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Aerospace Nuclear Safety Program

EVALUATING AEROSHELL MATERIALS FOR THE MJS/MULTI-HUNDRED WATT HEAT SOURCE

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FOREWORD

The work reported herein was completed jointly by personnel from the U. S. Energy Research and Development Administration, the General Electric Company, and the Aeronautics Division of the Applied Physics Laboratory. Activities of the Aeronautics Division are under the general supervision of Dr. William Avery. The Project Engineer for the Aerospace Nuclear Safety Program is James C. Hagan.

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ABSTRACT

In order to evaluate the possibility of improving upon an existing aeroshell design for the Multi-Hundred Watt power source, a trade-off study was conducted on a variety of candidate aeroshell materials. Mariner Jupiter/Saturn mission requirements and aeroshell material criteria were established to form a basis for the evaluation. Material data searches and reentry analyses were made to permit preparation of a quantitative comparison matrix. Depending upon the designer's constraints, either the well-known polycrystalline graphites (POCO-AXF-5Q, ATJS) or the more complex composite materials (AVCO 3D C/C, Pyrocarb-406) may be chosen.

SUMMARY

The application of the Multi-Hundred Watt Radioisotope Thermoelectric Generator, which was originally developed for the LES 8/9 satellites, to the NASA Mariner Jupiter/Saturn spacecraft provided a brief opportunity to review the heat source design. One aspect of the review concentrated on the material used for reentry protection.

To complete this review, a survey of available graphite and carbon-carbon materials was completed and preliminary reentry thermal and thermal stress analyses were completed for a number of the materials that appeared to be the most attractive and/or available.

If the designer is operating under schedule and funding constraints that take precedence, then POCO-AXF-5Q graphite or possibly ATJ-S graphite readily become the only possible material choices. With funding and time to improve deficiencies in the data and analytical procedures, the choice may have been the AVCO 3D C/C or the Pyrocarb material.

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I. INTRODUCTION

The Multi-Hundred Watt Radioisotope Thermoelectric Generator designed by the General Electric Company for the U. S. Energy Research and Development Administration to provide electrical power for the USAF LES 8/9 communications satellites is being revised for application to the NASA Mariner Jupiter/Saturn (MJS) mission.

One of the safety requirements that is imposed upon space nuclear system applications is that the heat source be capable of surviving reentry in the event of an abortive launch. In order to improve the reentry capability of the heat shield, one of the potential design modifications that has been evaluated is a change of the material from which the aeroshell is fabricated. In order to provide data to evaluate the merits of candidate materials, a program was initiated to compile comparative data regarding factors such as cost, availability, and predicted reentry performance for a number of prospective materials. This report summarizes the results from this study and presents the data in a weighted decision modeling format.

II. DESCRIPTION OF SYSTEM

The Multi-Hundred Watt Radioisotope Thermoelectric Generator (MHW-RTG)⁽¹⁾, was designed and built by the General Electric Company for the U. S. Energy Research and Development Administration to provide power for two USAF communications satellites (LES 8 and 9). Similar units will be used to power the two NASA Mariner Jupiter/Saturn (MJS) spacecraft to be launched in 1977. Each MHW/RTG is about 16 inches in diameter by 23 inches long, weighs

about 80 pounds and produces at least 150W(e) at start of life with an unattended lifetime of at least five years. Basically, the RTG consists of the isotope heat source and a thermoelectric converter. The heat source contains the basic reentry protection. For the USAF mission, the MHW/RTG used a POCO-AXF-5Q aeroshell; however, because the NASA mission involves a more powerful launch vehicle (Titan/Centaur vs. Titan IIIC), a re-evaluation of the aeroshell material was planned. Although design modifications other than the choice of aeroshell material were considered, in this paper we report only the results of the aeroshell material study.

Referring to Figure 1 for details, one sees that the MHW/RTG heat source consists of 24 individual fuel sphere assemblies (FSAs) comprised of 1.465-inch-OD $^{238}\text{PuO}_2$ fuel spheres, iridium post impact containment shells (PICS) and impregnated, Thornel-50 graphite impact shells. The FSAs are individually designed to survive both earth impact at heat source terminal velocity and the post impact environment following a postulated atmospheric reentry of the heat source. To assure that the heat source is integral during a reentry, it is provided with a 0.38-inch-thick POCO-AXF-5Q aeroshell, essentially a hollow cylinder 16.7 inches long by 7.2 inches OD which is fitted with end caps. The aeroshell contains the FSAs, which are grouped by retainer rings in clusters of eight, appropriately called "eight packs". A 0.01-inch-thick iridium outer clad surrounds the aeroshell to provide pneumatic isolation between the heat source and the converter. Structural support and improved thermal radiation emittance are provided to the can by a 0.05-inch thick (later modified to be a 0.10 inch thick) cylinder or sleeve

of woven Thornel-50. The sleeve and clad also provide additional reentry protection for multiple skip reentries and for high thermal stress (steep angle) reentries.

The converter consists of a beryllium housing with 312 Si-Ge thermoelectric elements emplaced within a Mo-Astroquartz thermal insulation system.

III. STUDY GUIDELINES

A. Reentry Environment

Titan/Centaur performance data were used, in conjunction with computer codes developed by the U. S. Air Force Weapons Laboratory and APL/JHU, to estimate preliminary velocity/flight path angle (V/γ) maps. These maps were constructed to provide an approximation to the upper bound velocity/flight path angle combinations that are appropriate for the MJS spacecraft, without consideration of the probability of occurrence of a particular velocity/flight path angle combination. Figure 2 shows one such boundary that was used for the study. This particular boundary was derived based on the assumption that the Titan/Centaur performed properly until the 90 nautical mile parking orbit had been achieved. The second Centaur burn, which would normally occur in a direction tangential to the circular parking orbit, was assumed to be mis-oriented in a random fashion. An inherent assumption is that the velocity was instantaneously changed by an amount that corresponded to either the Centaur second burn capability or the Centaur plus TE-364-4 capability. Subsequent calculations, which included the effect of finite burn time, led to the conclusion that reentry speeds in excess of about 36000 fps were not

possible. However, for the purpose of this study, which was to compare the predicted performances of candidate aeroshell materials, the instantaneous ΔV map provided a common trajectory to be used as a basis for the comparative analyses.

The initial reentry configuration for the purpose of this study was assumed to be an RTG that was free of the spacecraft.

B. Material Selection Criteria

A parallel effort to the definition of the possible reentry environment was the definition of the material selection criteria. The following criteria were established (not necessarily in order of importance).

- Cost Including the cost of the raw billet, the cost of manufacturing the aeroshell and the associated QA/QC costs.
- Availability This criterion was of importance in view of the short time available in the MJS MHW/RTG schedule for a re-design and, at the time of the study, the unknown effects of the Arab oil embargo on graphite production.
- Characterization Ideally it was desired for each material to have available the following data over a range of temperatures from ambient to $> 6000^{\circ}\text{F}$:
 - ultimate stress and strain in tension and compression vs. temperature (including stress/strain curves)

- coefficient of expansion
- thermal conductivity
- specific heat
- Poisson's ratio

- Ablation
Performance

Total surface recession estimates and the effect of ablation on surface roughness were required. Surface roughness is of importance since it could affect terminal velocity. The terminal velocity is of significance since the heat source must survive earth impact without breaching the iridium Post Impact Containment Shells.

- System
Constraints

- Dimensions...The heat source envelope must fit within the constraints imposed by the converter.
- Weight...The weight must be within the MJS weight allotment for the RTG.
- Impurities...The presence of impurities above a few ppm may lead to a requirement to complete extensive tests for unwanted reactions with other materials in the heat source or generator.
- Loads...The aeroshell is the principal load bearing component of the heat source; as such it must withstand the loads resulting from assembly and launch.

- Porosity...Redesign efforts were directed toward showing that the iridium outer clad was not needed for the MJS mission. In the event that the outer clad was eliminated the aeroshell material would be required to act as a barrier to any residual nuclear material left inside the heat source after assembly.
- Failure Modes Ideally, the aeroshell material should allow for stress relief in the event of excess loading, i.e., it should not fail catastrophically.
- Thermal Response The aeroshell material must not allow an excessive amount of heat into the heat source during reentry. The limit was taken as a temperature of 4020°F of the iridium PICS because of an iridium/carbon eutectic at this temperature.
- Thermal Stress Capability The material will be subjected to large temperature gradients in the event of steep angle reentries as well as the potential thermal shock of being suddenly subjected to the reentry environment when released from a burned out converter.
- Analysis Complexity The complexity of the reentry analysis may be increased by factors such as anisotropic strength and density, the presence of flaws, etc.

- Machinability The raw billet should be easily machinable to be competitive with the present materials.

- Proprietary While not an overriding concern, it was of interest to know whether government inspectors would be permitted to monitor the manufacturing process in the event that insufficient manufacturing data were available for one to judge reproducibility and QA/QC.

IV. MATERIALS CHOSEN FOR EVALUATION

The final list of materials to be evaluated was by no means exhaustive, rather it represented a best estimate selection based on consultations with DoD and NASA reentry personnel and on the general limitations of the study. However, the list did permit a selection between two known graphites, several promising composite materials and a representative of the newer generation of graphites.

The materials considered were*

<u>Candidate Material</u>	<u>Material Category</u>	<u>Supplier</u>
POCO-AXF-5Q ("POCO")	Polycrystalline grain	POCO Graphite (Pure Oil Co.)
AVCO 3D Carbon/Carbon Material No. 8 ("AVCO")	Composite	AVCO
Pyrocarb 406 ("Pyrocarb")	Composite	Hitco
Isostatically Pressed Graphite ("IP")	Polycrystalline grain with mixed fibers	Oak Ridge Y-12 plant

continued...

*Several other materials were briefly considered, e.g. Carbitex, other grades of POCO, ACN, Graphnol-N-1, reinforced carbonized systems, FMI weaves, 994/996 (Union Carbide), but these materials had to be dropped from consideration because of time constraints, manufacturing scale-up problems, lack of data, lack of response to requests for quote, etc.

Continued from Page 7....

<u>Candidate Material</u>	<u>Material Category</u>	<u>Supplier</u>
ATJS	Polycrystalline	Union Carbide
CVD Felt	Vapor-deposited, reinforced pyrolytic graphite felt	Sandia Lab.

V. MATERIAL EVALUATION BASIS

The reentry material manufacturers were contacted to establish cost, availability and characterization. In addition, a task force was established to contact various DoD and NASA agencies in order to assemble the best available data base for each of the six candidate materials.

Cost and availability were evaluated on the basis of the fabrication and delivery of ten aeroshells. Availability was also quoted by some manufacturers based on an early delivery of one or two aeroshells and a later delivery of the remainder of the lot. In the availability ranking to be discussed later in this report, the ranking is based on delivery time for all ten aeroshells. A different ranking would be obtained if the delivery time for the first aeroshell had been chosen as the ranking basis.

Reproducibility was evaluated based on the opinions of material users and, where necessary for the newer materials, on the opinions of materials analysts.

Characterization was evaluated by comparing the available material data to the range of properties that is required to provide a basis for a reentry analysis. Figures 3 through 6 give a comparison of the key property data obtained during the study.

The evaluation of aeroshell ablation was completed by studying an extreme superorbital, shallow angle abort reentry with a velocity of 48Kfps and a flight path angle of -7.5 degrees at 400 Kft altitude. A one-dimensional computer model of the MHW heat source with a POCO aeroshell was used for the reference calculation. The results of the POCO recession calculations are described in Figure 7. Recession estimates are provided for a configuration which has a 50 mil T-50 sleeve enclosing an iridium clad aeroshell and for a configuration which has neither a sleeve nor an iridium clad. For the case of an aeroshell without an outer sleeve, the total predicted recession was about 0.25 inch compared to an available thickness of 0.38 inch. No significant mechanical erosion was predicted for the trajectory evaluated in this study, the mechanical erosion model employed was that developed in Reference 2, which is based on data obtained from bulk graphite recession tests.

In view of the minimal mechanical erosion predicted and the lack of data to evaluate mechanical erosion for materials other than bulk graphites, the recession predictions for materials other than POCO graphite were made by simply scaling the POCO graphite computations by a density ratio.

With regard to the effect of ablation on surface roughness (hence terminal velocity) it was noted that ATJ-S and POCO and possibly IP would have similar surface finishes, whereas the composite materials (AVCO, Pyrocarb, CVD felt) were expected to show a greater roughness after ablation that might necessitate experiments to determine the impact velocity.

In as much as the dimensions, weights and impurities of all of the candidate materials were judged to be acceptable, the system constraints were weighted by only two factors - load capability (33%) and porosity (67%). The load capability was rated based on the yield strength of each material at the estimated launch temperature ($\sim 1000^{\circ}\text{F}$) of the aeroshell.

The failure mode comparison evolved into a qualitative judgment formed on the basis of opinions expressed by DoD reentry analysts. Basically the composite materials were believed to be much superior to the graphite materials with respect to a stress failure. Indeed, at the time of the study, the AVCO material had not been failed in any thermal shock facility tests. The graphites, especially POCO, were expected to fail catastrophically if driven to the failure point.

To examine the thermal response of each of the materials, the reference heating rate histories were determined from a three-degree-of-freedom ⁽³⁾ (3 DOF) trajectory code for the 48 kfps/ -7.5° reentry. Comparing the postulated MJS reentry with the design reentry for the USAF LES 8/9 mission as shown in Figure 8, one sees that the super-orbital velocity of the MJS return produces a significant shock layer radiative heating component. However, a 3-D thermal model calculation, the results of which are depicted in Figure 9, shows that the maximum PICS temperature (3860°F) for the windward leading FSA inside a POCO aeroshell is less than the iridium/carbon eutectic melting point (4020°F). The ranking of heat sources with the other aeroshell materials was determined by ratioing their radial thermal conductivities at the appropriate temperatures to that of POCO.

The analysis complexity for each of the materials was judged by the task force upon completion of the analyses. Pyrocarb, for example, was difficult to analyze because of its extreme density gradients and anisotropy although it was conceded that once the computer models were prepared, the analyses would be no more difficult than any other. IP was marked lower than most of the other materials because of the paucity of data on this material.

Machinability was qualitatively judged by DoD and GE personnel having experience with these materials. Except for a cautionary note about machining the composite materials (i.e., fibers tend to pull loose), the differences here were slight.

Likewise, the question of proprietary processing was qualitatively judged on the basis of how much of the manufacturing process would be open to government inspection. As stated earlier, barring future quality control problems, this criterion was not expected to be a major concern.

Thermal stress was the most involved evaluation associated with the study; this factor received particular emphasis because stress is the single most limiting factor in heat source reentry design. Using the V- γ map shown in Figure 2, cold wall heating rate calculations were performed for a variety of flight conditions. These calculations showed that the highest peak convective heating rate for this map occurred for a reentry velocity (V_0) of 39,186 fps (inertial) and a flight path angle (γ_0) of -19.2° (inertial) at 400 kft. A summary of the trajectory data is given in Table 1 and Figure 10 for the side-stable reentry attitude. The trajectory was calculated using the DYNAMASS computer code⁽⁴⁾. The DYNAMASS output was used as input to the ABTON heating

program⁽⁵⁾. One-dimensional THTDA⁽⁶⁾ thermal response/ablation models of the converter and candidate heat sources were used to evaluate their respective behavior when exposed to the ABTON heating results. Figure 11 shows the ABTON heating histories and Figure 12 shows the one-dimensional heat source thermal response model. The POCO heat source temperature histories with and without the clad and emissivity sleeve are shown in Figures 13 and 14. The other four materials exhibited the same qualitative behavior. (The IP material could not be studied in this manner because there were insufficient data for a meaningful reentry analysis).

As typified by Figure 13, in the cases analyzed with the clad and emissivity sleeve, considerable thermal shock was experienced at the time (23 seconds from 400 kft for all aeroshell materials) the emissivity sleeve burned through, because this burnthrough occurred only slightly after peak heating. The gradients developed at this time ranged from 1550°F for the CVD felt to 3050°F for 0.51-inch thick Pyrocarb, with POCO and ATJS both developing 1800°F gradients. Without the clad and emissivity sleeve, the peak gradients occurred at different times, with gradients varying from 1700°F for the CVD felt to 3560°F for 0.51-inch thick Pyrocarb. Again POCO and ATJS showed similar gradients, this time a value of approximately 2100°F.

The thermal stresses that correspond to the estimated temperature gradients were calculated using the ANISO computer code⁽⁷⁾. The calculations were one-dimensional, plane-strain analyses, taking into account the anisotropic material properties, the tensile and compressive properties and the stagnation

region thermal gradients of the aeroshells. The ANISO code provides an elastic/plastic stress-strain solution for various nodal locations in the material in the circumferential (hoop), axial and radial directions. With the exception of Pyrocarb, all candidate materials were assumed to have the original POCO reference design thickness (0.38 inch). Because of its expected higher ablation, Pyrocarb was analyzed for a 0.51-inch-thickness in addition to a 0.38 inch thickness.

The stress margin of safety (unity subtracted from the quantity ultimate strength divided by calculated stress) was used to evaluate each material's thermal stress performance. (A separate set of calculations based on strain-to-failure and calculated thermal strain yielded, on a comparative basis, higher margins for each material). Emphasis was given to the margin on the inside diameters of the materials (in the hoop direction) since experience has indicated that a tensile failure will be the dominant failure mode for the candidate materials.

One-dimensional stress calculations were made at various times clustered around the thermal shock points (23 seconds) as well as around the time of maximum temperature gradient and maximum surface temperature to determine the minimum margin encountered by the aeroshell during the sequence of reentry events. For reference, safety margins were calculated for all clad aeroshells at the time of maximum temperature, and for all unclad aeroshells at the time of maximum temperature gradient. Limitations in the time available to complete the study did not permit the determination of the minimum margin of safety for all of the cases studied.

The results of the thermal stress analysis indicated comparable safety margins for the two polycrystalline graphites and larger margins for two of the three composite materials. The least attractive composite material, according to this summary, was the AVCO 3-D Material No. 8, a surprising result in view of the extremely successful DoD test program with this material. The predicted poor performance of the AVCO material apparently occurs as result of an inadequate choice of the failure criterion. The ultimate strength obtained from uniaxial test specimens does not provide an accounting of the fact that this material, like some other composites, fails only locally thus relieving the stress. A further explanation of the low performance prediction may come from a room temperature strength data point that was obtained by Southern Research near the end of this study which indicated a factor of over two increase in strength compared to previous results. If the later data are correct, the predicted margin for the AVCO material would increase substantially, notwithstanding the lack of a proper failure criterion.

VI. COMPARISON OF MATERIALS

The results of the work outlined in the previous two sections were cast into quantitative terms suitable for use in a comparison matrix.⁽⁸⁾ First, for a given criterion, each material was ranked by a normalized number, or conditional likelihood estimate, that indicated by its magnitude how that material performed relative to another material (i.e., the larger the number the more superior the material). For each criterion, the sum of these conditional likelihood estimates should be unity (within the limits of roundoff error). Next, weighting factors were assigned to each criterion and were used as multipliers for the various conditional likelihood estimates. The result was a calculated

figure of merit for each material under the conditions established by each criterion. The intent of the matrix is to summarize the advantages and disadvantages of the various materials, thereby providing a more quantitative basis for the designer to make a material evaluation.

For this study, two comparison matrices were prepared. The first one, shown in Table 3, differs from the second one, shown in Table 4, in three respects:

- (1) Table 3 gives more weighting to the POCO characterization than to the ATJS characterization because there were some data on POCO billets of the MHW size and none on ATJS. (Otherwise, ATJS was considered to be better characterized.
- (2) Table 3 downgrades the ablation performance for all of the materials except POCO and ATJS because these other materials could require expensive air drop tests to verify their terminal velocity.
- (3) The thermal stress performance shown in Table 3 is based on the ANISO calculations* while Table 4 is based on the coefficient of thermal expansion. The preparation of Table 4 in this fashion has no theoretical basis; however, it does rank the materials in an order that corresponds approximately to the reentry community's confidence in the materials. No sensitivity study was performed on the two tables. Question marks are used in both tables to indicate places where a particular criterion produces uncertain behavior. This usually occurs because of insufficient data on the material. This lack of data is also reflected by using question marks in the sums.

*The thermal stress indicators in Table 3 were taken from the uncladded calculations since this was the favored design approach. The inside diameter margins at the maximum temperature gradient were used.

VII. CONCLUSIONS

Table 3 indicates that if one is constrained by time and funding, the polycrystalline graphites such as POCO and ATJS are the most logical material choice. If the designer has the opportunity to fund research to clear up certain deficiencies in the data and in the analytical tools then the choice may well be AVCO or Pyrocarb (Table 4).

For the MHW heat source, as it will be used in the MJS mission, it was ultimately decided by the project designers to use POCO-AXF-5Q as the aero-shell material. However, the advantages in terms of reduced thermal gradient, of having an emissivity sleeve during reentry led to the selection of Pyrocarb for an outer sleeve around the POCO to enhance the thermal stress margin.

Considerable data on Pyrocarb 406 had already been obtained during the Apollo/SNAP-27 program (cf., e.g. References 9 and 10). In addition to the material evaluation, a design improvement effort was initiated to reduce the stress concentration in the regions of the two threaded end caps. Ultimately, the elimination of the iridium outer can, the addition of a Pyrocarb sleeve and the re-design of the end closures provided the major changes in reentry configurations between the LES 8/9 and the MJS versions of the MHW heat source.

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TABLE 1

SUMMARY OF TRAJECTORY DATA FOR MJS MHW/RTG

<u>Event</u>	<u>Time (sec)</u>	<u>Altitude (kilofeet)</u>	<u>Velocity (ft/sec)</u>	<u>Path Angle (Degrees)</u>	<u>Comments</u>
Beginning of Reentry	0.0	400.0	39186 (inertial)	-19.20 (inertial)	Free RTG reentering with converter fin offset 30° to the air flow.
RTG Breakup Heat Source Release	11.5	254.1	37872 (relative)	-19.22 (relative)	Converter has been melted 30° around stagnation line leading to an assumed instantaneous release of the heat source.
Emissivity Sleeve Burnthrough (For The Case Where It Was Included)	23.0	121.6	27382 (relative)	-18.64 (relative)	The sleeve is removed by mechanical and thermochemical erosion. It is assumed to be totally removed when it burns through at the stagnation line. The clad has already melted.

TABLE 2
ANISO THERMAL STRESS RESULTS
Thermal Load Only

	With Clad and Emissivity Sleeve						Without Clad and Emissivity Sleeve					
	At Max. Surface Temp.			At Min. M. S.			At Max. ΔT			At Min. M. S.		
	σ_T (psi)	T (°F)	M.S.	σ_T (psi)	T (°F)	M.S.	σ_T (psi)	T (°F)	M.S.	σ_T (psi)	T (°F)	M.S.
*POCO AXF-5Q .386" wall	6300	3300	.52	6200	3300	.52	5950	3600	.52	6600	3100	.26
*ATJ-S(W) Elastic Plastic	4120	3300	.37	4130 3800	3500	.37 .49	5100	3800	.11	5250 4350	3900	.10 .32
Pyrocarb 406 .386" wall	2100	2800	.88	2140	2800	.85	2500	2800	.52			
Pyrocarb 406 Elastic Plastic							2650	2300	.37	3000 2650	2200	.23 .44
AVCO 3D C/C .386" wall	17100	2900	.20				19330	2900	.06			
Sandia CVD Felt .386" wall	2710	3750	.89	2530	3500	.82	3380	3900	.82			

* Results from Ref. 11, other results are from Ref. 12.

TABLE 3

RANKING OF AEROSHELL MATERIALS

APPROACH A

Assumption: No clad or emissivity sleeve
 Heavy weighting for porosity
 Use GE calculations for thermal stress
 Heavy weighting for impact/drop tests

CRITERIA	WEIGHTING FACTOR	POCO	AVCO	PYROCARB	IP	ATJS	SANDIA CVD
COST	0.01	0.001	<0.001	0.001	0.001	0.002	0.003
AVAILABILITY	0.20	0.027	0.032	0.039	0.033	0.039	0.029
REPRODUCIBILITY	0.10	0.020	0.016	0.016	0.013	0.018	0.016
CHARACTERIZATION	0.20	0.054	0.023	0.031	0.015	0.046	0.031
ABLATION, SURFACE EFFECTS, IMPACT VELOCITY	0.05	0.025	0	0	0	0.025	0
SYSTEM CONSTRAINTS (1/3 load + 2/3 porosity)	0.10	0.018	0.021	0.017	0.016	0.015	0.013
FAILURE MODES	0.07	0.008	0.016	0.016	0.008	0.008	0.012
THERMAL RESPONSE	0.10	0.009	0.031 (?)	0.038	0.009 (?)	0.008	0.006 (?)
THERMAL STRESS	0.10	0.025	0.002	0.011	0.026 (?)	0.016	0.021
ANALYSIS (Isotropy, Density gradients, etc.)	0.01	0.002	0.002	0.001	0.001	0.002	0.002
MACHINABILITY	0.05	0.009	0.007	0.007	0.009	0.009	0.008
PROPRIETARY	0.01	0	0.003	0.002	0.003	<0.001	0.002
SUM	1.00	0.198	0.154 (?)	0.179	0.134 (?)	0.189	0.143 (?)

TABLE 4

RANKING OF AEROSHELL MATERIALS

APPROACH B

Assumption: No clad or emissivity sleeve
 Heavy weighting for porosity
 Use α to weight thermal stress

CRITERIA	WEIGHTING FACTOR	POCO	AVCO	PYROCARB	IP	ATJS	SANDIA CVD
COST	0.01	0.001	<0.001	0.001	0.001	0.002	0.003
AVAILABILITY	0.20	0.027	0.032	0.039	0.033	0.039	0.029
REPRODUCIBILITY	0.10	0.020	0.016	0.016	0.013	0.018	0.016
CHARACTERIZATION	0.20	0.046	0.023	0.031	0.015	0.054	0.031
ABLATION, SURFACE EFFECTS, IMPACT VELOCITY	0.05	0.017	0.004	0.003	0.005	0.017	0.004
SYSTEM CONSTRAINTS (1/3 load + 2/3 porosity)	0.10	0.018	0.021	0.017	0.016	0.015	0.013
FAILURE MODES	0.07	0.008	0.016	0.016	0.008	0.008	0.012
THERMAL RESPONSE	0.10	0.009	0.031 (?)	0.038	0.009 (?)	0.008	0.006 (?)
THERMAL STRESS	0.10	0.005	0.043 (?)	0.019 (?)	0.011 (?)	0.011	0.011
ANALYSIS (Isotropy, Density gradients, etc.)	0.01	0.002	0.002	0.001	0.001	0.002	0.002
MACHINABILITY	0.05	0.009	0.007	0.007	0.009	0.009	0.008
PROPRIETARY	0.01	0	0.003	0.002	0.003	<0.001	0.002
SUM	1.00	0.162	0.199 (?)	0.190 (?)	0.124 (?)	0.184	0.137 (?)

Fig. 1 MHW Heat Source LES 8/9 Version

Fig. 2 MJS-77 V- γ Map Boundaries Initial 90 nmi Circular Orbit
Instantaneous ΔV Approximation

Fig. 3 Graphite Thermal Conductivity

Fig. 4 Circumferential Thermal Expansion

Fig. 5 Tensile Elastic Modulus

Fig. 6 Circumferential Ultimate Strength Lower Bound

Fig. 7 Preliminary Estimate of Aeroshell Recession MHW/RTG Heat Source for a Severe MJS Mission Abort Reentry

Fig. 8 Preliminary Comparison of Reference Heating Rates for Severe Heating Reentries, MJS and LES 8/9 Missions

Fig. 9 Preliminary Comparison of Critical PICS Thermal Response for Severe Heating Reentries, MJS and LES 8/9 Missions

Fig. 10 MJS - Alternate Aeroshell Materials Study
RTG's Only Side-On at 400 Kft - $V_0 = 39186 \text{ FPS}$ (Inertial)

Fig. 11 Heating Histories MJS - Alternate Aeroshell Materials Study
 $V_0 = 39186 \text{ FPS (Inertial)}$ $\gamma_0 = -19.2^\circ$

- WITH CLAD AND EMISSIVITY SLEEVE
- ALSO WITHOUT CLAD AND EMISSIVITY SLEEVE
- LES 8/9 DIMENSIONS (SOME RUNS MADE WITH AEROSHELL THICKNESS ADJUSTED FOR DENSITY DIFFERENCES)

- EMISSIVITY SLEEVE REMAINS IN PLACE UNTIL IT BURNS THROUGH AT STAGNATION POINT
- THERMOCHEMICAL ABLATION WITH MECHANICAL EROSION SUPERIMPOSED
- EMISSIVITY SLEEVE BURN THROUGH AT 23 SEC
121,553 FT V = 27,382 FT/SEC $\gamma = -18.64^\circ$ (RELATIVE)
- CLAD MELT PRIOR TO E.S. REMOVAL

Fig. 12 HSA Thermal Response Calculated with One-Dimensional Center Section Model of Stagnation Point

Fig. 13 HSA Temperature History — POCO AXF5Q (With Clad and E.S.)

Fig. 14 HSA Temperature History — POCO AXF5Q (Without Clad and E.S.)

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