virtually the same. In-depth density and temperature profiles exhibit some minor differences, believed to be of little operational significance. The FM5822A unfilled material shows greater mass loss and recession than either the FM5055A or the FM5055G filled materials.

2. The FM5055G material generally exhibits a smoother, more regular appearance with less evidence of local delamination after ablation tests than does the FM5055A material. Consistent with this, the maximum measured surface micro-roughness of FM5055G is less than that of the FM5055A, although the nominal roughness heights are the same. The FM5822A material has a more irregular gross appearance, more evidence of delamination, and both a larger maximum and larger nominal surface micro-roughness than either of the filled materials.

3. The roll performance of the 50 MW test specimens from the 1978-79 tests can be summarized as follows:

   a. Eleven out of 12 IRC FM5055A models with left-hand splices and left-hand helices, externally bagged, gave regular, repeatable roll performance. (The construction of the remaining model is in question.)

   b. Two out of three IRC FM5055A models with left-hand splices, internally bagged, performed comparably to the externally bagged models. The third model has a smooth roll history but about one-half the torque of the others.

   c. Two out of two AVTEX FM5055G models with left-hand splices and left-hand helices, internally bagged, exhibited smooth torque production at the lower level of the singular model described in b. above.

   d. Out of five IRC FM5055A models with right-hand splices and left-hand helices, internally bagged, two showed smooth torque comparable to the higher level of previously described models, one had smooth torque comparable to the lower level of previous models, but in the opposite direction, and two showed somewhat irregular torque production.

   e. Out of three AVTEX FM5055G models with right-hand splices, internally bagged, one exhibited smooth torque of high magnitude, and the remaining two showed apparently smooth torque but of uncertain magnitude because of delayed roll initiation.

   f. Three AVTEX FM5822A models with right-hand splices and internally bagged exhibited very low, almost neutral, torques.

4. The only data available at the time of this study for comparison of bagging effects is on FM5055A. In general, the 50 MW arc jet in-situ ablation movies show that the externally bagged specimens have a slightly more regular surface with fewer local spots of delamination than the internally bagged specimens. These differences are subtly qualitative and hence subjective. As enumerated in 3. above there are no clear differences in 50 MW roll performance due to bagging. In-situ closeup still pictures of one pair of 10 MW runs giving a bagging comparison show no surface feature differences.

CONCLUSIONS

The AVTEX filled FM5055G material provides a close substitute for the IRC filled FM5055A in terms of both thermal protection and roll torque performance.

Pure bagging effects, isolated from tapelap and tapewrap differences, are difficult to discern from the ground tests, where bagging appears to be a secondary parameter at most. If uniformity in surface appearance during ablation is indicative of predictable roll performance, as was indicated by the ground test experience with staple rayon, then external bagging may be preferable to internal bagging.

In all 50 MW arc jet tests and in some staple rayon flight tests, the tapewrap helix angle appears to dominate roll torque behavior. Although other mechanisms may dominate on continuous fiber heatshields in most flight regimes, the wrap helix mechanism is still present. It was recommended that a right-hand wrap helix be selected for future flight test vehicles to preclude the possibility of helix-induced negative (left-hand) torque in any flight interval.

REFERENCES

1. L. Groener, Final Data Report for Roll Torque Manufacturing Comparison Tests -- AFFDL 50 MW Arc Jet Facility, PDA TR 1353-39-29, 12 February 1979.

2. J. Stetson, et al., "Technique for In-Situ Roll Torque Measurements," Paper presented at the 26th ISA Int. Inst. Sym., 5-8 May 1980, Seattle, WA.

3. L. S. Groener, et al., "Ground and Flight Test Investigations of Reentry Vehicle Heatshield Roll Torque," AIAA Paper 80-0447, March 1980.

4. J. W. Metzger, "Thermal Shield Study--HY-ARC Channel Flow Tests," GE-AEDM-79-001, 13 March 1979.

5. H. E. Hoercher, et al., Avco Ten Megawatt Arc Facility Staple Fiber Material Test Results, Avco Report AVSD-0005-79-CR, 9 February 1979.

TABLE I. ALTERNATE FABRICATION PROCESSES

Supplier	Process A HITCO	Process B Kaiser	Process C HAVEG
Tape orientation	Fill side in	Fill side in	Fill side in
Bias cut	Parallel to warp	Parallel to warp	Parallel to warp
Direction of winding[a]	LH Helix	RH Helix	LH Helix
Tape splice orientation	RH	RH	RH
Splice facing direction	FWD facing	AFT facing	FWD facing
Cure	Internal bag	External bag	External bag
Finish machine	Grind	Grind	Single - point
Debulk cycles[b]	Two max.	None	None
Cure cycle	Per GE spec.	Per GE spec.	Per GE spec.

[a]A left-hand (LH) wrap is defined by feeding the tape onto the mandrel from the right side (looking forward). A right-hand (RH) wrap is defined by feeding the tape from the left side (looking forward).
[b]Staple rayon only

TABLE II. ARC JET TEST MATRIX

AFFDL 50 MW	GE HY-ARC	AVCO 10 MW
FM 5055A (5)	FM 5055A (4)	FM 5055A Calibration (1)
FM 5055A LH Splice (ext) (3)	FM 5055A Special instrum. (2)	FM 5055A (HITCO) (3)
FM 5832A Lot C0186 (3)	FM 5832A Lot C0186 (6)	FM 5832A Lot C0186 (3)
FM 5832A (HITCO) Lot C0422 (3)	FM 5832A Lot C0422 (6)	FM 5832A Lot C0186 (3) (No pre-heat)
FM 5832A (Kaiser) Lot C0422 (3)	FM 5832A Lot C0079 (3)	FM 5832A (HITCO) Lot C0422 (3)
FM 5822A (3)	FM 5832A Special config. (3)	FM 5832A (HITCO) Lot C0422 (3) (No pre-heat)
FM 5055G (3)	FM 5832A Special instrum. (3)	FM 5832A (Kaiser) Lot C0422 (3)
FM 5055G LH Splice (2)	FM 5822A (3)	FM 5832A Lot C0079 (3)
	FM 5055G (4)	FM 5829A Calibration (1)
	FM 5055G Special instrum. (1)	FM 5822A (3)
		FM 5055G (3)
25 models	35 models	29 models

TABLE III. COMPARISON OF GROUND AND FLIGHT TEST ENVIRONMENTS

		M_e	H_e	P_e	q_{cw}	τ_w
Flight	Alt. (ft)	--	1000 BTU/lb	ATM	1000 BTU/ ft^2-sec.	PSF
	60K	8.2	9.0	1.3	2.5	150
	30K	5.8	4.5	2.9	2.1	170
Ground Facilities						
AFFDL 50MW		2.2	2.[illegible]	4.5	2.4	120
AVCO 10MW		1.5	7.0	1.5	1.1	47
GE-HYARC		0.8	9.7	6.0	1.1	17

TABLE IV. 50 MW ROLL TORQUE MANUFACTURING COMPARISON TEST MATRIX

50 MW Run No.	Strut	Model S/N (Exp. Ref.)	Heatshield Variation	Part No. SK43173-	Rationale/ Remarks
RTN 109-1	1	RB-1	FM5055A(IRC) LH splices	-29	Reference Baseline
	2	FB-1	FM5055A(IRC) RH splices	-35	Female Baseline
	3	S16-1	FM5832A, Lot C0186	-31	STM 16 Material
	4	S17-1	FM5832A, Lot C0422	-31	STM 17 Material
	5	PV-1	FM5832A, Process B	-31	Process Variation- Alternate Fabricator
RTN 109-2	1	FB-2	FM5055A, RH splices	-35	Female Baseline
	2	PV-2	FM5832A, Process B	-31	Replicate
	3	S16-2	FM5832A, Lot C0186	-31	Replicate
	4	S17-2	FM5832A, Lot C0422	-31	Replicate
	5	RB-2	FM5055A, LH splices	-29	Reference Baseline
RTN 109-3	1	FB-3	FM5055A, RH splices	-35	Female Baseline
	2	RB-3	FM5055A, LH splices	-29	Reference Baseline
	3	S17-3	FM5832A, Lot C0422	-31	Replicate
	4	S16-3	FM5832A, Lot C0186	-31	Replicate
	5	PV-3	FM5832A, Process B	-31	Replicate
RTN 109-4	1	AF-1	FM5055G, (Avtex Filled)	-35	Alternate Material
	2	FB-5	FM5055A, RH splices	-34R	Female Baseline
	3	AU-3	FM5822A, (Avtex Unfilled)	-33	Alternate Material
	4	AL-1	FM5055G, LH splices	-34L	Splice/Wrap Effects
	5	AL-2	FM5055G, LH splices	-34L	Replicate
RTN 109-5	1	FB-6	FM5055A, RH splices	-35	Female Baseline
	2	AF-4	FM5055G, (Avtex Filled)	-34R	Replicate
	3	AU-1	FM5822A, (Avtex Unfilled)	-33	Replicate
	4	AF-5	FM5055G, (Avtex Filled)	-34R	Replicate
	5	AU-4	FM5822A, (Avtex Unfilled)	-33	Replicate

TABLE V. SUMMARY OF 50 MW ROLL TORQUE MEASUREMENTS, ABRES TESTS

Model S/N	SK43173 P/N	Heatshield	Lot No.	Manuf. Date	Condition	Run No.	Strut	Air Bearing S/N	Final Rpm[b]	Measured Torque In-lb	Torque Corrected For Roll Damping In-lb
B-1	-1D	Standard Baseline	C0295	3/23/78		103-8	1	5	-6000	-.35	-.475
B-2	-1D	(LH splices male	C0295	4/07/78		7	3	4	+1600[a]	+.13	+.13
B-3	-1D	cure)	C0295	3/23/78		6	1	2	Jammed	--	--
B-4	-1E		C0295	6/15/78		8	3	3	-10,000	-.65	-.85
B-5	-1E		C0295	6/15/78		9	1	5	-11,500	-.55	-.75
B-6	-1G		C0295	8/25/78	HI Residual Volatiles	12	5	5	-3200	-.24	-.34
B-7	-1G		C0295	8/25/78	Moderate bunching	13	5	5	-2900	-.29	-.38
B-8	-1G		C0295	8/25/78	Some bunching	14	1	1	-7500	-.58	-.72
R-1	-2D	RH splices, male	C0295	3/23/78	Heavy bunching	6	3	4	Jammed	—	—
R-2	-2D	cure	C0295	3/23/78	Heavy bunching	8	4	4	-600	~ 0	-.06
R-3	-2E		C0295	6/15/78	Heavy bunching	9	3	3	-4500	-.425	-.5
D-1	-3D	Isotropic Dixiecup	C0295	3/23/78		8	2	1	0	0	—
D-2	-3D		C0295	3/23/78		7	4	F	Non rotating		—
D-3	-3D		C0295	3/23/78		6	2	3	Jammed		—
D-4	-3D		C0295	3/23/78		6	4	F	Non rotating		--
D-5	-3E	0-180 Dixiecup	C0325	6/16/78		9	2	1	+2800	+.2	+.18
D-6	-3E		C0325	6/15/78		9	4	4	+200	~ 0	—
D-7	-3G	Isotropic Dixiecup	C0424	9/15/78		13	2	2	0	0	--
D-8	-3G		C0424	9/15/78		14	3	3	+1400	+.12	+.10
AFJ-1	-19G	LH splices, Aft	C0295	8/25/78		103-10	3	5	-6000	-.375	-.52
AFJ-2	-19G	Facing Joints	C0295	8/25/78		10	4	4	-6800	-.48	-.63
AFJ-3	-19G		C0295	8/25/78		12	4	4	-1500	-.12	-.14
SB-1	-29G	Short configura-	C0295	8/25/78		11	3	5	-5900	-.32	-.41
SB-2	-29G	tion Baseline	C0295	8/25/78		12	1	1	-7500	-.75	-.90
FM-1	-7G	LH splices,	C0295	8/25/78	As molded	11	4	4	-4500	-.28	-.39
FM-2	-7G	Female mold,	C0295	8/25/78	As molded	12	2	2	-1100	-.18	-.26
FM-3	-7G	Short Configura-tion	C0295	8/25/78	As molded	12	3	3	-4100	-.28	-.36
LRS-1	-28G	Unfilled Staple,	C0422	9/15/78	Mod bunching	13	4	4	<20	0	-.05
LRS-2	-28G	FM 5832A, LH	C0422	9/15/78	Mod bunching	14	2	2	<20	0	-.05
LRS-3	-28G		C0422	9/29/78	Little bunching	14	4	4	<20	0	-.05
LHF-1	-30G	Fill direction	C0407	9/15/78		13	1	1	-30,000	-1.7	-2.1
LHF-2	-30G	splices, LH	C0407	9/15/78		13	3	3	-30,000	-1.9	-2.4

[a]All heatshields IRC FM5055A, External bag cured, with LH forward facing splice joints except where noted.
[b]At end of nominal 5 second exposure (except as noted).
[c]4 second exposure.

TABLE VI. THERMOCOUPLE RESPONSE TIMES, HY-ARC TESTS

T = 2000°F

Run No.	Material	Time to 2000°F, sec	Depth, in.
40	FM5055A	14.7	0.113
41	↓	15.3	0.105
42	↓	12.6	0.093
43	FM5832A, Lot C0186	(19.8)P	0.250
44	↓	17.0	0.141
45	↓	-	-
46	↓	-	-
71	FM5055G	(14.6)P	0.045
72	↓	(15.8)P	0.093
84	FM5832A, Lot C0422	(17.0)P	0.139
85	↓	15.0	0.134
86	↓	15.1	0.138
87	FM5832A-QA	12.1	0.108
88	FM5055A	15.0	0.098
89	FM5832A-QA	15.1	0.106
90	↓	(14.0)P	0.118
96	FM5832A, Lot C0186	13.4	0.120
97	↓	14.4	0.131
98	FM5822A	13.9	0.110
99	↓	12.7	0.110
100	↓	13.7	0.125
101	FM5055A	14.2	0.103
102	FM5055G	13.2	0.105
103	↓	13.3	0.106
105	↓	13.5	0.112

P = Projected intercept value

TABLE VII. COMPARISON OF SURFACE ROUGHNESS, HY-ARC CHANNEL FLOW

Material	Max HT, mils	Frequency, Fraction of Sample Length	Nominal HT, mils
IRC FM5055A			
HITCO	1.10	0.09	0.35
HAVEG	1.10	0.07	0.30
FM5832A			
Lot C0186	0.85	0.03	0.25
Lot C0422	0.90	0.05	0.35
QA SHIELD	0.95	0.13	0.25
AVTEX			
FM5055G	0.70	0.06	0.30
FM5822A	1.30	0.02	0.40

TABLE VIII. SUMMARY OF ABLATIVE PERFORMANCE OF HEATSHIELD MATERIALS, 10 MW ARC JET TESTS

Run. No.	Sample Description*	Weight[a] Grams			Thickness[b] Inches			Peak Surface Brightness[c] Temperature, °R	Recession Rate[d] $\dot{S}$, in/sec
		Pre	Post	Loss	Pre	Post	Loss	T_b	
11,848	FM5055A	35.2	29.2	6.0	0.600	0.574	0.026	2710-6120	f
11,849	FM5829A	24.4	17.3	7.1	0.420	0.398	0.022	3040-6210	0.00330
11,850	FM5832A Lot C0186 (No pre-heat)	29.9	22.8	7.1	0.500	0.410	0.090	6340	f
11,851	FM5832A Lot C0186 (No pre-heat)	29.7	22.6	7.1	0.500	0.407	0.093	6270	f
11,852	FM5832A Lot C0186 (No pre-heat)	29.8	22.8	7.0	0.499	0.408	0.091	6382	0.00160[g]
11,855	FM5832A Lot C0186	29.3	21.3	8.0	0.500	0.417	0.083	2970-6250	0.02094[g]
11,856	FM5832A Lot C0186	29.6	22.1	7.5	0.499	0.412	0.087	3030-6060	0.00666[g]
11,857	FM5832A Lot C0186	29.7	22.5	7.2	0.500	0.422	0.078	3100-6110	0.00323
11,858	FM5832A Lot C0422 (No pre-heat)	28.5	21.8	6.7	0.500	0.468	0.032	5970	0.00252
11,859	FM5832A Lot C0422 (No pre-heat)	28.4	21.3	7.1	0.500	0.425	0.075	6370	0.00242
11,860	FM5832A Lot C0422 (No pre-heat)	28.3	21.1	7.2	0.500	0.410	0.090	6300	0.00209
11,861	FM5832A Lot C0422	28.6	21.4	7.2	0.500	0.450	0.050	~3200[e] -6070	0.00367
11,862	FM5832A Lot C0422	[illegible].6	21.1	7.5	0.501	0.444	0.057	3180-6170	0.00360
11,863	FM5832A Lot C0422	28.4	21.1	[illegible].3	0.500	0.441	0.059	3160-6100	0.00411
11,864	FM5055A	30.5	23.9	6.6	0.491	0.463	0.028	2890-6150	0.00264
11,865	FM5055A	31.0	24.5	6.5	0.501	0.479	0.022	2800-6190	0.00297

TABLE VIII. SUMMARY OF ABLATIVE PERFORMANCE OF HEATSHIELD MATERIALS
10 MW ARC JET TESTS (Continued)

Run. No.	Sample Description*	Weight[a] Grams			Thickness[b] Inches			Peak Surface Brightness[c] Temperature, °R	Recession Rate[d] $\dot{S}$, in/sec
		Pre	Post	Loss	Pre	Post	Loss	T_b	
11,866	FM5055A	31.0	24.8	6.2	0.500	0.475	0.025	2730-6220	0.00211
11,867	FM5832A (Kaiser) Lot C0422	27.4	20.3	7.1	0.466	0.419	0.047	3020-5930	0.00306
11,868	FM5332A (Kaiser) Lot C0422	27.5	20.2	7.3	0.468	0.468	0.048	3030-5930	0.00333
11,869	FM5832A (Kaiser) Lot C0422	27.5	20.2	7.3	0.469	0.416	0.053	~3110[+e]-5930	0.00232
11,870	FM5055G	25.5	18.9	6.6	0.406	0.377	0.029	2840-6070	0.00252
11,871	FM5055G	25.5	19.0	6.5	0.406	0.379	0.027	2790-6000	0.00216
11,872	FM5055G	25.5	19.2	6.3	0.406	0.384	0.022	2770-6010	0.00209
11,873	FM5822A	24.4	17.2	7.2	0.402	0.375	0.027	32.00[+e]-6460	0.00106[g]
11,874	FM5822A	24.4	17.4	7.0	0.402	0.355	0.047	3310-6180	0.00287
11,875	FM5822A	24.4	17.4	7.0	0.402	0.367	0.035	3280-6240	0.00260
11,876	FM5832A Lot C0079	30.0	22.2	7.8	0.501	0.441	0.060	3310-6320	0.00353
11,877	FM5032A Lot C0079	30.0	22.3	7.7	0.500	0.427	0.073	3270-6420	0.00193
11,878	FM5832A Lot C0079	30.0	22.5	7.5	0.500	0.456	0.044	3260-6270	0.00228

*All specimens are HITCO process unless otherwise noted.

[a]Total weight including thermocouple wires and adhesive.

[b]Centerline location 1.125 inches from test surface leading edge.

[c]Measurement taken by a high resolution Thermodot Recording Pyrometer sensitive to radiation at 0.8 microns. This unit was focused 1.125 inches from the specimen's leading edge, along the centerline and covered a 0.176 inch spot diameter.

[d]Estimate from Nikon film profile camera.

[e]Scale change, reading did not peak.

[f]NO ESTIMATE. Considerable data scatter as a result of surface expansion.

[g]Questionable estimates.

ACKNOWLEDGMENTS

This report was prepared by The Aerospace Corporation and is based upon ground tests conducted and documented by Prototype Development Associates, Inc., the General Electric Company Reentry and Environmental Systems Division, and the Avco Corporation Systems Division. All work was sponsored by the United States Air Force Systems Command, Space and Missile Systems Organization (now Ballistic Missile Office).

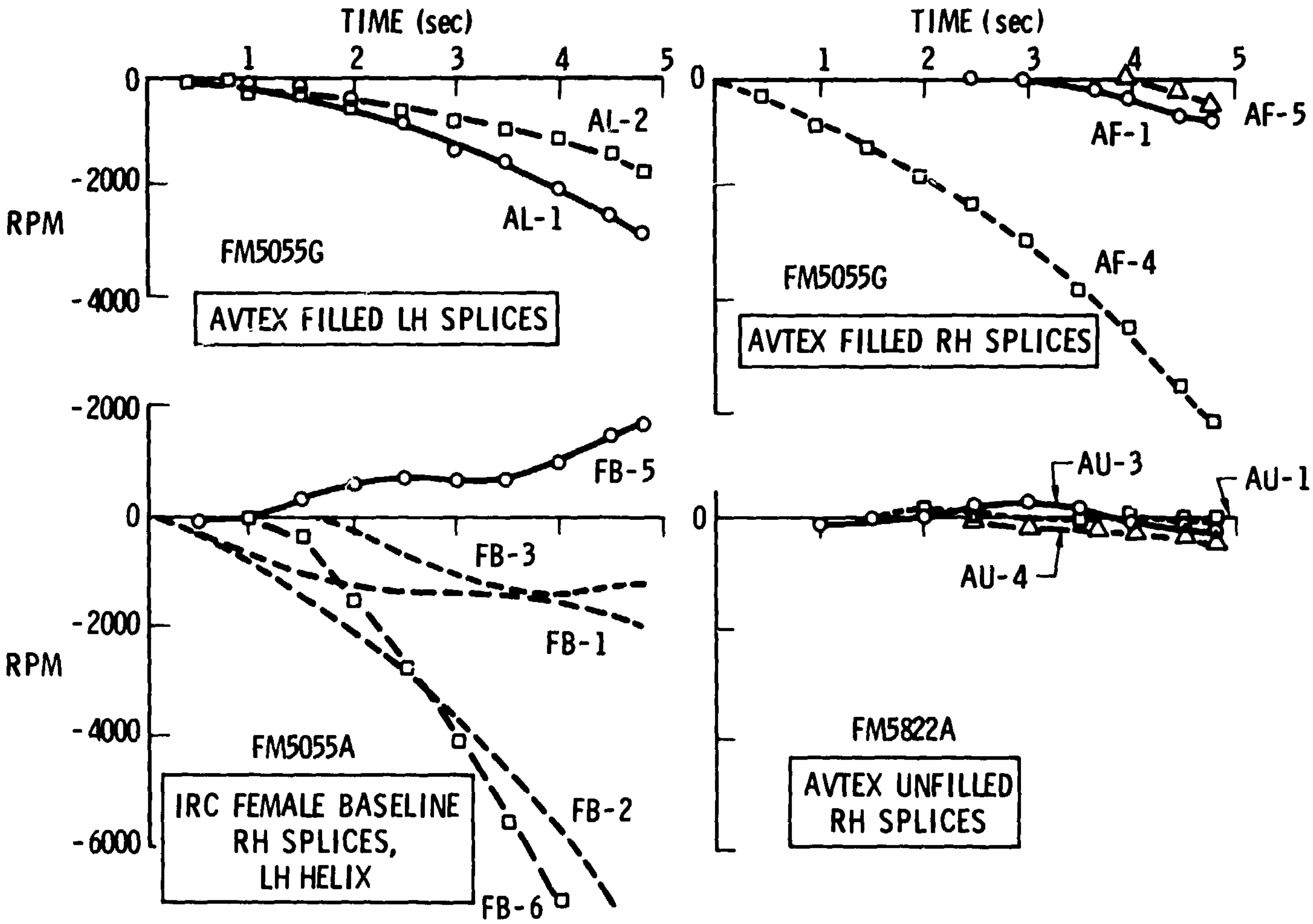

Fig. 1. Roll Rate Histories, Runs 109-4 and 109-5

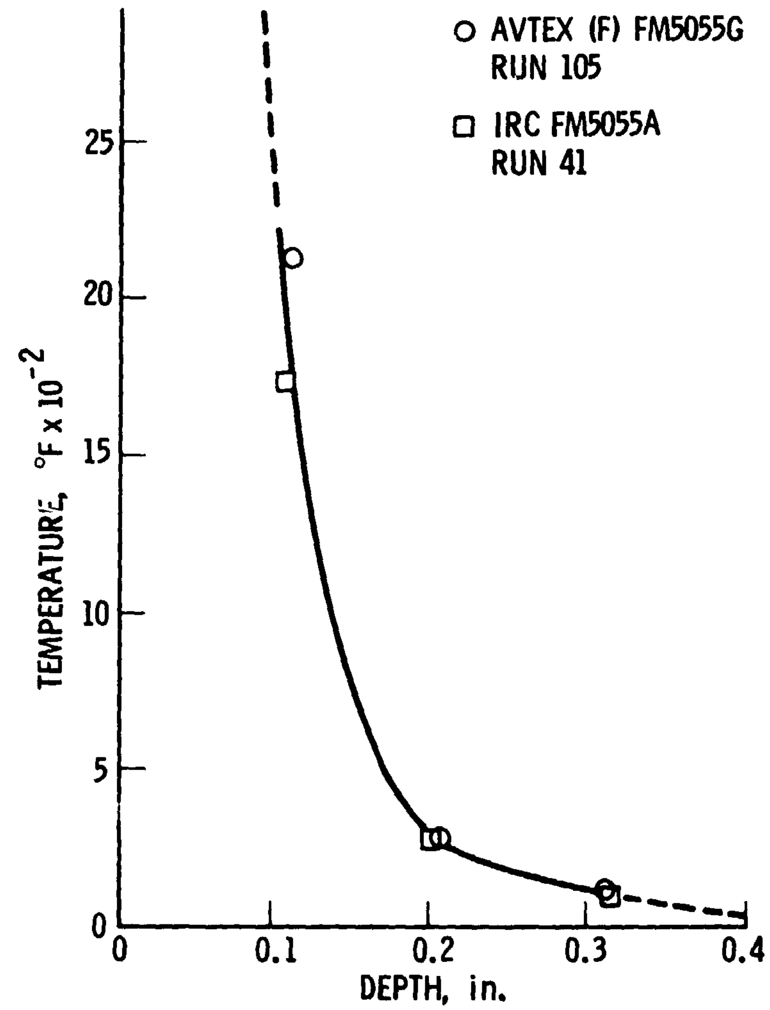

Fig. 2. Temperature Distribution, 14 Seconds

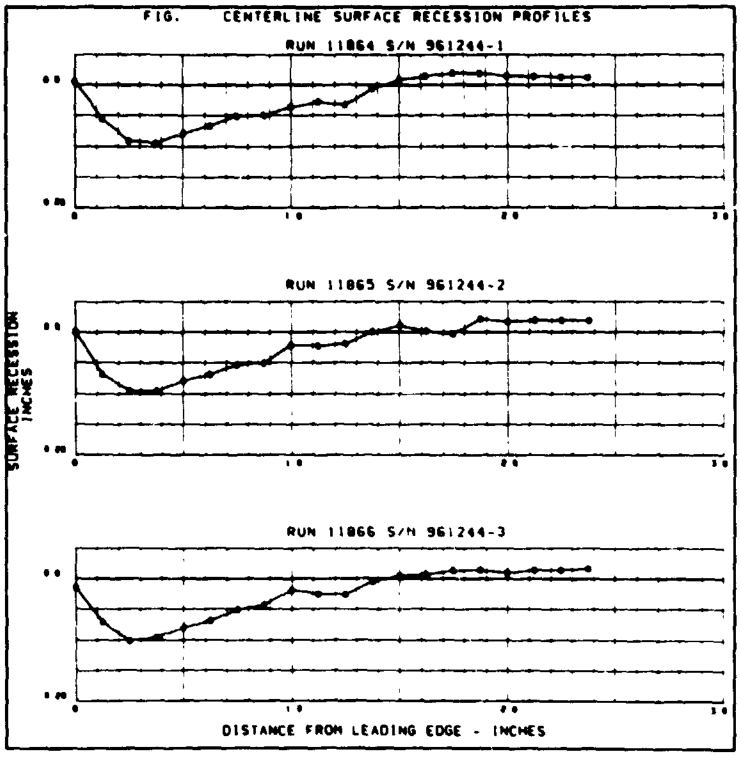

Fig. 3. Centerline Surface Recession Profiles - Preheat Cycle, IRC FM5055A

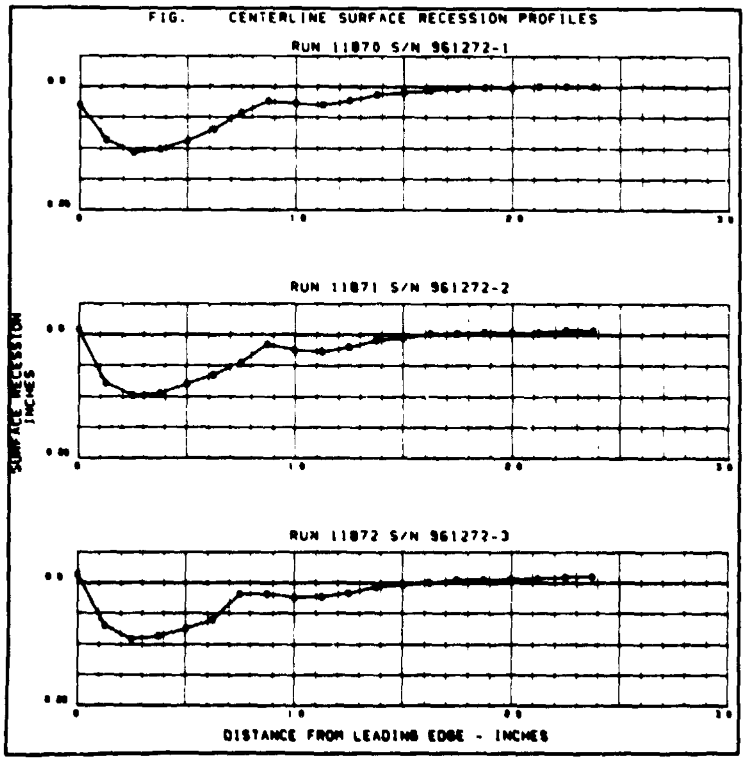

Fig. 4. Centerline Surface Recession Profiles - Preheat Cycle, AVTEX (F) FM5055G