NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Technical Report 32-1436

A Systematic Review of Heat-Shield Technology for Extraterrestrial Atmospheric Entry

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Preface

The work described in this report was performed by the Engineering Mechanics Division of the Jet Propulsion Laboratory.

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Abstract

Heat-shield technology is reviewed systematically by considering individually each parameter that contributes to heat-shield design. These parameters range from ablation models to pyrometer calibration, from the effects of adding fluorine to polymeric molecules to nondestructive testing of finished heat-shield subsystems. Each parameter has been rated as to its effect upon mission success and heat-shield design, and tasks have been formulated to investigate the most important parameters analytically or experimentally. As an example of the utility of the review methodology, alternative research and development support activities have been delineated for typical Venus-entry missions based upon the formulated tasks and their criticality ratings.

A Systematic Review of Heat-Shield Technology for Extraterrestrial Atmospheric Entry

I. Introduction

In 1965, NASA began seriously to consider a Mars-entry mission. An informal NASA heat-shield coordination group was formed, at the urging of the Jet Propulsion Laboratory (JPL), to investigate the special problems of extraterrestrial planetary entry. The membership of this group included Ames Research Center (ARC), Langley Research Center (LaRC), Lewis Research Center (LeRC), Manned Spacecraft Center (MSC), and JPL. This group has met informally one or more times a year since 1965 to review current research and development (R&D) programs and to provide coordinated direction to the NASA programs in the heat-shield area.

Based upon the extensive information exchange set up by these meetings, a myriad of new problems in extraterrestrial atmospheric entry have been uncovered. In the planetary exploration program, vast funding to solve these problems is not likely. To make the best use of available funds, it is necessary to investigate the anticipated problem areas systematically, and to fund only those efforts that are critical to mission success. The remainder of this report describes such a review. A Venus-entry heat-shield development program is delineated as an example of the program plans that use of the review makes possible.

II. The Review Process

Various approaches to carrying out a technology review of heat shields or thermal-protection systems were considered. A flow chart of the methodology actually used in the review is provided in Fig. 1. The conceptual basis for the review process is shown on the left of the figure. First, all parameters of any importance to heat-shield technology are examined and listed. Each parameter is then rated as to its importance to particular problem areas in each of the missions under consideration. The importance ratings are used to define specific tasks, grouping the related parameters and delineating specific areas that warrant effort. Each of these tasks is then assigned manpower and funding requirements. The availability of both facilities and applicable experience in each area is also estimated. The importance ratings and resource information may be used to construct specific programs that match the stated funding emphasis of each NASA Headquarters agency, and yet provide a balanced technology advance in each area.

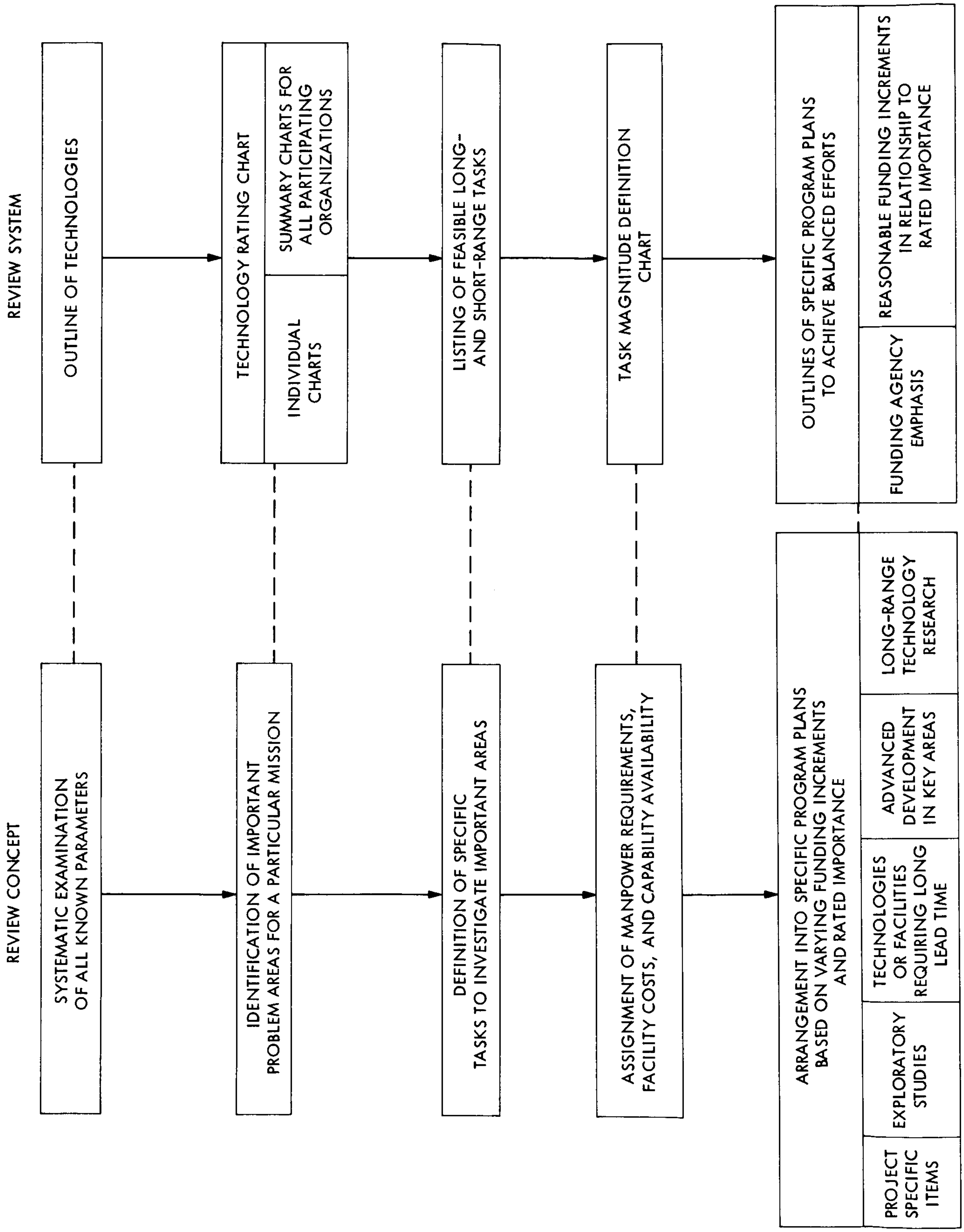

Fig. 1. A technology review process for planning heat-shield technology

The review system, shown on the right of Fig. 1, represents the documentation evolved to carry out the flow process. A comprehensive outline of heat-shield technology for extraterrestrial atmospheric entry missions was evolved at JPL with assistance from industry. An attempt was made to break down each technology area to a depth consistent with present knowledge in that area. All assumptions in theory or experiment (where known) were listed, and each measurement was again separated into its component parts (where known). Rating charts for individual evaluation of the identified problem areas were formulated, along with summary sheets comparing the ratings of different participating organizations. A listing of the feasible long- and short-range tasks was evolved based upon preliminary ratings. Resource estimations were made for those tasks considered critical for Venus entry as an example of the practicality of the process. Alternative program plans were formulated for Venus-entry heat-shield development dependent upon representative classes of missions.

A. Technology Outline

An outline of heat-shield technology for extraterrestrial atmospheric entry missions is provided in Appendix A. The contents of the outline are listed in Table 1. Definitions of each of the 18 categories in the outline are included as part of the appendix. The first two categories cover the mathematical theory of ablation computer analysis, including shock and boundary-layer chemistry and numerical processes, as well as the normal ablation processes. Categories III through VIII provide an evaluation of the basic material properties used in analysis, and the effects upon heat-shield performance during entry of the entire ground-handling, sterilization, launch, and transit environments. Categories IX through XIII describe the problems of ground simulation and flight test of the entry portion of a mission. The remaining categories cover material development and manufacturing process control, concluding with recommendations for parametric studies.

In this report, a first attempt is made to detail all of the technologies used in heat-shield research and development, with special emphasis upon applications for extraterrestrial planetary entry. The report should in no way be considered complete. It is meant to be used in two ways: (1) As a checklist at various stages in the development of a heat-shield material or subsystem, whereby the anticipated environments and mission constraints for a particular mission or class of missions can be matched systematically with the present state of the art. This allows an evaluation of the areas that must be emphasized by further activity, the areas that must be used to acquire design data at whatever accuracy possible, and the areas that may be safely ignored. (2) Managers of research and advanced development activities can use the outline to evaluate systematically future needs in perspective with the entire technology required. This allows support in such a way as to emphasize both a balanced capability and specific emphasis upon areas with the greatest potential for significant advances in reliability, weight minimization, and cost reduction.

Table 1. Contents of technology outline (Appendix A)

Number	Category
I	Ablation theory
II	Computer program development
III	Characterization and physical properties
IV	Thermal and optical properties
V	Mechanical properties
VI	Electrical properties
VII	Degradation kinetics investigations
VIII	Pre-entry environmental compatibility tests
IX	Entry-simulator development
X	Entry-simulator testing
XI	Diagnostic instrumentation development
XII	Flight test
XIII	Rocket-nozzle testing
XIV	Resin development
XV	Filler development
XVI	Composite development and fabricability investigations
XVII	Nondestructive testing
XVIII	Design criteria and parametric studies for design

B. Technology Rating

Given the technology review outlined in Appendix A, it was necessary to evolve some systematic method of assigning each of the identified factors a figure of relative merit compared to each of the other factors. Figure 2 shows the technology rating chart used to make this comparison. The nominal Mars, Venus, and Jupiter missions indicated at the top of the figure are briefly defined in Table 2.

Missions are available that could provide almost any combination of heating rate and pressure up to that

Mars				Venus				Jupiter				Time scope	Effort scope
Out of orbit		Direct entry		Earth similar		High energy		Low energy		High energy			
Importance	Potential	Importance	Potential	Importance	Potential	Importance	Potential	Importance	Potential	Importance	Potential	Years	Man-years / Year

Fig. 2. Technology rating chart for planetary entry

Table 2. Entry environment definition

Parameter	Mars		Venus		Jupiter	
	Out of orbit	Direct entry	Earth similar	High energy	Low energy	High energy
Peak convective heating, Btu/ft²/s	50	500	1000	3000	6000	10×10^3
Peak radiative heating, Btu/ft²/s	—	50	1000	14×10^3	6000	10×10^6
Peak pressure, atm	0.5	1.0	3.0	10.0	20	200

specified for high-energy Jupiter entry. With heating-rate ranges from 0 to 10^6 Btu/ft²/s, all earth-entry missions are also included (at least as to degree of severity) because differences in atmospheric composition have some effect.

The two columns under each mission in Fig. 2 (importance and potential) are filled in according to the five-point rating scale given in Table 3. The importance rating is essentially a measure of the effect of the individual parameter upon mission feasibility or success. Therefore, an item may be key (*); may have a very large effect (1); could be of long-range significance only, with the magnitude and timing of an output that is not immediately obvious (2); could be needed as a computer input, but without significant accuracy requirements (3); or could be without relative merit (4). The ratings for potential or probability of achieving an improvement in reliability, weight, or cost—given reasonable funding—is a more difficult scale. Two attempts at quantification are shown in Table 3; however, it really comes to a personal feeling of potential rather than any real, definable break between categories.

The following 14 organizations have been contacted, at one stage or another, to participate in the rating:

(1) Ames Research Center, Moffett Field, Calif. (NASA).

(2) Langley Research Center, Langley Station, Hampton, Va. (NASA).

(3) Lewis Research Center, Cleveland, Ohio (NASA).

(4) Manned Spacecraft Center, Houston, Tex. (NASA).

(5) Jet Propulsion Laboratory, Pasadena, Calif. (NASA).

(6) Air Force Materials Laboratory (Department of Defense).

Table 3. Rating scale

Rating	Importance	Potential (reliability, cost, weight)
*	Key	Key
1	High	Large (>50%)
2	Long range	Significant (10–50%)
3	Needed, but small effect	Refinements (1–10%)
4	Minor	Insignificant (<1%)

(7) Aerotherm Corp., Mountain View, Calif.

(8) Avco Corp., Lowell, Mass.

(9) Boeing Co., Seattle, Wash.

(10) General Electric Co., Valley Forge, Pa.

(11) Lockheed Corp., Sunnyvale, Calif.

(12) Martin Co., Denver, Colo.

(13) McDonnell Douglas Corp., St. Louis, Mo.

(14) McDonnell Douglas Corp., Santa Monica, Calif.

A sample summary sheet to provide cross-company comparison of the individual ratings for a particular mission is shown in Fig. 3. This sheet can be used not only to make a consensus of the relative importance of each parameter, but also to provide NASA with a guide to the biases in the various organizations active in the field. Up to the time of this writing, only the Avco Corporation, the General Electric Company, JPL, the Martin Company, and the St. Louis division of the McDonnell Douglas Corporation had submitted a full response to the rating activity. Most of the other organizations aided in making the technology outline (Appendix A) complete, but had not yet responded on the rating sheets.

JPL	ARC	LaRC	LeRC	MSC	AFML	AERT	AVCO	BOEG	DOUG	GE	LOCK	MART	McD

Fig. 3. Summary sheet for comparing company technology ratings and for emphasis rating

C. Task Definition

The available ratings from participants were used to compile a list of over 350 tasks covering the first three rating categories only. This list is included as Appendix B. Each task contains one or more parameters from the technology outline, grouped together in such a way as to take advantage of particular analytical techniques or experimental facilities. The list of tasks is organized as shown in Table 1. Some of the task listings have (*), (1), or (2) following the task number. These symbols represent the composite rating of the participants for the two nominal Venus missions. Tasks listed without a symbol in parentheses are peculiar to Mars or Jupiter, but not to Venus. In each subcategory, tasks are listed according to their Venus priority. Of the 335 tasks with some Venus priority, only 6% were given the critical priority rating. Another 30% were given the next priority rating, which means that they could have a large effect upon weight, cost, reliability, and mission success. The remaining tasks are all tasks with long-range research implications. A number of these should always be funded as a link to the future, but specific selection is normally dependent upon individual interest in the NASA research centers rather than upon realizeable immediate benefit. Major funding emphasis, on the other hand, should go to the critical or key tasks.

D. Task Magnitude Assignment

To establish plans for an R&D program, some estimates of funding requirements are desirable. Beginning with the form shown in Fig. 4, and based upon discussions held with representatives of the various NASA research centers and industry, each of the tasks listed in Appendix B can be assigned an estimated resource requirement. It is important to know (1) the length of time the effort will take, (2) the average manpower requirement per year, (3) the type of manpower needed, (4) the typical support personnel requirements (e.g., technicians or computer operators) needed for each technical man-year, (5) any facility cost, and (6) where the capability exists (in NASA or in industry). At this point, only the critical tasks discussed below have been assigned an estimated resource requirement. Although information is readily available for most of the other tasks, it has not been systematically reviewed and incorporated.

E. Program Plans

At this stage, with the tasks identified, priorities assigned, and estimates of necessary resource allocations defined, specific programs can be structured to solve the problems of particular missions or groups of missions to Mars, Venus, or Jupiter. Funding responsibility can be assumed by each NASA agency according to the stated interests and desires of that agency. Tasks without natural funding sources can be identified, and action taken to relieve the obvious gaps. For each funding agency, different incremental levels of funding can be delineated, with a description of the gains and losses inherent in each level. It is important to create a balance among specific project or mission needs, exploratory studies, technologies or facilities requiring long lead times, advanced development, and long-range technology research. A program plan for a variety of Venus-entry missions is provided as an example.

III. Venus-Entry Heat-Shield Development Program

Recent exploratory studies of 1973 or 1975 Venus-entry probe missions, with 1971 or 1973 project-funding starts, have provided an example to verify the utility of such a technology review. Because design normally freezes after the first 6 mo of a 2-yr project of this type, some preliminary heat-shield advanced development must be accomplished before the project begins if the new ablation-regime experience of Venus entry is to be feasible. A look at the Venus-entry environment for a spread of typical missions provides some rationale for the criticality of the key tasks selected from the review, with special emphasis upon ground proof-test feasibility. If these critical tasks are then placed in a time perspective, R&D support plans can be delineated.

A. Typical Spread of Venus-Entry Missions

Three representative missions can be examined as examples of various degrees of severity in the entry-heating pulse for Venus. These missions are shown in Fig. 5.

The most severe heating condition is shown as mission A, which represents a 44,000-ft/s entry at −45 deg to the planet from a 1973 Venus–Mercury flyby. With a ballistic coefficient of 0.6 slug/ft^2, this mission provides an extreme radiative-heating rate at the nose of approximately 10,000 Btu/ft^2/s—even after the tradeoffs between nose bluntness, dynamic stability, etc., have been made. This magnitude of heating on blunt bodies exceeds earth experience, and provides considerable uncertainty in heat-shield weight calculations.

Mission B represents a limitation chosen to keep the heating and pressure pulse within ground test-facility

Emphasis rating	Time scope	Effort scope	Manpower type		Support ratio	Facility cost, 10^6 dollars				Existing NASA capability	Industry capability
	Years	Man-years / Year	Analy	Exper	Support / Prof	<0.01	<0.1	<1	>1		

Fig. 4. Task resource summary

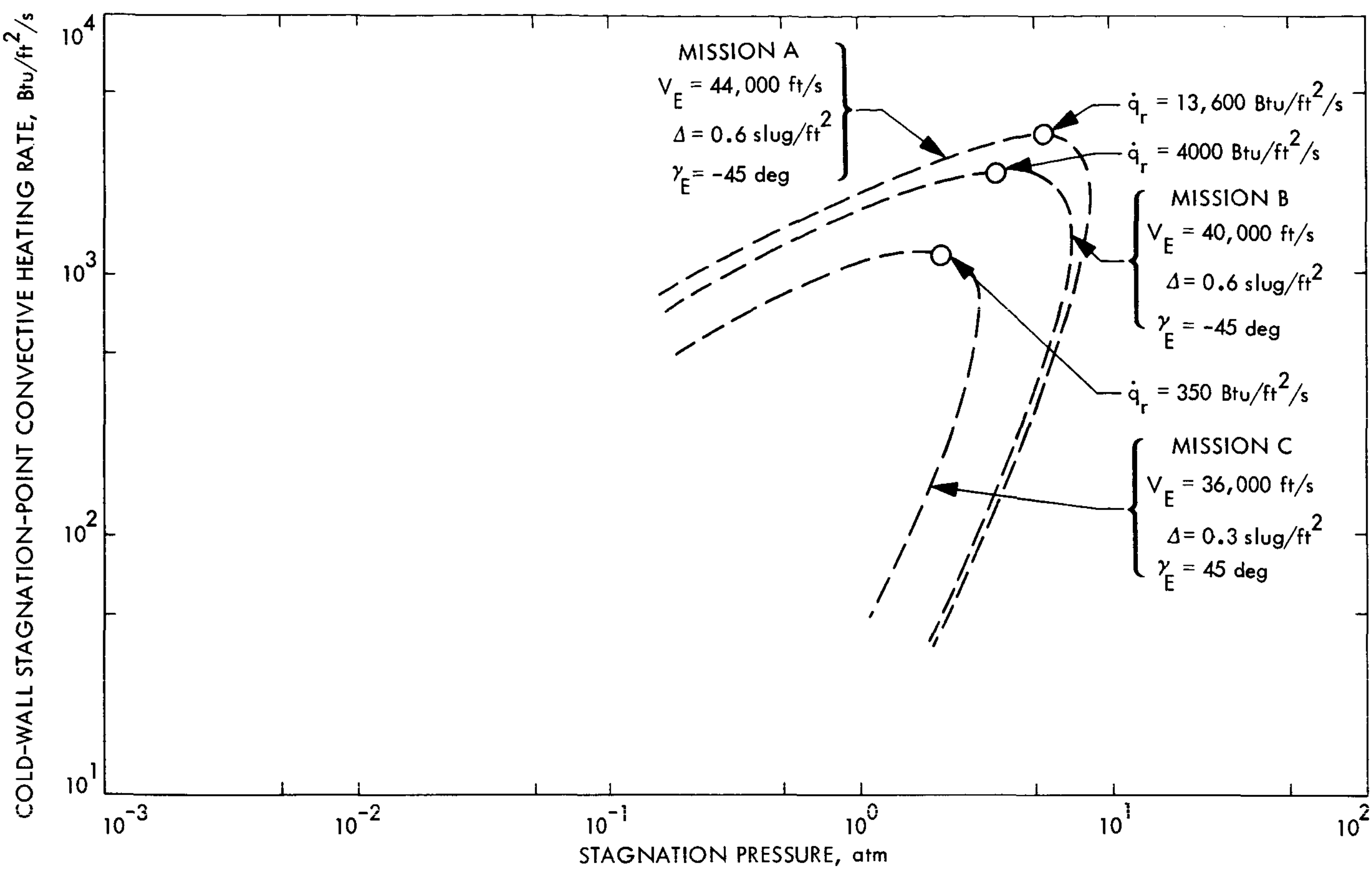

Fig. 5. Representative Venus-entry missions

capability. (This comparison is discussed below.) The mission consists of a 40,000-ft/s entry at a −45-deg angle to the planet and with a ballistic coefficient of 0.6 slug/ft^2.

Mission C is typical of a low-energy Venus entry, either direct or out of orbit, with *Apollo* technology providing sufficient heat-shield qualification. In this case, the initial entry velocity is held below 36,000 ft/s, at the same −45-deg entry angle to the planet, and the ballistic coefficient is reduced to 0.3 slug/ft^2.

B. Critical Tasks From Review

The critical computer-analysis tasks taken from the review are summarized as follows:

(1) Establish credence limits on available computer programs for Venus-entry material-response analysis.

(2) Carry out parametric studies of Venus-entry heat-shield requirement, using best available program.

(3) Make minimal modifications to best available programs to make them more representative of true state of art for Venus entry.

(4) Develop improved mathematical models to empirically represent critical uncertainty areas:

(a) Internal flow processes, including degree of equilibrium, cracking and redeposition, chemical erosion, etc.

(b) Internal degradation processes under high heating rates.

(c) High-blowing-rate effects.

(d) CO_2 atmosphere radiative heating.

(e) Rough surface-radiation balance.

(f) Turbulent transition on cone.

The input-data-measurement tasks taken from the review are summarized as follows:

(1) With existing capabilities, measure thermal, optical, mechanical, and degradation properties of heat-shield materials of interest to Venus entry (where not already available).

(2) Establish brittle transition criteria for Venus-entry heat-shield materials.

(3) Ensure that ground, launch, and transit environments introduce no catastrophic failure mechanisms by making judicious material selections and carrying out simple supplemental tests.

The test-facility-development tasks taken from the review are summarized as follows:

(1) Establish a minimum-acceptable calibration procedure for existing ablation-test facilities.

(2) Establish applicability of monochromatic laser radiation to high-heating-rate material-response measurements.

(3) Build a large laser test facility (required only for Venus-entry velocities greater than 40,000 ft/s).

The ablation-test-program tasks taken from the review are summarized as follows:

(1) Establish constraints on Venus-entry mission choice due to ground test-simulation limitations.

(2) Screen ground-testable Venus-entry environments for ablation-mechanism definition, using standard ablative composites.

(3) Screen a variety of readily available improved materials, using standard critical environments, and loop with material development.

(4) Characterize ablative performance of final candidate materials.

The material-development tasks taken from the review are summarized as follows:

(1) Tailor available resins and fillers into a composite that more closely satisfies transit and entry requirements for Venus.

(2) Investigate applicability of easily fabricable dual-density composites (high-density, high-ablation-efficiency surface layer with a low-density, high-insulation-efficiency sublayer).

Accurate input data are not generally available on the materials of interest, and must be measured, along with some evaluation of the effect of environmental prehistory upon the Venus-entry performance.

The same historical testing problem exists of inadequate facility definition. High-energy radiant-heating facilities (if applicable) will be necessary to produce the 10,000-Btu/ft^2/s radiative-heating rate typical of mission A. The available facilities must then be used to best advantage, within funding constraints, to qualify the heat-shield candidates and furnish data for analysis.

Polymer-chemistry advances allow better resin systems and better processing control than those generally used in the ablation industry. Some of these materials and techniques could be incorporated in any development program to increase ablator reliability. Composites with a hard outer layer and a low-density insulating inner layer are one form with great promise of weight savings for missions with longer entry times.

C. Proof-Test Feasibility

A comparison of proof-test feasibility is made in Fig. 6 for the three missions shown in Fig. 5 and the four major NASA entry-heating test-facility operations. The key to specific facilities is provided in Table 4. All of the facilities cover the *Apollo*-similar mission, as expected, because these facilities were primarily developed to support the *Apollo* program. The Structures Division at LaRC appears to provide the best simulation of the early portion of the trajectory, whereas ARC and the MSC appear to provide better high-pressure simulation for the later portion of the trajectory. The MSC facility designated (13) on Fig. 6 does not actually provide the testing capability shown. The nozzle exit for these conditions is only 1.5 in. Therefore, the heating rates quoted for a flat-faced 1.25-in. sample are, for the most part, not really possible. Even with this in mind, extrapolation to the 40,000-ft/s trajectory is probably reasonable. The 44,000-ft/s trajectory, on the other hand, represents a questionable extrapolation.

These conclusions are further complicated by the necessary radiative-heating simulation (see Fig. 5). On a 1-in. sample, ARC can superimpose 1000 Btu/ft^2/s with 14 arc lamps, MSC can superimpose 500 Btu/ft^2/s with four arc lamps, and JPL can superimpose 300 Btu/ft^2/s with two arc lamps. Although the ARC, MSC, and JPL facilities are sufficient for the *Apollo*-similar mission, only the ARC facility gives a sufficient indication of extrapolation for the 40,000-ft/s entry case.

To investigate the material compatibility with radiative-heating rates of the order of magnitude of 10,000 Btu/ft^2/s, a high-energy radiant-heating facility is needed. One such

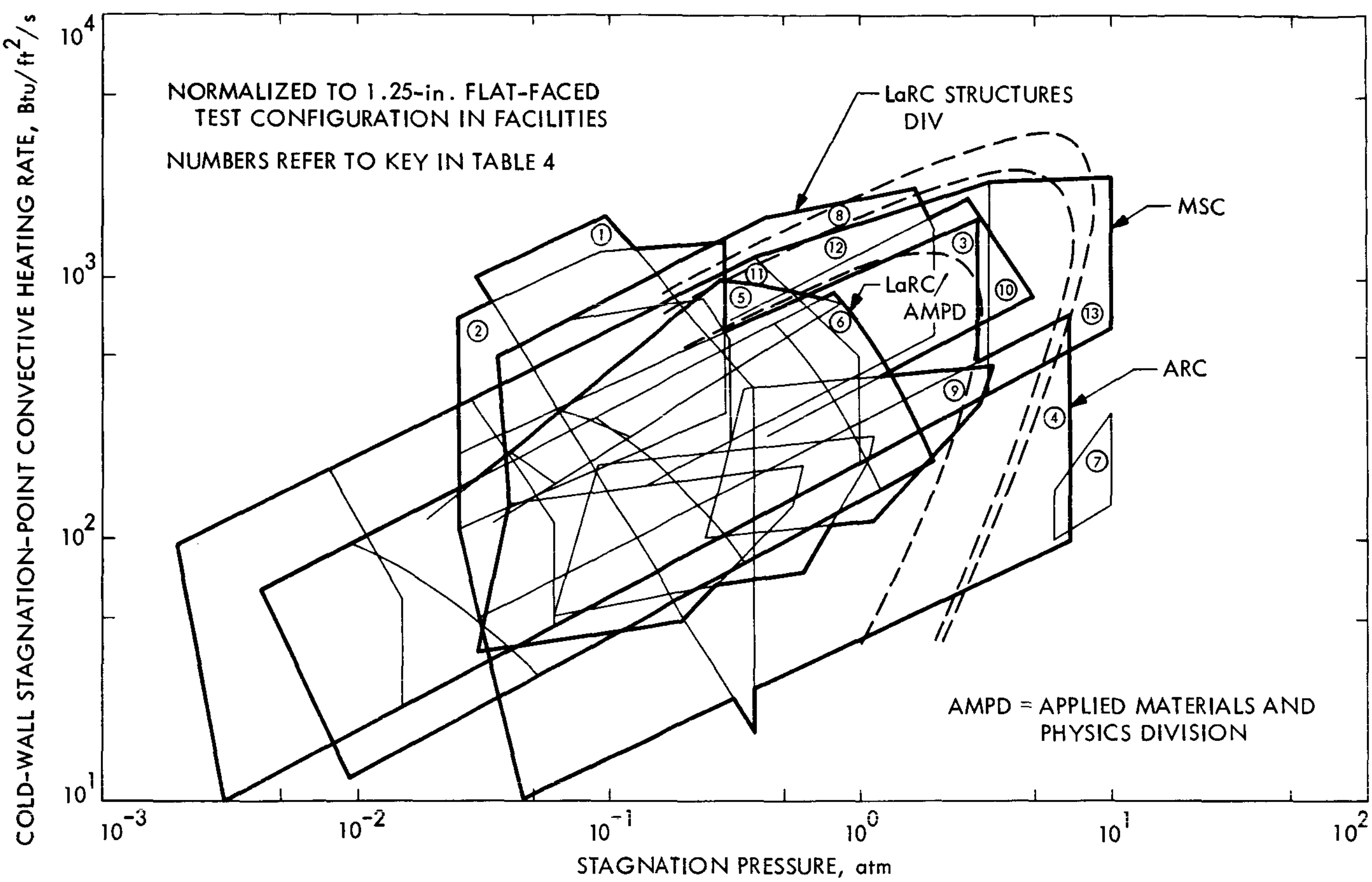

Fig. 6. NASA ground test-simulation capability compared to typical Venus-entry trajectories

facility is being constructed by ARC at present, and JPL is investigating the possibility of achieving even higher-energy densities. All of this indicates that (1) the high-energy radiant-heating facility is needed for mission A, (2) existing facilities provide adequate extrapolation for mission B, and (3) existing data will suffice, for the most part, for mission C.

D. R&D Support Plan for 1973 Mission Alternatives

A typical flow diagram for the preproject R&D support on a 1973 Venus spacecraft mission at 44,000 ft/s from a Venus–Mercury flyby is shown in Fig. 7. Most of the FY 69 tasks have been funded. To carry out the remainder of the tasks in FY 70, the NASA organization with project managership would have to assume direction and coordination leadership. Most of the activities within NASA already exist as tasks; only direction for a specific mission is needed.

The extra funds needed for industry to manufacture and characterize materials, to build facility components, and to carry out supplemental tests are estimated in a gross sense in Table 5.

For the mission A assumption (the Venus–Mercury flyby), about $1.5 million is needed. For the mission B assumption, the need for a laser facility is eliminated; therefore, the funding requirement drops. For the mission C assumption, *Apollo* technology eliminates some of the analysis and testing, further reducing the total.

Assumption D provides a heavy heat shield (15% or more of the entire vehicle weight), which contains a high enough factor of safety in relation to heat-absorption capability for reliability to be assured without more than superficial tests after the project begins. Detailed calculations of heat-shield requirements, with the limited analysis techniques available at present, indicate that approximately 3–10% of the vehicle should be heat shield. The percentage is dependent upon the trajectory and statistically estimated factors of safety, which are calculated from uncertain inputs. Under assumption D,

Table 4. NASA ground test-simulation facilities for nominal Venus-entry trajectories

Number (Fig. 6)	Facility	Equipment
1	Ames Research Center[a]	2.5-cm constricted arc: 2-in. exit
2	Ames Research Center	1.25-cm constricted arc: 2.75-in. exit
3	Ames Research Center	Linde N-4001: 2-, 7-, 12-, and 24-in. exits
4	Ames Research Center	Linde N-4000: 2-, 7-, 12-, and 24-in. exits
5	Langley Research Center, AMPD	Linde N-4001: 2-, 4.6-, and 7.6-in. exits
6	Langley Research Center, AMPD	Rotating arc: 2-, 3.3-, 6.6-, and 20-in. exits
7	Langley Research Center, AMPD	Ceramic tunnel
8	Langley Research Center, Structures Division	Linde N-4001: 2-, 4-, and 6-in. exits
9	Langley Research Center, Structures Division	3-phase ac arc: 2.75-, 4-, and 6-in. exits
10	Langley Research Center, Structures Division	TD double-end arc: 2- and 6-in. exits
11	Manned Spacecraft Center[b]	ARMSEF: 5-, 10-, 15-, and 20-in. exits
12	Manned Spacecraft Center	DCA: 1.5-in. exit
13	Manned Spacecraft Center	MRA: 1.5-in. exit
—	Jet Propulsion Laboratory[c]	PG500 arc: 2- and 3-in. exits

[a]Superimposed radiative heating of 1000 Btu/ft²/s is available at present. Radiative heating up to 10,000 Btu/ft²/s is projected with the new high-energy radiation system.

[b]Superimposed radiative heating of 500 Btu/ft²/s is available at present.

[c]Superimposed radiative heating of 300 Btu/ft²/s is available at present.

no preproject funds are required in the heat-shield technology area, and reliability is achieved by an overweight condition.

E. R&D Support Plan for 1975 Mission Alternatives

Missions projected for 1975 are less severe than the comparative 1973 examples. A 38,000-ft/s mission in 1973 is replaced by a 36,000-ft/s mission with the same general launch-energy requirements. The comparison is made on a similar basis, however, with the maximum-entry-velocity mission still above the present ground test-facility capability and requiring development of a high-energy radiant-heating test facility.

A typical flow diagram for the preproject support of a 1975 Venus-entry spacecraft mission, with a maximum entry velocity of 42,000 ft/s, is shown in Fig. 8. Again, most of the FY 69 tasks have been funded. The other tasks are essentially the same as those for the 1973 mission; they are spread out in time, however, and more opportunity is provided for the development of material improvements and unique testing capabilities within the framework of the critical tasks listed in Section III-B, above. Typical fund projections (Table 6) show about half again as much as those estimated for the 1973 mission (see Table 5). Most of this increase is due to additional effort towards increasing the confidence level in the heat shield that will finally be chosen for the mission.

It should be remembered that these estimates are for the items the review has designated as critical. Other, or looser, interpretation of the review could add a considerable number of additional tasks, with the inherent need for additional funds. Assumption D still eliminates the need for any preproject R&D.

Table 5. Typical preproject fund projections for 1973 mission

Assumption	Fiscal Year funding, 10^3 dollars		Total preproject funding, 10^6 dollars
	1969	1970	
Mission A	600	900	1.5
Mission B	300	700	1.0
Mission C	100	400	0.5
D	0	0	0

Table 6. Typical preproject fund projections for 1975 mission

Assumption	Fiscal Year funding, 10^3 dollars				Total preproject R&D funds, 10^6 dollars
	1969	1970	1971	1972	
Mission A	0	600	900	800	2.3
Mission B	0	300	500	500	1.3
Mission C	0	200	200	400	0.8
D	0	0	0	0	0

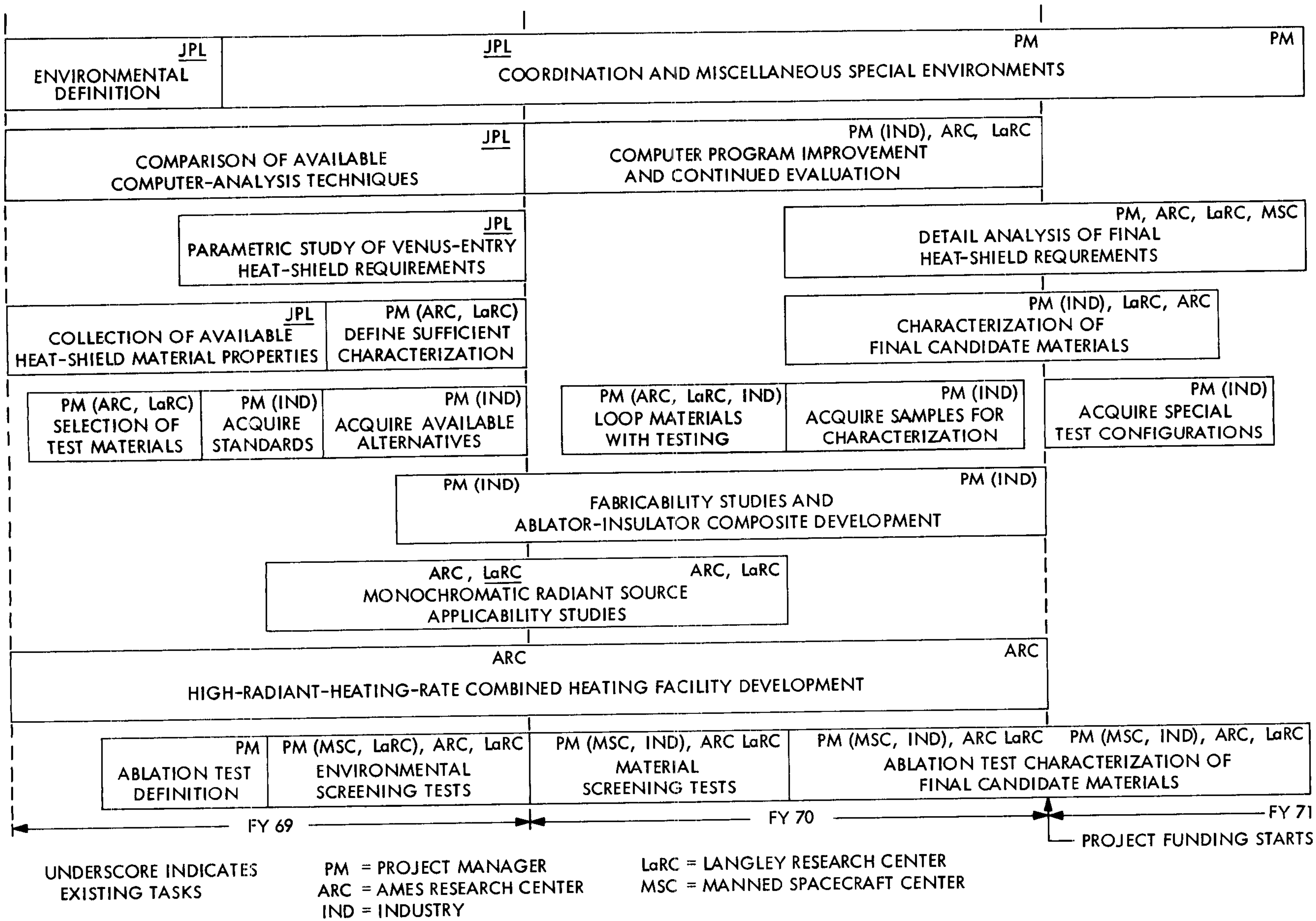

Fig. 7. Flow diagram for preproject heat-shield R&D support of a Venus 1973 spacecraft mission (36,000- to 44,000-ft/s entries)

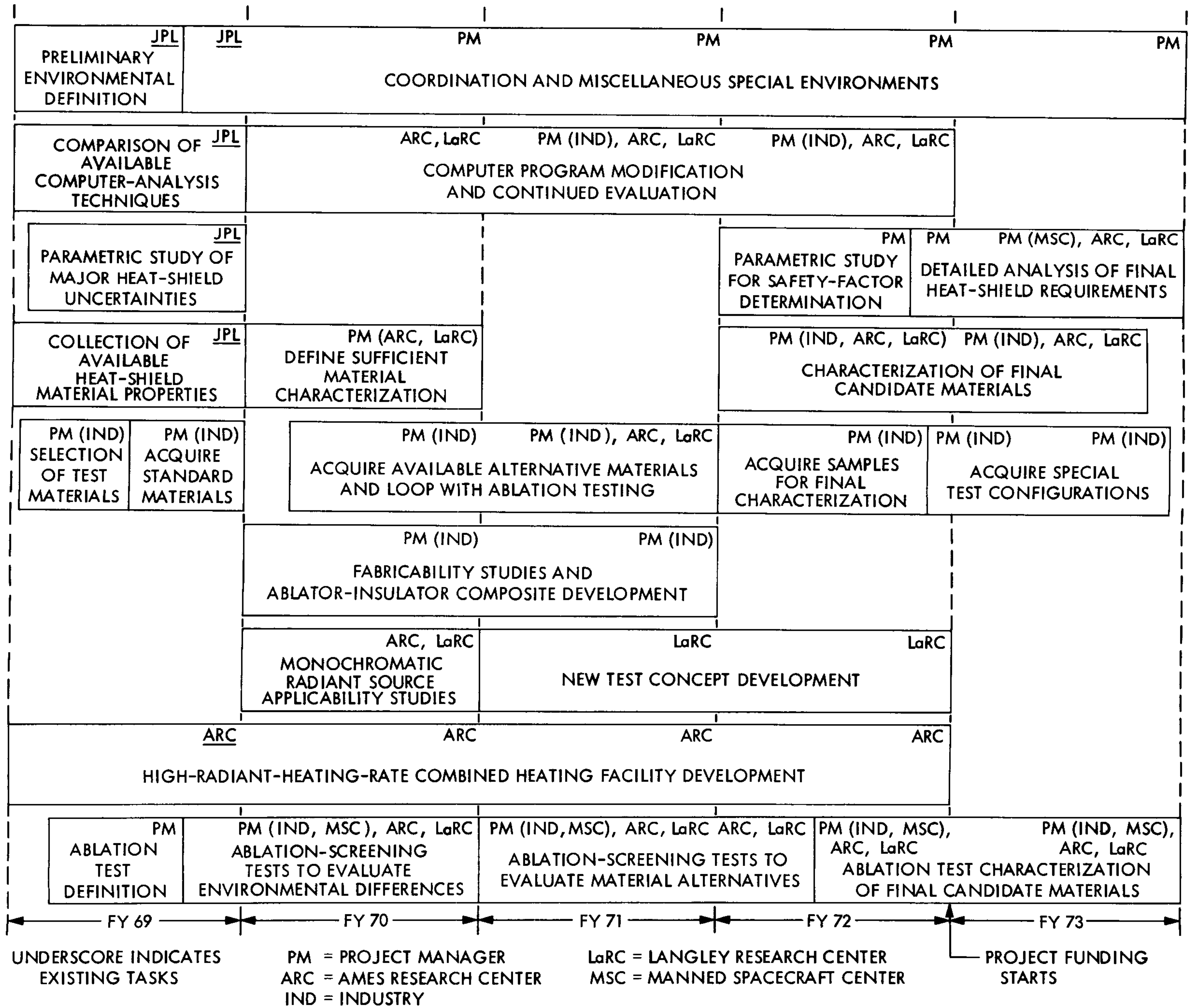

Fig. 8. Flow diagram for preproject heat-shield R&D support of a Venus 1975 spacecraft mission (34,000- to 42,000-ft/s entries)

Appendix A

Contents

Appendix A

An Outline of Heat-Shield Technology for Extraterrestrial Atmospheric-Entry Missions

Survival of an entry vehicle during the atmospheric-deceleration portion of an extraterrestrial scientific mission is an important part of the total mission reliability. Rocket-nozzle performance provides a similar contribution. On a flight vehicle, these heat shields may appear to be reasonably simple coatings over a structure; however, many disciplines are involved in providing that simplicity (see Table 1). Chemistry evolves a material. Numerous thermal, optical, physical, chemical, mechanical, and electrical properties are measured to characterize the material and allow analysis. Aerothermal, thermal, and structural analysis techniques are combined to predict performance. Complicated and expensive facilities are evolved and operated to simulate as much as possible of the ground-storage, launch, transit, and entry environments. Finally, an attempt is made to manufacture this somewhat idealized material in large, reproducible quantities; then to apply it to real vehicle shapes, without inhomogeneities or significant manufacturing errors.

I. Ablation Theory

Ablation has been defined by the American Society for Testing Materials (ASTM) as "a self regulating heat and mass transfer process in which incident energy is expended by sacrificial loss of material." As outlined here, ablation theory covers the mathematical models believed to represent the physical processes actually occurring during this sacrificial loss of material. The items listed in the outline that follows are those parameters or effects that actually influence each of the physical processes under consideration. Any particular parameter may or may not be incorporated in any mathematical model that exists at present. Both solutions in which material response is coupled to the flow field and those with various forms and degrees of empiricism are considered, without more than superficial separation, to emphasize the individual physical processes. Heat sinks, reradiators, transpiration cooling, etc., are taken to be simplified cases of this theory. The various kinds of computer programs that might be developed out of these theories are discussed in Section II of this appendix.

A. Internal Heat-Transfer Processes

1. Solid conduction.

a. Temperature effects.

(1) Low-temperature dropoff.

(2) Degradation layer transition.

(3) High-temperature variation.

(4) Hysteresis.

b. Virgin material structure.

(1) Anisotropy.

(2) Filler material (oxide, carbon, etc.).

(3) Filler form (fiber, powder, cloth, microballoon, etc.).

(4) Honeycomb.

(5) Permeability.

c. Char structure.

(1) Char solid structure (geometric form).

(2) Porosity.

(3) Ordering.

(4) Swelling or shrinkage.

(5) Anisotropy.

(6) Pyrolytic or nonpyrolytic deposition.

(7) Sublimation.

(8) Micro- or macrocracking.

(9) Silicone oxides and carbides.

(10) Filler material and form.

2. Gaseous conduction.

a. High-temperature effects.

(1) High-temperature variations.

(2) Species variations.

b. Pressure effects.

(1) Vacuum.

(2) Pressure gradient.

(3) Pore structure (size and geometric form).

3. Radiation conduction or transfer.

a. Temperature effects—high-temperature variation.

b. Char structure.

(1) Pore structure (size and geometric form).

(2) Pore optical properties.

(3) Micro- or macrocracking.

(4) Filler material and form.

4. Transmittance of surface radiation.

a. Optical effects.

(1) Absorption coefficient.

(2) Internal reflectance.

b. Geometry effects.

(1) Surface roughness.

(2) Pore geometry.

(3) Cracks in char.

5. Mass transfer.

a. Thermochemical state.

(1) Equilibrium.

(2) Nonequilibrium.

(3) Frozen.

(4) Cracking.

(5) Redeposition.

b. Flow phenomena.

(1) Pressure and pressure gradient.

(2) Flow velocity.

(3) Diffusion.

(a) Darcy's law.

(b) Other.

(4) Pore structure (size and geometry).

(5) Species.

(6) Solid entrainment.

B. Internal Heat Absorption

1. Specific energy absorption.

a. Solid phase.

(1) Swelling or shrinkage effects.

(2) Specific heat.

(3) Multiple constituents.

b. Liquid phase.

(1) Density variation.

(2) Specific heat.

(3) Blowing or flow.

(4) Multiple constituents.

c. Gas phase.

(1) Pressure-density relation.

(2) Specific heat of individual species.

(3) Species identification.

(4) Flow.

2. Thermal degradation of polymers.

a. Form of mathematical representation.

(1) Arrhenius.

(2) Polynomial.

(3) Other.

b. Control parameters.

(1) Temperature.

(2) Heating rate.

(3) Atmospheric species.

(4) Pressure.

(5) Geometric size or shape.

c. Order of reaction.

3. Phase change.

a. Melting and vaporization.

(1) Organic.

(2) Inorganic.

(3) Blowing or flow.

(4) Char interaction.

(5) Structural vs nonstructural phases.

b. Sublimation.

(1) Vapor pressure.

(2) Temperature.

(3) Diffusion from surface.

(4) Pressure or velocity gradient.

c. Crystalline transformations.

(1) Carbon.

(2) SiO_2.

(3) Other.

4. Thermochemical reactions.

a. Cracking of gases.

(1) Temperature.

(2) Pressure.

(3) Species.

(4) Char catalysis.

b. Chemical erosion and internal oxidation.

(1) Temperature.

(2) Pressure.

(3) Species.

(4) Char composition.

c. Pyrolytic or nonpyrolytic deposition.

(1) Temperature.

(2) Pressure.

(3) Species.

(4) Char catalysis.

d. Silicon carbide formation.

(1) Temperature.

(2) Pressure.

e. Char-reinforcement reactions.

f. Photochemical reactions from incident radiation.

g. Mixing and friction.

C. External or Surface Heat-Transfer Processes

1. Convective heat transfer.

a. Planetary gases.

(1) Mars: CO_2, N_2, Ar.

(2) Venus: CO_2, N_2, H_2O, O_2, Ar.

(3) Jupiter: H_2, He, CH_4, NH_3.

(4) Monatomic theory.

b. Continuum flow.

(1) Transition from free molecular.

(2) Deviations.

c. Chemical state of boundary layer.

(1) Equilibrium.

(2) Nonequilibrium.

(3) Frozen.

(4) Other.

d. Pressure.

(1) Level.

(2) Gradient.

e. Surface effects.

(1) Catalysity.

(2) Roughness.

(3) Protuberances, holes, or slits.

f. Velocity effects.

(1) $<30{,}000$ ft/s.

(2) $<50{,}000$ ft/s.

(3) $>50{,}000$ ft/s.

(4) $>100{,}000$ ft/s.

g. Distribution around body.

(1) Flow field, two- and three-dimensional.

(2) Vehicle shape.

(3) Heat-transfer theory, two- and three-dimensional.

(4) Angle-of-attack effects.

(5) Base heating.

h. Transition criteria.

(1) Reynolds number.

(2) Enthalpy ratio.

(3) Velocity (ρu) ratio.

(4) Molecular weight of species.

(5) α.

(6) Surface roughness.

i. Turbulence.

(1) Model development.

(2) Vorticity interaction.

j. Mass injection coupling (see I-C-3, below).

k. Boundary layer suction.

2. *Radiative heat transfer.*

a. Planetary gases.

(1) Mars: CO_2, N_2, Ar.

(2) Venus: CO_2, N_2, H_2O, O_2, Ar.

(3) Jupiter: H_2, He, Ne, CH_4.

(4) Monatomic.

b. Surface absorptance at low wavelengths.

c. Equilibrium.

(1) Level.

(2) Pressure.

(3) Nonablative inviscid flow.

d. Nonequilibrium.

(1) Level.

(2) Pressure.

(3) Collision-limiting effects.

(4) Truncation.

e. Distribution around body.

(1) Equilibrium.

(2) Nonequilibrium.

(3) Vehicle shape.

(4) Angle-of-attack effects.

f. Entropy layer.

g. Precursor.

h. Reynolds-number effects.

i. Self-absorption.

j. Ablative species absorption.

(1) Gross.

(2) Spectral.

k. Blackout.

l. Velocity effects.

(1) $<30{,}000$ ft/s.

(2) $<50{,}000$ ft/s.

(3) $>50{,}000$ ft/s.

m. Turbulence effects.

3. *Blocking or mass addition.*

a. Coupling with external flow.

(1) Effective velocity vector of evolved gases.

(2) Change in boundary-layer dimensions.

(3) Change in shock-layer dimensions.

(4) Temperature-gradient changes.

(5) Pressure-gradient changes.

(6) Upstream effects.

b. High-blowing-rate theory.

(1) Laminar.

(2) Turbulent.

c. Radiative-heating coupling.

(1) Absorption.

(2) Molecular weight of injected species.

d. Convective-heating coupling.

(1) Effective velocity vector of evolved gases.

(2) Molecular weight of injected species.

e. Transpiration coefficient.

4. *Reradiation from surface.*

a. Emittance.

(1) Level.

(2) Change during ablation or mechanical erosion.

(3) Spectral distribution.

(4) View angle.

b. Surface effects.

(1) Surface porosity.

(2) Superheating at the surface.

(3) Temperature gradient (in depth).

(4) Temperature gradient (laterally).

c. Reabsorption in gas—convective–radiative coupling.

5. *Combustion processes in boundary-layer gas and at char surface.*

a. Reaction-rate-limited oxidation.

b. Diffusion-role-limited oxidation.

c. Gaseous combustion.

d. CO_2 *equivalent oxidation.*

e. Reactions with nitrogen.

f. Pressure effects.

g. Combustion cutoff.

h. Impurities.

i. Oxidation inhibitors.

j. Combustion heating.

k. Mass-transfer cooling from combustion species.

6. *Sublimation.*

a. Rate equations.

(1) Arrhenius form.

(2) Knudsen–Langmuir equation.

(3) Other.

b. Pressure effects.

(1) Partial-pressure equation.

(2) Vapor-pressure data.

c. Diffusion effects.

(1) Escape (out) from surface.

(2) Collision with species moving toward surface.

(3) Fick's law.

(4) Diffusion limit.

(5) Superheating at surface.

d. Species properties.

(1) C_n, Si, SiO, etc.

(2) Free energy functions.

(3) Heats of formation.

(4) Entropy.

(5) Sublimation point.

(6) Triple point.

(7) Vaporization coefficient.

(8) Micro- vs macrocrystallites.

e. Impurities.

7. *Vaporization.*

a. Oxides.

(1) Silica.

(2) Glass.

(3) Other.

b. Blowing by subvaporizing species or lateral flow.

c. Sublimation (see 1-C-6, above).

8. *Solid-mass removal processes.*

a. Liquid layer.

(1) From glassy fillers.

(2) From silicone elastomers.

(3) Flow processes.

(4) In-depth melting.

(5) Viscosity dependence.

b. Shear removal.

(1) Pressure gradient.

(2) Upstream transpiration.

c. External-pressure effects.

(1) Crushing.

(2) Movement of boundary layer into char.

d. Porosity effects.

(1) Pressure failure from confining of evolved gases.

(2) Internal lateral gas flow.

e. Thermal stress effects.

(1) Char failure.

(2) Bond-line failure.

f. Coupling turbulent boundary layer with ablator response.

g. Cross-hatching.

h. All of the above (a–g) superimposed.

D. Sublayer Heat-Transfer Mechanisms

1. Thin superconducting layers or sublayer heat sinks.

2. Foam conductance.

3. Honeycomb-sandwich conductance.

(1) Metallic.

(2) Nonmetallic.

4. Multilayer-insulation conductance.

(1) Normal temperatures.

(2) High temperatures.

5. Unlike interfaces.

(1) Contact resistance.

(2) Thermostructural compatibility.

6. Rear surface cooling.

(1) Active.

(2) Passive.

7. Joints, windows, feedthroughs, etc.

II. Computer Program Development

To decrease costs and improve accuracy and understanding, computer program development includes both the formulation of total programs—to analyze ablation theory or reduce ablation-related data—and the investigation of computation processes and data handling.

A. Computer Usage Techniques

1. Numerical processes.

a. Node selection.

(1) Variable size.

(2) Change with time.

(3) Material property dependence.

b. Numerical method.

(1) Explicit.

(2) Implicit.

(3) Implicit/explicit.

(4) Other methods.

c. Differences between theory and numerical method.

(1) Form.

(2) Range of validity.

(3) Biases.

(4) Truncation errors.

d. Time shortcuts.

(1) Numerical method.

(2) Computing-interval optimization.

e. Simplification of calculation matrix.

f. Time-integrating techniques.

g. Multidimensional techniques.

2. Standardization.

a. Notation.

b. Units.

c. Common subroutines.

d. Input techniques.

e. Output techniques.

(1) Listing.

(2) Plotting.

(3) Punched card.

f. Coordinate system reference.

3. ***Data storage and retrieval.***

   a. *Storage techniques.*

   b. *Retrieval access.*

   c. *Graphical output.*

   d. *Punched-card output.*

B. Heat Shield Design Programs

1. ***Preliminary design.***

   a. *Simplified model.*

   b. *Sophisticated one-dimensional model for checkpoints.*

   c. *Simplified multidimensional singularity model.*

2. ***Final design.***

   a. *Sophisticated one-dimensional uncoupled model.*

   b. *Fully-coupled model for checkpoints.*

   c. *Sophisticated multidimensional uncoupled model.*

   d. *Specialized sophisticated singularity models.*

C. Data Reduction and Analysis Programs

1. ***Plasma-jet data reduction.***

   a. *Flow-field analysis.*

      (1) Definition of stream parameters.

      (2) Including mass addition.

      (3) Including specimen shape change.

   b. *Correlation of ablation test data with facility parameters.*

   c. *Conversion of digital output data to diagnostic tables and plots and to ablation records.*

   d. *Correlation of flight environments with facility parameters.*

   e. *Derivation of ablation properties from ground test data.*

      (1) Extensive.

      (2) Limited.

2. ***Material properties (per property where applicable).***

   a. *Derivation of property from laboratory test data.*

      (1) Extensive.

      (2) Limited.

   b. *Derivation of property from thermocouple data.*

      (1) Nonlinear regression.

      (2) Parameter optimization.

      (3) Other.

III. Characterization and Physical Properties

The measurements outlined in this section are those that are used—to a greater or a lesser degree—to characterize ablative specimens before testing them for some other property. These measurements are essentially used to define the instantaneous state of the material after exposure to a particular environment and before the changes inherent in the next form of property measurement are initiated. Hence, undegraded ablative composites have specific component and elemental distributions, and have density, permeability, and porosity. Chars may be similarly defined, but also require a measurement of their micro-ordering.

A. Elemental Analysis

1. ***C, H, O, N, Si, F, Cl, S, P, etc.***

   a. *Microcombustion.*

2. ***Alkali metals.***

   a. *An electron-beam microprobe.*

3. ***Relative accuracy of experimental techniques.***

B. Component Distribution

1. ***Virgin material.***

   a. *Volume or weight percent of original materials.*

   b. *Additives.*

   c. *Cross-linking density.*

   d. *Infrared spectrum.*

   e. *Thin sectioning.*

      (1) Cutting problems.

      (2) Mounting problems.

f. Photomicrographs.

(1) Filler distribution.

(2) Mixing efficiency.

2. Char.

a. Carbon content.

b. SiO_2 and other oxide contents.

c. SiC content.

d. X-ray diffraction pattern.

(1) Diffraction intensities.

(2) Crystal spacings.

e. Thin sectioning.

(1) Cutting problems.

(2) Mounting problems.

f. Photomicrographs.

(1) Pore shape and size.

(2) Filler structure.

(3) Char structure.

(4) Pyrolytic deposition.

C. Permeability

1. As a measure of low-temperature diffusion of species out of or through an undegraded ablative composite.

2. Adequate experimental setup needed.

3. Permeability factors.

a. Temperature dependence.

(1) Activation energy.

(2) Frequency factor.

b. Flow factors.

(1) Area.

(2) Time.

(3) Quantity of permeant.

(4) Natural porosity.

(5) Open vs closed cell foam.

D. Specific Volume (or Density) and Porosity

1. Measurement techniques.

a. Micrometer.

(1) Surface roughness.

(2) Repeatability.

(3) Applicability to partially charred samples.

b. Photomicrograph.

(1) Thin sectioning.

(2) Area summation.

(3) Representativeness.

c. Fluid displacement.

(1) Water.

(2) Mercury.

(3) Nitrogen (B.E.T.).

(4) Apparent vs true density.

(5) Open vs closed cells.

(6) Two levels of porosity.

(7) Shape effects.

d. Grinding and weighing.

e. Dye penetrant.

f. X-ray.

2. Special problems.

a. Variation with temperature.

b. Cracking and pyrolytic deposition.

c. Swelling or shrinkage.

E. Vapor Pressures

1. Equipment development.

a. High temperature.

b. High pressure.

2. Special problems.

a. Carbon triple point.

IV. Thermal and Optical Properties

Thermal properties, as outlined below, are primarily nonkinetically controlled, specific-energy-absorption-process constants and internal-energy-transfer constants for solids and fluids. Emphasis is upon low-density, polymeric-based materials and porous derivatives such as chars.

Optical properties, as outlined below, consist of surface phenomena or reactions to external radiation sources only. Emittance and reflectance techniques are basically well established, and require only adaptation to particular situations or materials. Transmittance measurements and absorption-coefficient concepts on low-density heat-shield materials and their porous derivatives are both less available and less understood.

Thermal expansion is also outlined in this section, although it could as well be located under Mechanical Properties (Section V).

A. Thermal Expansion

1. ***Comparison of alternate techniques.***
   - a. *Appropriateness to analysis requirements.*
   - b. *Environmental limitations.*
     - (1) Temperature.
     - (2) Pressure.
     - (3) Gas species.
     - (4) Heating rates.
   - c. *Accuracy.*
     - (1) Temperature measurements.
     - (2) Heat losses.
     - (3) Expansion measurement.
     - (4) Sample distortion.
     - (5) Window distortion.
   - d. *Biases.*
     - (1) Equipment.
     - (2) Analytical model.
   - e. *Standardization.*
2. ***Equipment development.***
   - a. *Dilatometer.*
     - (1) Increase useful temperature range.
     - (2) Improve sensing mechanism.
     - (3) Improve environmental compatibility.
   - b. *Optical comparators.*
     - (1) Increase useful temperature range.
     - (2) Define sensitivity limit.
     - (3) Minimize optical distortions.
   - c. *Interferometer.*
     - (1) Increase useful temperature range.
     - (2) Define sensitivity limit.
     - (3) Minimize optical distortions.
   - d. *Diffraction.*
     - (1) Increase useful temperature range.
     - (2) Define sensitivity limit.
     - (3) Minimize distortions.
   - e. *Other.*
3. ***Special problems.***
   - a. *Temperature.*
     - (1) Low (to −200°F).
     - (2) High (to 7000°F).
     - (3) Time at temperature.
   - b. *Surrounding atmosphere.*
     - (1) Vacuum.
     - (2) Extreme pressure.
     - (3) Chemically active gaseous species.
   - c. *High heating rate.*
     - (1) Experimental approach needed.
   - d. *Sample representativeness.*
     - (1) Shape.
     - (2) Ablation state.
     - (3) Fabrication.

B. Specific Heat of Solids

1. ***Comparison of alternate techniques.***
   - a. *Appropriateness to analysis requirements.*
   - b. *Environmental limitations.*
     - (1) Temperature.
     - (2) Pressure.
     - (3) Gas species.

c. Accuracy.

(1) Temperature measurements.

(2) Heat losses.

(3) Sample weight and shape.

d. Biases.

(1) Equipment.

(2) Inherent model.

e. Standardization.

2. Equipment development.

a. Method of mixtures (drop method).

(1) Expand temperature limits.

(2) Automate operation and data recording.

(3) Minimize oxidation and shock effects at high temperature.

(4) Investigate environmental effects.

b. Adiabatic calorimeter.

(1) Expand temperature limits.

(2) Automate operation and data recording.

(3) Investigate environmental effects.

c. Bunsen ice calorimeter.

(1) Expand temperature limits.

(2) Automate operation and data recording.

(3) Investigate environmental effects.

d. Differential scan calorimeter.

(1) Expand temperature limits.

(2) Automate operation and data recording.

(3) Increase environmental-simulation capability.

(4) Investigate heating-rate effect.

(5) Investigate representativeness of specimens.

e. Other.

3. Special problems.

a. Temperature.

(1) Low (to −200°F).

(2) High (to 7000°F).

(3) Time at temperature.

b. Surrounding atmosphere.

(1) Extreme pressure.

(2) Trapped internal gases.

(3) Chemically active gaseous species.

c. Sample representativeness.

(1) Shape.

(2) Ablation state.

(3) Fabrication.

C. Specific Heat of Evolved Gases

1. Comparison of alternate techniques.

a. Appropriateness to analysis requirements.

b. Environmental limitations.

(1) Temperature.

(2) Pressure.

(3) Species.

c. Accuracy.

(1) Temperature measurements.

(2) Heat losses.

d. Biases.

(1) Calculation technique.

(2) Equipment limits.

e. Standardization.

2. Equipment development.

a. Calculation from basic principles.

(1) Availability of applicable data.

b. Differential scan calorimeter.

(1) Increase temperature limit.

(2) Automate operation and data recording.

(3) Adapt for liquid or gas measurements.

c. Other.

3. Special problems.

a. High temperature (to 7000°F).

b. Surrounding atmosphere.

(1) Extreme pressure.

(2) Ionization and dissociation.

D. Thermal Conductance

1. *Comparison of alternate techniques.*

   a. *Appropriateness to analysis requirements.*

   b. *Environmental limitations.*

      (1) Temperature.

      (2) Pressure or vacuum.

      (3) Gas species.

   c. *Accuracy.*

      (1) Temperature measurements.

         (a) Surface.

         (b) In depth.

         (c) Along an interface.

      (2) Heat losses.

      (3) Sample configuration.

      (4) Anisotropy.

      (5) Surface contact.

   d. *Biases.*

      (1) Equipment.

      (2) Inherent model.

   e. *Standardization.*

      (1) Equipment.

      (2) Sample materials.

2. *Equipment or technique development.*

   a. *Guarded hot plate.*

      (1) Expand temperature limits.

      (2) Automate operation and data recording.

      (3) Increase environmental-simulation capability.

      (4) Adapt for honeycomb sandwich or similar composite materials.

      (5) Adapt for superinsulation.

   b. *Radial measuring techniques.*

      (1) Expand temperature limits.

      (2) Automate operation and data recording.

      (3) Increase environmental-simulation capability.

      (4) Improve sample configuration; set size and shape limits.

      (5) Improve measurement precision.

      (6) Adapt to nonhomogeneous material.

   c. *Cut bar.*

      (1) Expand temperature limits.

      (2) Automate operation and data recording.

      (3) Increase environmental-simulation capability.

      (4) Adapt to absolute rather than comparative measurement.

      (5) Adapt to low-conductivity materials.

      (6) Adapt to anisotropic materials.

   d. *Reverse calculation from internal temperature response.*

      (1) Define accuracy in temperature-response data.

      (2) Investigate other factors lumped under *conductance*.

   e. *Pulse methods.*

      (1) Expand temperature limits.

      (2) Automate operation and data recording.

      (3) Increase environmental capability.

      (4) Investigate applicability of laser source.

      (5) Improve measurement precision.

      (6) Investigate radiation interaction.

         (a) With porous material.

         (b) With glassy reinforcements.

      (7) Investigate analytical model of interaction of a high-energy, short-time pulse on a porous surface.

   f. *Other.*

3. *Special problems.*

   a. *Temperature.*

      (1) Low (to −200°F).

      (2) High (to 7000°F).

      (3) Time at temperature.

b. *Surrounding atmosphere.*
   (1) Vacuum.
   (2) Extreme-pressure gaseous conduction.
   (3) Chemically active gaseous species.

c. *Sample representativeness.*
   (1) Geometrical shape.
   (2) Pore structure.
      (a) Open.
      (b) Closed.
      (c) Shape.
   (3) "Graphitization."
   (4) Ablation state.
   (5) Inhomogeneity.

d. *Anisotropy.*

e. *Core-sandwich configurations.*

f. *Superinsulation configurations.*

g. *Joint, feedthrough, window, etc., conductances.*

h. *Geometric limitations.*
   (1) Flat plate vs radial.
   (2) Sample size.

i. *Internal radiative heat-transfer mechanisms.*

j. *Differences between steady-state and transient techniques.*

E. Optical Properties

1. ***Comparison of alternate techniques.***

a. *Appropriateness to analysis requirements.*

b. *Environmental limitations.*
   (1) Temperature.
   (2) Pressure or vacuum.
   (3) Gas species.
   (4) Wavelength.
   (5) Angle of incidence.

c. *Accuracy.*
   (1) Temperature level.
   (2) In-depth gradient.
   (3) Laterial gradient.
   (4) Heat losses.
   (5) Sample configuration.
      (a) Shape.
      (b) Anisotropy.
      (c) Surface roughness.
   (6) Optics.
      (a) Wavelength.
      (b) Beam spreading.
      (c) Beam distortion.

d. *Biases.*
   (1) Equipment.
   (2) Emittance model.
   (3) Reflectance model.
   (4) Sample.

e. *Standardization.*
   (1) Equipment.
   (2) Sample materials.

2. ***Equipment or technique development.***

a. *Hemispherical emittance.*
   (1) Expand temperature limits.
   (2) Automate operation and data recording.
   (3) Increase environmental-simulation capability.
   (4) Increase wavelength range for both spectral and total measurements.

b. *Directional emittance.*
   (1) Expand temperature limits.
   (2) Automate operation and data recording.
   (3) Increase environmental-simulation capability.
   (4) Increase wavelength range for both spectral and total measurements.

c. *Parallel-beam source/hemispherical readout.*
   (1) Expand temperature limits.
   (2) Automate operation and data recording.
   (3) Increase environmental-simulation capability.

(4) Increase wavelength range for both spectral and total measurements.

(5) Improve source.

(6) Improve optics (lens, filters, etc.).

d. Hemispherical source/parallel-beam readout.

(1) Expand temperature limits.

(2) Automate operation and data recording.

(3) Increase environmental-simulation capability.

(4) Increase wavelength range for both spectral and total measurements.

(5) Improve source.

(6) Improve optics (lens, filters, etc.).

3. Special problems.

a. Temperature.

(1) Low (to −200°F).

(2) High (to 7000°F).

(3) Time at temperature.

(4) Lateral temperature gradient.

(5) Internal temperature gradient.

b. Surrounding atmosphere.

(1) Vacuum.

(2) Extreme pressure.

(3) Chemically active gaseous species.

c. Sample representativeness.

(1) Geometric shape.

(2) Surface roughness.

(3) Pore configuration.

(4) Inhomogeneity.

(5) Fillers.

(6) Anisotropy.

(7) Spectral vs diffuse.

(8) Angle of incidence and lobing.

(9) Laboratory specimens vs true samples.

d. Apparent inequality of spectral emittance to spectral absorptance for ablative chars.

e. Source development.

(1) Higher temperatures.

(2) Wider range of wavelengths.

f. Optics development.

(1) Diffraction gratings.

(2) Prisms.

(3) Filters for lower wavelengths.

g. Absorptance coefficient.

(1) Define adequately in relationship to porous surfaces.

h. Transmittance.

(1) Development of measuring equipment.

(2) Total vs diffuse.

i. Char profiling with reflectance measurements.

j. Hot-gas optical properties.

k. Light-pipe effects.

V. Mechanical Properties

As outlined below, mechanical properties cover all of the common properties used in structural analysis plus many of the structurally oriented tests investigating special failure mechanisms, e.g., shock, impact, etc.

A. Tensile and Compressive Strength and Modulus

1. Evaluation of measurement techniques.

a. Appropriateness to analysis requirements.

b. Environmental factors.

(1) Temperature.

(2) Pressure.

(3) Gaseous species.

(4) Heating rate.

c. Accuracy.

(1) Temperature level.

(2) Uniformity.

(3) Sample configuration.

(4) Loading.

(a) Rate.

(b) Load-cell sensitivity.

(c) Cell mounting.

(5) Strain measurement.

d. Biases.

(1) Equipment.

(2) Inherent model.

e. Standardization.

(1) Equipment.

(2) Sample materials.

(3) Specimen shape.

2. *Equipment or technique development.*

a. Expand temperature limits.

b. Automate operation and data recording.

c. Adapt for high-heating-rate tests.

d. Expand loading-rate capability.

e. Adapt for pyrolyzed samples.

f. Improve load-cell sensitivity.

g. Adapt for bidirectional-loading techniques.

h. Adapt for vacuum testing.

i. Adapt for testing during pyrolysis.

j. Improve strain-measuring devices.

3. *Special problems.*

a. High heating rate.

b. High loading rate.

c. In situ test.

(1) In vacuum.

(2) During pyrolysis.

d. Temperature.

(1) Low (to −200°F).

(2) High (to 7000°F).

(3) Creep during time at temperature.

(4) Cycling.

e. Stress concentration.

f. Investigation of flow and fracture behavior.

g. Investigation of bidirectional loading.

h. Material.

(1) Ablative state.

(2) Sample configuration.

(3) Strain sensitivity at high compensation.

(4) Ordering and pyrolytic deposition effects.

(5) Directional properties or anisotropy.

(6) Composites.

i. Investigation of applicability of normal analytical concepts.

(1) Relationship between yield strength and ultimate strength.

(2) Relationship between Young's, secant, and tangent modulus.

(3) Poisson's ratio.

(4) Elongation to failure.

B. Flexure Strength and Modulus

1. *Evaluation of measurement techniques.*

a. Appropriateness to analysis requirements.

b. Environmental factors.

(1) Temperature.

(2) Pressure.

(3) Heating rate.

c. Accuracy.

(1) Temperature level.

(2) Uniformity.

(3) Sample configuration.

(4) Loading.

(a) Rate.

(b) Sensitivity.

(5) Strain measurement.

d. Biases.

(1) Equipment.

(2) Inherent model.

e. Standardization.

(1) Equipment.

(2) Specimen configuration.

(3) Sample materials.

2. *Equipment or technical development.*

a. *Expand temperature limits.*

b. *Adapt for temperature gradient through thickness.*

c. *Automate operation and data recording.*

d. *Adapt for high-heating-rate tests.*

e. *Adapt for prepyrolyzed or partially pyrolyzed samples.*

f. *Adapt for vacuum testing.*

g. *Improve strain-measuring device.*

h. *Adapt for high loading rate.*

3. *Special problems.*

a. *Temperature.*

(1) Low (to −200°F).

(2) High (to 7000°F).

(3) Cycling.

(4) Creep.

(5) Test with temperature gradient through thickness.

b. *High heating rate.*

c. *High loading rate.*

d. *Material.*

(1) Pyrolyzed level.

(2) Anisotropy.

(3) Composites.

e. *In situ tests.*

(1) Vacuum.

f. *Sample configuration.*

(1) Three- vs four-point loading.

(2) Beam length.

(3) Beam width.

(4) Span-to-depth ratio.

C. Shear Strength and Modulus

1. ***Evaluation of measurement technique.***

a. *Appropriateness to analysis requirements.*

b. *Environmental factors.*

(1) Temperature.

(2) Vacuum.

c. *Accuracy.*

(1) Temperature level.

(2) Uniformity.

(3) Sample configuration.

(4) Loading.

(5) Strain measurement.

d. *Biases.*

(1) Equipment.

(2) Inherent model.

e. *Standardization.*

(1) Equipment.

(2) Specimen configuration.

(3) Sample materials.

2. *Equipment or technique development.*

a. *Short beam.*

b. *Torsion.*

c. *Plate shear.*

d. *Pin shear.*

e. *Aerodynamic shear.*

f. *Sandwich shear.*

g. *New techniques.*

(1) Char shear.

(2) During aerodynamic ablation.

3. *Special problems.*

a. *Identity of true shear test without tensile or compressive components.*

b. *Temperature.*

(1) Low (to −200°F).

(2) High (to 7000°F).

(3) Cycling.

c. Shear application.

(1) High rate.

(2) Aerodynamic.

d. Material.

(1) Pyrolyzed level.

(2) During ablation or after cooldown.

(3) Anisotropy.

(4) Composites.

e. In vacuum.

f. Relation of shear modulus to Young's modulus and Poisson's ratio.

D. Brittle Transition Temperature

1. Evaluation of measurement techniques.

a. Appropriateness to analysis requirements.

b. Environmental factors.

(1) Pressure.

(2) Rate of loading.

c. Accuracy.

(1) Temperature level.

(2) Uniformity.

(3) Sample configuration.

(4) Loading.

d. Biases.

(1) Equipment.

(2) Inherent model.

e. Standardization.

2. Equipment or technique development.

a. Differential thermal analysis.

b. Differential scanning calorimeter.

c. Expansion.

d. Torsional pendulum.

e. Penetration.

f. Electrical properties.

g. Thermal properties.

3. Special problems.

a. Physical identity of brittle transition temperature.

b. What brittle transition temperature measures.

(1) Change in polymer morphology.

(2) Cohesive energy density.

(3) Hindered rotation.

(4) Chain stiffness.

(5) Geometry variations.

(6) Toughness.

c. Material.

(1) Fillers and reinforcements.

(2) Pores.

(3) Internal lubricants.

d. Kinetics of transition.

E. Thermal Shock

1. Evaluation of alternate methods.

a. Appropriateness to analysis requirements.

b. Environmental factors.

(1) Heat.

(2) Cold.

(3) Pressure.

c. Accuracy.

(1) Initial temperature.

(2) Shock temperature.

(3) Rate of shock.

d. Biases.

(1) Equipment.

(2) Inherent method.

e. Standardization.

2. Equipment or technical development.

a. Extreme heating rates.

b. Extreme cooling rates.

3. *Special problems.*

a. *Meaningfulness of any test.*

b. *Relationship of results.*

(1) To tensile strength and modulus.

(2) To thermal expansion.

(3) To thermal conductance.

(4) To specific heat.

c. *Trapped volatiles.*

F. Impact and Micrometeoroid Penetration

1. ***Evaluation of measurement techniques.***

a. *Appropriateness to analysis requirements.*

b. *Environmental factors.*

(1) Temperature.

(2) Pressure.

(3) Fluid contact.

(a) Gas.

(b) Full oxidizer.

c. *Accuracy.*

(1) Ability to define sample dimensions.

(2) Temperature.

(3) Ability to measure loading.

d. *Biases.*

(1) Equipment.

(2) Inherent model.

e. *Standardization.*

2. ***Equipment development.***

a. *Izod.*

(1) Expand temperature limits.

(2) Automate operation and data recording.

(3) Adapt for vacuum testing.

(4) Increase impact rate.

b. *Charpy.*

(1) Expand temperature limits.

(2) Automate operation and data recording.

(3) Adapt for vacuum testing.

(4) Increase impact rate.

c. *Falling ball.*

(1) Expand temperature limits.

(2) Automate operation and data recording.

(3) Adapt for vacuum testing.

(4) Increase impact rate.

d. *Projectile guns.*

(1) Expand temperature limits.

(2) Automate operation and data recording.

(3) Adapt for vacuum testing.

(4) Increase impact rate.

e. *Mass accelerators.*

3. ***Special problems.***

a. *Temperature.*

(1) Low (to −200°F).

(2) Cycling.

b. *Impacting rate.*

c. *Material.*

(1) Pore structure.

(2) Filler.

(3) Reinforcement.

(4) Backup structure.

d. *Relationship to area under stress–strain curve.*

e. *Fuel sensitivity.*

(1) Liquid oxygen.

(2) Nitrogen oxides.

f. *In situ testing.*

(1) Vacuum.

(2) Other transit environments.

g. *Angle-of-incidence effects.*

h. *Ablator contamination.*

i. *Effect of penetration on thermal performance.*

j. *Shielding requirements.*

G. Peel Strength at Ablator–Structure Interface

1. *Evaluation of measurement techniques.*
   - a. *Appropriateness to analysis requirements.*
   - b. *Environmental factors–temperature.*
   - c. *Accuracy.*
     - (1) Temperature level.
     - (2) Uniformity.
     - (3) Measure of strains from all sources.
   - d. *Biases.*
     - (1) Equipment.
     - (2) Prestresses.
     - (3) Inherent model.
   - e. *Standardization.*
2. *Equipment or technique development needed.*
3. *Special problems.*
   - a. *Nature of structure.*
     - (1) Metallic vs nonmetallic.
     - (2) Original surface roughness.
     - (3) Surface preparation.
     - (4) Primer.
   - b. *Nature of adhesive.*
     - (1) Thickness and uniformity.
     - (2) Reinforcement.
     - (3) Rigidity.
   - c. *Nature of ablator.*
     - (1) Porous.
     - (2) Rigidity.
   - d. *Temperature.*
     - (1) Low (to −200°F).
     - (2) High (to 1000°F).

H. Virgin-Char–Interface Strength

1. *Equipment or technique development.*
   - a. *During ablation.*
   - b. *After cooldown.*
2. *Special problems.*
   - a. *In situ testing.*
   - b. *Combined stress sources.*
   - c. *Reinforcement contributions.*

I. Combined Strength of Ablator–Structure Composite

1. *Equipment or technique development.*
   - a. *Flexure test with superimposed thermal gradients and pressure.*
2. *Special problems.*
   - a. *Material considerations.*
     - (1) Flexibility.
     - (2) Interface compatibility.
     - (3) Charring.
     - (4) Structure selection.
   - b. *Dynamic damping effects.*
   - c. *Structural deformations.*
   - d. *Temperature gradients across thickness.*

J. Fatigue

1. *Equipment or technique development.*
   - a. *Low cycle–high strain.*
   - b. *High cycle–low strain.*

VI. Electrical Properties

The electrical properties of ablators are primarily concerned with signal transmission for altimeters or communications systems. For certain types of missions, staging operations and subsystem complication are decreased if antennas are built into the ablator–structure subsystem or look through it at the planet. To do this, the structure and heat shield must either be entirely transparent to the signal wavelength or must have compatible transparent windows built into the flight configuration. Signal attenuation before, during, and after ablation thus becomes important. A method of predicting this attenuation from basic composite electric properties is also desirable.

A. Signal Attenuation

1. *Comparison of alternate techniques.*
   - a. *Appropriateness to analysis requirements.*

b. Environmental limitations.

(1) Temperature.

(2) Vacuum.

(3) Gas species.

(4) Heating rate.

(5) Continuity of exposure.

c. Accuracy.

(1) Sample distortion.

(2) Waveguide design.

(3) Hot-gas attenuation.

(4) Contamination.

d. Biases.

(1) Equipment.

(2) Analytical model.

e. Standardization.

2. *Equipment development.*

a. Rotating disk with point or line heater.

(1) Expand heating-rate limits.

(2) Automate operation and data recording.

(3) Increase environmental-simulation capability.

(4) Increase frequency and wavelength range.

(5) Decrease exposure time per rotation.

b. Wedge in plasma arc.

(1) Expand heating-rate limits.

(2) Investigate other sample configurations.

(3) Improve sending–receiving units.

(4) Allow wider range of sources.

(a) G planar arrays, etc.

(5) Automate operation and data recording.

(6) Increase environmental-simulation capability.

c. Other.

3. *Special problems.*

a. Temperature.

(1) High (to 7000°F).

(2) Time at temperature.

b. Surrounding atmosphere.

(1) Vacuum and vacuum breakdown.

(2) Contamination.

c. Sample representativeness.

(1) Geometric shape.

(2) Ablation state.

(a) Virgin material.

(b) Partially pyrolyzed.

(c) Fully pyrolyzed.

(3) Thickness effects.

d. Optical.

(1) Wavelength.

(2) Incident angle.

e. Analytical determination of transmission properties from temperature profile and dielectric data as a function of temperature.

f. Develop facilities for microwave transmission under simulated ablation conditions.

g. Flight test.

B. Dielectric Properties

1. *Dielectric strength and dielectric constant.*

a. Short time vs step by step.

b. Frequency–to kilomegacycle region.

c. Temperature.

d. Vacuum.

e. Gaseous species.

2. *Volume and surface resistivity.*

3. *Power factor.*

4. *Loss tangent—less than 0.001.*

5. *Electrical conductance.*

VII. Degradation Kinetics Investigations

This section emphasizes the basic chemical processes involved in the degradation of pure and filled polymer systems. Mechanisms are stressed, and quantitative data may or may not be directly applicable to real ablative systems on reentry vehicles or in rocket nozzles.

A. Reaction-Energy Studies

1. *Comparison of alternate techniques.*
   - a. *Appropriateness to analysis requirements.*
   - b. *Environmental limitations.*
     - (1) Temperature.
     - (2) Pressure or vacuum.
     - (3) Gas species.
     - (4) Heating rate.
     - (5) Gas flow rate.
   - c. *Accuracy.*
     - (1) Temperature measurements.
     - (2) Sample mass and configuration.
     - (3) Heat losses.
     - (4) Endo- vs exothermal changes.
   - d. *Biases.*
     - (1) Equipment.
     - (2) Inherent model.
   - e. *Standardization.*

2. *Equipment or technique development.*
   - a. *Differential thermal analysis (DTA).*
     - (1) Expand temperature limits.
     - (2) Automate operation and data recording.
     - (3) Increase environmental-simulation capability.
     - (4) Investigate heating-rate effects.
     - (5) Investigate representativeness of specimens.
   - b. *Differential scanning calorimeter (DSC).*
     - (1) Expand temperature limits.
     - (2) Automate operation and data recording.
     - (3) Increase environmental-simulation capability.
     - (4) Investigate heating-rate effects.
     - (5) Investigate representativeness of specimens.

3. *Special problems.*
   - a. *Temperature.*
     - (1) Low (to −200°F).
     - (2) High (to degradation temperature or temperature range).
     - (3) Time at temperature.
     - (4) Rate of temperature change.
   - b. *Surrounding atmosphere.*
     - (1) Vacuum.
     - (2) Extreme pressure.
     - (3) Chemically active gaseous species.
     - (4) Gas flow rate.
   - c. *Sample representativeness.*
     - (1) Geometrical shape.
     - (2) Mass.
     - (3) Pretreatment.
     - (4) Inhomogeneity.
   - d. *Variations due to change in specimen-specified heat.*
   - e. *Variations due to change in thermocouple to sample thermal conductance.*
   - f. *Derivation of heat of pyrolysis from data.*
     - (1) Identification of baseline.
     - (2) Standards.
     - (3) Area under exo- or endotherm.
   - g. *Sublimation-energy studies.*
   - h. *Liquid and gas studies.*

B. Reaction-Rate Studies—Thermogravimetric Analysis (TGA)

1. *Comparison of alternate techniques.*
   - a. *Appropriateness to analysis requirements.*
   - b. *Environmental limitations.*
     - (1) Temperature.
     - (2) Pressure or vacuum.
     - (3) Heating rate.

(4) Gaseous species.

(5) Gas flow rate.

c. *Accuracy.*

(1) Temperature measurement.

(2) Heat balance.

(3) Furnace temperature gradients.

(4) Sample configuration.

(5) Sample-holder configuration.

(6) Buoyancy effect.

(7) Humidity effect.

(8) Weight-loss measurement.

(9) Time identification.

d. *Biases.*

(1) Equipment.

(2) Inherent model.

e. *Standardization.*

2. ***Equipment or technique development.***

a. *Establish differences.*

(1) Isothermal.

(2) Constant temperature rise.

(3) Constant heating rate.

b. *Automate operation and data recording.*

c. *Adapt for high-heating-rate investigations.*

d. *Investigate effect on kinetics of specimen seeing hot wall vs specimen seeing cold wall.*

e. *Investigate furnace-configuration effects.*

3. ***Special problems.***

a. *Difference between isothermal, constant-temperature-rise, and constant-heating-rate methods.*

b. *Rate mechanisms under high heating rates.*

c. *Specimen representativeness.*

(1) Size and shape effects.

(2) Powder vs film vs block.

(3) Diffusion dependence.

(4) View temperature.

(5) Pretreatment.

d. *Comparison with DTA and DSC.*

e. *Correlation with char elemental analysis.*

f. *Correlation with electrical conductance.*

C. Species and Reaction Identification

1. ***Evaluation of techniques.***

a. *Appropriateness to analysis requirement.*

(1) Gas chromatograph.

(2) Mass spectrometer.

(3) Time-of-flight mass spectrometer.

(4) Infrared spectrometry.

b. *Environmental limitations.*

(1) Temperature.

(2) Pressure.

(3) Species.

c. *Accuracy.*

(1) Discrimination.

(2) Area under curves.

(3) Pyrolysis representativeness.

(4) Second reactions or effects.

d. *Biases.*

(1) Equipment.

(2) Inherent model.

e. *Standardization.*

2. ***Equipment or technique development.***

a. *Gas chromatograph.*

(1) Evaluate control parameters.

(a) Carrier gas and flow rate.

(b) New column materials and column length.

(2) Improve pyrolysis method.

(3) Compare detection systems.

(a) Flame ionization.

(b) Conductivity cell.

(4) Develop elevated temperature columns.

(5) Improve discrimination.

(6) Investigate H_2 and H_2O detectability.

(7) Automate operation and data recording.

b. Mass spectrometer.

(1) Evaluate control parameters.

(a) Carrier gas and flow rate.

(b) Ionization voltage.

(c) Pressure.

(2) Improve pyrolysis method.

(a) Wire.

(b) Knudesen cell.

(c) Other.

(3) Improve quantitative identification.

(4) Automate operation and data recording.

c. Infrared spectrometry.

3. Special problems.

a. Postcracking of gases on adjacent hot walls.

b. Repolymerization transients.

c. Condensation of evolved gases in cooler regions.

d. Pyrolysis representativeness.

(1) Heating-rate effects.

(2) Specimen-configuration effects.

(3) Heating-method effects.

e. Mass balance.

f. Coupling of gas chromatograph and mass spectrometer.

D. Secondary Reactions

1. Cracking and pyrolytic deposition.

a. Equipment development.

(1) Temperature dependence.

(a) Gas.

(b) Surface.

(c) Rise rate.

(2) Pressure dependence.

(3) Leakage limitations.

(4) Species-handling capability.

(a) Inertness.

(b) Tagged.

(5) Porosity effects (choking).

(6) Gas flow rate.

(7) Definition of adequate facility.

(8) Weight pickup.

(9) Analysis of deposited material.

(10) Mass balance.

b. Special problems.

(1) Establishment of magnitude of cracking effect on heat balance.

(2) Investigation of interaction of cracking with porosity.

(3) Investigation of interaction of cracking with conductance.

(4) Pyrolysis-product-mixture cracking vs cracking of individual species.

(5) Cracking in porous carbon or graphite chars vs cracking in porous-silica chars.

(6) Test representativeness.

(a) Temperature gradient.

(b) Species.

(c) Gas flow rate.

(d) Catalysity.

(e) Path length.

(7) Mechanism and kinetics of cracking process.

(8) Investigation of interaction of cracking with mechanical strength.

(9) Development of computer model.

2. Carbon–silica reactions.

a. Equipment development.

(1) Temperature dependence.

(2) Definition of adequate facility.

b. Special problems.

(1) Establish effect on char conductance.

(2) Establish effect on char mechanical strength.

(3) Establish mechanism of reaction and further vaporization.

(4) Catalysis by presence of transition-metal compounds.

3. Carbon–CO_2 and carbon–H_2O reactions.

a. Special problems.

(1) Meaningful facility.

(2) Magnitude of effect on heat balance.

E. Heat of Combustion

1. Comparison of alternate techniques.

a. Appropriateness to analysis requirements.

2. Equipment or technique development.

a. Parr bomb calorimeter.

3. Special problems.

a. Analysis of char variations.

b. Analysis of variations in effective heat of combustion using simulated planetary atmospheres.

c. Combustion of reinforced plastics.

d. Ash analysis (from combustion products).

F. Flammability

1. Comparison of alternate techniques.

a. Appropriateness to analysis technique.

2. Equipment or technique development.

a. ASTM methods.

b. Radiant heaters.

c. Plasma-arc adaptation.

3. Special problems.

a. Investigate control parameters.

(1) Temperature.

(2) Pressure.

(3) Atmospheric species.

(4) Evolved species.

(5) Catalysis.

(6) Gas phase vs surface.

(7) Stream velocity.

(8) Diffusion.

(9) Convective cooling.

b. Establish flammability criteria.

(1) Burning rate.

(2) Self-extinguishing.

G. Diffusion Constants for Gases

1. Equipment or technique development.

2. Special problems.

a. Temperature.

b. Use in ablation analysis.

c. Thermal diffusion vs gas diffusion.

VIII. Pre-entry Environmental Compatibility Tests

Tests to evaluate the performance degradation in ablative composites caused by pre-entry environmental exposure are especially important in planetary-entry missions. Exposure to foreign chemicals and long exposure to vacuum and space radiation greatly affect some polymeric materials and composites.

A. Chemical Resistance

1. Definition of problem.

a. Fuels and oxidizers spilled during tank filling.

(1) N_2O_4.

(2) Hydrazine and derivatives.

(3) Diborane B_2H_6.

b. Vapor leakage during long-time storage for a propulsive lander.

2. Test development.

a. Change in chemical nature.

b. Change in properties required at a later time.

B. Sterilization

1. Comparison of alternate methods.

a. Appropriateness to analysis requirements.

2. Equipment or technique development.

a. Chemical surface decontamination.

(1) Decontaminate.

(a) Ethylene oxide.

(b) Other.

(2) Carrier gas.

(a) Freon 12.

(b) CO_2.

(c) Other.

(3) Temperature control.

(4) Humidity control.

(5) Concentration control.

b. Dry-heat sterilization.

(1) Effluent.

(a) Nitrogen.

(b) Other.

(2) Temperature control.

(3) Heatup and cooldown ramps.

3. Special problems.

a. Long-term degradation by retained chemical decontaminant.

b. Effect of dry-heat sterilization on retained chemical decontaminant.

c. Redeposition of volatiles during cooldown phase.

d. Explosive hazard.

e. Sterile assembly.

f. Biological vents or feedthroughs.

g. Freon 12 a solvent for fluorocarbons.

C. Vibration

1. Special problems.

a. Brittle behavior at launch conditions.

b. Brittle behavior while cold in space under midcourse propulsion correction or injection into planet.

D. Rapid Pumpdown

1. Special problems.

a. Ability of low-density ablators to withstand a sudden decrease in external pressure without exploding or cracking because of entrapped gases.

E. Vacuum Compatibility

1. Comparison of alternate techniques.

a. Appropriateness to analysis requirements.

b. Environmental limitations.

(1) Vacuum level.

(2) Temperature.

(3) Time.

c. Accuracy.

(1) Weight-change sensitivity.

(2) Temperature rise rate and level control.

(3) Vapor pressure.

(4) Vacuum level.

(5) Diffusion rate.

(6) Prior conditioning.

d. Biases.

(1) Equipment.

(2) Inherent model.

e. Standardization.

(1) Equipment.

(2) Samples.

2. Equipment or technique development.

a. Vacuum balance.

(1) Quartz-crystal balance.

(2) Dimensional-change monitoring.

(3) Coupling with species identifiers.

b. Microvolatile condensible material tests.

(1) Screening only.

(2) Establish prior temperature level for sample and plate.

(3) Establish proper pressure level for standard materials.

(4) Lower vacuum-level capability.

c. Macrovolatile condensible material tests.

(1) Establish proper sample size and shape.

(2) Investigate diffusion dependence.

(3) Investigate secondary evaporation from cold plate.

(4) Establish proper temperature level for sample and plate.

(5) Lower vacuum-level capability.

3. Special problems.

a. Investigate effects of condensibles.

(1) On optical properties.

(2) On electrical properties.

b. Investigate vacuum-loss effects.

(1) On mechanical properties.

(2) On conductance.

F. Radiation Resistance

1. Comparison of alternate techniques.

a. Appropriateness to analysis requirements.

2. Equipment or technique development.

a. Source development.

3. Special problems.

a. Space radiation.

(1) Particle vs ultraviolet.

(2) Synergistic effects.

(3) Temperature at radiation.

(4) Kinetics of radiation degradation.

(5) Effects of additives and protective agents.

(6) Combined with TGA.

(7) With *in situ* mechanical properties.

b. Nuclear radiation.

(1) Dose requirement.

(2) Temperature.

(3) Additives and protective agents.

(4) With *in situ* mechanical properties.

IX. Entry-Simulator Development

To simulate entry, the time histories of pressure, heating rate, and enthalpy must be matched in the specific planetary gaseous composition. These must be matched on a specimen that has been both exposed to an identical pre-environment and so manufactured that flight shape and size are directly simulated. Radiant heaters are needed that span heating ranges from 1 to 10^6 Btu/ft^2/s (for certain Jupiter entries). Convective heaters are needed to produce a wide range of heating rates, pressures, and enthalpies. Combinations of these two types of heat source must be coupled with each other and with various degrees of exposure to pre-entry environments.

A. Plasma-Arc Facility Development

1. Arc-configuration development.

a. Types of arc.

(1) Ring.

(2) Constricted.

(3) AC.

(4) Gerdien.

(5) Vortex or aerodynamically stabilized.

(6) Magnetically stabilized.

(7) Regenerative.

(8) Transpiration cooled.

(9) Inductive.

(10) Other.

b. Limitations.

(1) Electrode materials.

(2) Electrode shape and location.

(3) Flow.

(4) Power: towards 300 MW.

(5) Size.

(6) Cooling system.

(7) Energy-transfer efficiency: 1000 to 100,000 Btu/lb.

(8) Pressure: 10^{-6} torr to 200 atm.

(9) Working fluid species: air, CO_2, N_2, O_2, H_2, Ar, CH_4, He, etc.

(10) Calibration.

c. *Starting techniques.*

(1) Jumpwire.

(2) Vacuum.

(3) Touch.

(4) High frequency.

(5) Capacitive discharge.

d. *Special problems.*

(1) Energy-transfer mechanisms.

(2) Transport properties of gases.

(3) Radiation loading.

(4) Arc-column studies.

(5) Size scaling.

(6) Reactive working fluid.

(7) High enthalpy in high-working-fluid flow rates.

(8) Difference in energy distribution in inductive arc vs other arcs.

(9) Enthalpy pulsing.

(a) Power.

(b) Flow.

(10) Simultaneous increase in heating rate and pressure.

2. ***Power source development.***

a. *DC types.*

(1) Batteries.

(2) Dynamo.

(3) Moving-coil or core-controlled rectifier.

(4) Saturable-core-reactor-controlled rectifiers.

(5) Silicon-controlled rectifiers.

b. *Special problems.*

(1) Ripple.

(2) Power-factor correction.

(3) Control speed and flexibility.

(4) Component life.

(5) Control for multiple arcs.

(6) Control feedback for pulsing enthalpy.

3. ***Exhaust configuration.***

a. *Types.*

(1) Sonic nozzles.

(2) Supersonic nozzles.

(3) Mixing chambers.

(4) Multiple-arc mixing.

(5) Dual ducts.

(6) Turbulent ducts.

(7) Shrouding.

(8) Two-dimensional shear nozzles.

(9) Rectangular nozzles.

b. *Special problems.*

(1) Mixing uniformity.

(2) Reproducibility.

(3) Coring.

(a) Central.

(b) Donut.

(4) Mach-number control: 1 to 20.

(5) Shock-diamond location and control.

(6) Turbulence.

(a) Intensity level.

(b) Initiation control.

(c) Test-specimen meaningfulness.

(7) Stream contamination.

(8) Arc radiation.

(9) Coupling plasma heads to produce high shear (to 300 lb/ft^2).

4. ***Exhaust-species removal and static-pressure control.***

a. *Pumping system development.*

(1) Mechanical pump—booster systems.

(2) Steam-ejector systems.

(3) Control-valve sensitivity improvement.

(4) Diffusers.

(5) Heat exchangers.

(6) Air-ejector systems.

b. *Special problems.*

(1) Backfilling without changing exhaust uniformity.

(2) Pressure balance between nozzle exit and chamber.

(3) Pressure pulsing at sample surface.

5. ***Sample-injection-mechanism development.***

a. *Types.*

(1) Linear.

(2) Angular.

b. *Limitations.*

(1) Speed of entrance and exit.

(2) Oscillations.

(3) Recession compensation.

(4) Scanning speed and sensitivity.

c. *Special problems.*

(1) Three-dimensional scanning.

(2) Easy-access and simple model switching methods.

(3) Multiple-precision insertion.

(4) Recession compensation and rate-measuring system.

(5) Protection of model in stowed position.

6. ***Sample configuration development.***

a. *Types.*

(1) Flat-faced probe.

(2) Isothermal-surface probe.

(3) Hemispherical probe.

(4) Special-curvature probe with shroud.

(5) Flat plate.

(6) Cone.

(7) Wedge.

(8) Cylindrical pipe.

(9) Channel.

(10) Complex combinations.

b. *Limitations.*

(1) Size.

(2) Guarding.

(a) Side.

(b) Rear.

c. *Special problems.*

(1) Temperature measurement and sensor mounting.

(a) Rear surface.

(b) Internal.

(2) Subsonic vs supersonic configurations.

7. ***Readout instrumentation development.***

a. *Recorder–computer–plotter system.*

b. *Special problems.*

(1) Recorder speed.

(2) Shortening return time on plots.

B. Radiant-Heater Facility Development

1. ***Filament lamps.***

a. *Types.*

(1) Tungsten-filament tubes.

(2) Quartz.

b. *Limitations.*

(1) Filament life.

(2) Low heating rates (less than 200 Btu/ft^2/s).

(3) Time limitation on pulsing.

(4) Venetian-blind effect of heating distribution.

c. *Special problems.*

(1) Lamp arrangement for large specimens.

(2) Integration into coupled system.

2. *Carbon-arc imaging furnace.*

a. *Types.*

(1) By mirrors.

(a) Parabolic.

(b) Ellipsoidal.

(c) Spherical.

(2) By electrodes.

(a) Opposing dc.

(b) Carbon-vapor-lamp ac.

b. *Limitations.*

(1) Carbon-electrode lifetime.

(2) Mirror imperfections.

(3) Electrode splatter.

(4) Source-shape irregularity.

(5) Time fluctuations.

(6) Shadowing.

(7) Low heat fluxes.

c. *Special problems.*

(1) Degradation kinetics in a controlled environment.

3. *Solar-furnace limitations.*

(1) Sun dependence and time fluctuations.

(2) Mirror imperfections.

(3) Tracking accuracy.

4. *High-pressure compact arcs.*

a. *Types.*

(1) Clear-glass spherical or ellipsoidal envelope.

(2) Metal cavity.

(3) Mercury, xenon, CO_2, or combinations.

b. *Limitations.*

(1) Poor flux distribution.

(2) Inefficiency.

(3) Low flux.

c. *Special problem.*

(1) Defining useful range.

5. *High-pressure vortex-stabilized plasma arcs.*

a. *Types.*

(1) By working fluid.

(a) Xenon.

(b) Neon.

(c) Argon.

(d) N_2.

(e) CO_2.

(2) By electrode configuration.

(a) Opposing.

(b) Concentric.

(3) By optics.

b. *Limitations.*

(1) Electrode configuration and lifetime.

(2) Mirror.

(a) Lifetime.

(b) Imperfections.

(c) Clouding.

(d) Cooling.

(3) Pressure efficiency.

(4) Container strength.

(a) Body.

(b) Window.

(5) Focusing lens or window.

(a) Imperfections.

(b) Strength.

(c) Clouding.

(d) Transmission characteristics.

(e) Cooling.

(6) Size.

(a) Arc.

(b) Optics.

(7) Heat flux (maximum).

(8) Spectral characteristics.

(a) Wavelength.

(b) Distribution.

(c) Blockage.

(9) Starting.

(a) Touch.

(b) High frequency.

(10) Power.

c. Special problems.

(1) Optical materials.

(2) Column efficiency vs brightness.

(3) Shape vs brightness.

(4) Dousing.

(5) Remote calibration.

6. Laser.

a. Limitations.

(1) Preheater.

(a) Size.

(b) Fuel.

(2) Power.

(a) Capability.

(b) Efficiency.

(3) Optics.

(a) Focusing.

(b) Mirrors and lenses (to four decimal points).

(4) Wavelength – CO_2.

(5) Sample size and shape.

(6) Time stability.

(7) Lateral flux gradient.

b. Special problems.

(1) Extension to other wavelengths.

(2) Scaling size.

7. Peripheral equipment development for low-shear environment.

a. Species removal and static-pressure control. (See IX-A-4, above.)

b. Sample configuration development. (See IX-A-6, above.)

c. Readout instrumentation. (See IX-A-7, above.)

8. General problem areas.

a. Heat flux.

(1) Uniformity with time.

(2) Uniformity over surface.

(3) Accurate calorimetry.

b. Pressure and evolved-gas removal.

(1) Control at sample surface from 10^{-6} torr to 100 atm.

(2) Surface blowing or splatter.

(3) Window fogging.

c. Specimen temperature.

(1) Internal and lateral gradients.

(2) Surface-temperature determination.

(3) Optical-property changes.

d. Surface recession.

(1) Irregularities.

(2) Subsurface vaporization.

(3) Change in calibration from splatter.

e. Radiation transfer.

(1) Wavelength distribution of source.

(2) Attenuation by pyrolysis-production absorption.

(3) Subsurface vaporization.

f. Optics.

(1) Mirrors.

(2) Lenses.

(3) Windows.

C. Radiant Heater Coupled With Cold-Gas Flow for Shear Simulations

1. Validity of aerothermal-simulation concept.

a. Heating rate.

(1) Radiative simulation of convective heating.

(2) Wavelength effects.

(3) Variations caused by local erosion.

b. Flow field.

(1) Inequivalence of local pressure gradients.

(2) Inequivalence of local temperature gradients.

(3) Local erosion effects.

2. Need for development and verification of an analytical model.

D. Convective–Radiative Heater Coupling

1. Plasma arc—arc-imaging furnace.

a. Special problems.

(1) Optics.

(a) Donut effect in radiant image.

(b) Clouding and splatter.

(c) Focusing quality.

(2) Specimen.

(a) Size limitations.

(b) Shape limitations.

(3) Diagnostics.

(a) Heating-rate determination.

(b) Surface-temperature determination.

(4) Pulsing control.

2. Plasma arc—high-pressure plasma-arc radiators.

a. Special problems.

(1) Optics.

(a) Focusing quality.

(b) Clouding and splatter of mirrors and lenses.

(c) Wide incident angle.

(2) Specimen.

(a) Size limitations.

(b) Shape limitations.

(3) Diagnostics.

(a) Heating-rate determinations.

(b) Surface-temperature determination.

(4) Pulsing control.

3. Plasma arc—plasma-arc radiant source.

a. Special problems.

(1) Ratio of one heating rate to the other difficult to control.

(2) Specimen size and shape limitations.

(3) Diagnostics.

E. Other Heater Sources

1. Oxyacetylene torch.

a. Limitations.

(1) Low enthalpy.

(2) Chemical-reactivity differences.

b. Special problems.

(1) Evaluation of thermostructural compatibility.

(2) Shear tests.

(3) Comparison with plasma-arc data.

(4) Validity of simulation.

2. Pebble-bed heater and porous-resistance heaters.

a. Limitations.

(1) Low enthalpy.

(2) Time-variant enthalpy.

b. Special problems.

(1) Long-time, low-heating-rate tests on comparatively large specimens.

3. ***Rocket test facility.***

   a. *Limitations.*

      (1) Low enthalpy.

      (2) Pressure control coupled.

      (3) Lack of gas-composition simulation.

   b. *Special problems.*

      (1) Evaluation of thermostructural compatibility.

      (2) Scaling to larger sizes possible.

4. ***Wave superheater.***

   a. *Limitations.*

      (1) Small specimen size.

      (2) Poorly defined environment (discontinuous heat pulses).

      (3) Uninterpretable surface gradients.

   b. *Special problems.*

      (1) High-pressure effects.

5. ***Magneto accelerators in combination with plasma arcs.***

   a. *Limitations.*

      (1) Acceleration not uniformly applied.

      (2) Inefficiency.

6. ***Shock tunnels.***

   a. *Limitations.*

      (1) Short test duration.

      (2) Small specimen size for Reynolds-number simulation.

      (3) Pressure range not simulated.

   b. *Special problems.*

      (1) Validity of simulation.

      (2) Transient model behavior.

7. ***Free-flight range.***

   a. *Limitations.*

      (1) Small specimen size.

      (2) Short test duration.

   b. *Special problems.*

      (1) Impact destruction of model for postanalysis instrumentation.

8. ***Nuclear explosions.***

   a. *Limitations.*

      (1) Short test duration.

   b. *Special problems.*

      (1) Jupiter entry.

X. Entry-Simulator Testing

If suitable entry simulators are available, much can be done to delineate theoretical concepts in ablation technology, as well as to provide specific information on material performance in simulated missions. Mars, Venus, and Jupiter each presents individual problems in simulation.

A. General Studies

1. ***Boundary layer.***

   a. *Boundary-layer structure.*

   b. *Interaction with ablation recession.*

   c. *Gaseous combustion with evolved ablation products.*

2. ***Surface oxidation.***

   a. *Reaction-rate limited.*

      (1) Air.

      (2) CO_2.

   b. *Diffusion-rate limited—air.*

   c. *CO_2–N_2 equivalent to air.*

   d. *Effect of other species.*

      (1) Argon.

      (2) Water.

3. ***Other reactions.***

   a. *Nitration.*

   b. *CH_4, NH_3, He, and H_2 atmospheres.*

   c. *Other gases.*

4. Sublimation.

a. Heating-rate limits.

b. Pressure effects.

5. Blocking.

a. Blowing studies—concentric calorimeters and specimens.

b. Radiation-absorption studies.

6. Standardization.

a. Interfacility correlation.

b. Shape standardization.

c. Definition of minimum stream and specimen calibration.

7. Radiation effects.

a. Gas-cap emittance and absorption.

(1) Various gases.

(2) Ablation products.

b. Gas-cap spectral distribution effects on ablator response.

8. Scaling studies.

9. Surface-roughness effects.

a. Turbulence tripping.

b. Surface-temperature determination.

10. RF transparency during ablation.

11. In situ testing.

a. After long exposure to vacuum.

b. After sterilization.

c. With simulated micrometeoroid damage.

d. With cold models.

e. After exposure to nuclear radiation.

12. Effects of joints, cracks, protuberances, holes, and erosion on ablative heat transfer with radiation.

B. Specific Studies

1. Mars.

a. Material response to integrated Mars transit and entry environment.

(1) Out of orbit (peak heating <100 Btu/ft^2/s).

(2) Direct entry (peak heating <500 Btu/ft^2/s).

b. Scaling tests.

(1) Plasma arc to 24-in. diam.

(2) Radiant heaters to 20-ft diam.

c. CO_2 combustion equivalence.

2. Venus.

a. Material response to Venus entry.

(1) Low angle, low ballistic coefficient, low velocity.

(2) High-energy entry.

b. CO_2 combustion equivalence.

c. Sublimation regime.

(1) CO_2 effects.

(2) Pressure effects.

d. Laser applicability.

e. Applicability of direct-arc exposure.

f. Ground test-simulation limits.

3. Jupiter.

a. Correlation of atomic-blast data with entry-material response.

b. Development of analytical model spanning heating rates from 10,000 to 60,000,000 Btu/ft^2/s.

XI. Diagnostic Instrumentation Development

Exotic test equipment is only as good as the ability to define the environment produced by the equipment and the response of the test material to that environment.

A. Calorimetry

1. Types.

a. Absolute.

b. Slug.

c. *Thin foil.*

d. *Gardon.*

e. *Null.*

f. *Bimetal-wafer stacks.*

g. *Radiometer.*

h. *Other.*

2. ***Limitations.***

a. *Reads average of a distributed flux.*

b. *Window transmission and contamination.*

c. *Two- and three-dimensional effects.*

(1) Shape.

(2) Lateral heat flow.

d. *Heating-rate maximums.*

e. *Surface-temperature differences.*

f. *Catalytic behavior.*

g. *Electrical interaction.*

h. *Calibration.*

i. *Response time.*

3. ***Special problems.***

a. *Stream property influence.*

(1) Velocity gradients.

(2) Contaminants.

(3) Thermal distribution.

(4) Gas composition.

b. *Calibration technique.*

(1) Measurement standard.

(2) Validity of analytical technique.

(3) Reproducibility.

c. *Blocking effects.*

d. *Contamination probe.*

e. *Concentric calorimeters.*

f. *Wall calorimeters.*

B. Stream Pressure

1. ***Sensor type.***

a. *Transducer.*

b. *Manometer.*

c. *Other.*

2. ***Limitations.***

a. *Response time.*

b. *Orifice size and shape.*

c. *Probe configuration.*

d. *Temperature-gradient effects.*

e. *Frequency.*

f. *Noise.*

3. ***Special problems.***

a. *Separation of static and dynamic pressure.*

b. *Pitch and yaw effects.*

c. *Pressure on ablating models.*

C. Stream Enthalpy

1. ***Methods and limitations.***

a. *Energy balance.*

(1) Small temperature rises magnify importance of measurement errors.

(2) Average enthalpy only.

b. *Fay–Riddell reverse calculation.*

(1) Model inaccurate for highly ionized flows.

(2) Must have accurate pressure and heating-rate measurements.

c. *Sonic flow.*

(1) Basic and equilibrium method.

(2) Extrapolatible to frozen and nonequilibrium flow.

(3) Requires plenum chamber.

(4) Rotational flow negates pressure measurements.

d. *Total collection.*

(1) Unwieldy.

(2) Inaccurate.

e. Tare probes.

(1) Good for high enthalpies.

(2) Split flow vs standard.

(3) Guarding techniques critical.

(4) Analytical model questionable.

(5) Measurement tolerances large.

(6) Interjacket heat transfer.

(7) Equal heating outside and inside.

f. High-sensitivity, stagnation-point probe.

(1) Two mutually insulated jackets.

(2) Comparatively large size.

g. Shock-swallowing probe—low-density, low-heat-flux only.

h. Transient fast-response probe.

2. Special problems.

a. Coring and enthalpy distribution.

b. Very high enthalpies and pressures.

c. Difference in needs for super- and subsonic probes.

D. Flow-Field Analysis

1. Measurement techniques.

a. Probes.

(1) Langmuir.

(2) Electrostatic.

(3) Hall effect.

(4) Magnetic.

b. Optical.

(1) Spectroscopy.

(2) Electron beam.

(3) Microwave.

(4) Ultrasonics.

(5) Schlieren.

(6) Interferometer.

(7) Laser.

(8) Optical and nuclear tracers.

2. Important parameters.

a. Mach number.

b. Local density and pressure distribution.

c. Mass-flow distribution.

d. Ionization level and distribution.

e. Temperature distribution.

f. Electrical conductivity.

3. Limitations.

a. Measurement tolerances.

b. Validity of analytical model.

4. Special problems.

a. Shock interactions.

b. Chemical state.

(1) Frozen.

(2) Equilibrium.

(3) Nonequilibrium.

c. Tank and probe interference.

d. Rotational flow and vorticity.

e. Imbalance of energy states relative to equilibrium.

(1) Translational.

(2) Rotational.

(3) Vibrational.

(4) Electronic.

E. Material-Response Data

1. Internal temperature.

a. Thermocouples.

(1) Initial calibration and drift.

(2) Cold junction.

(3) Connections to external components.

(4) Sensitivity to stray currents or magnetic fields.

b. Resistance thermometers.

(1) Thin film.

(2) Location along isothermal surface.

(3) Size disruption of local temperature field.

(4) Contact resistance.

2. ***Internal density.***

a. *Postanalysis.*

(1) Thin-slice representativeness.

(2) Loss of transient nature.

b. *X-ray.*

(1) Averages over thickness.

(2) Flat isothermal surfaces necessary in depth.

3. ***Surface temperature.***

a. *Methods.*

(1) One-color pyrometry.

(2) Two-color pyrometry.

(3) Total-radiation pyrometry.

(4) Spectrographic.

b. *Limitations.*

(1) Optical properties must be known.

(2) Model assumes nonrough surface.

(3) Gas-cap contributions.

(4) Arc reflections.

(5) Readout sensitivity.

c. *Special problems.*

(1) Surface-roughness effects.

(2) Relationship to computer-node model.

4. ***Surface recession and mass-loss rate.***

a. *Methods.*

(1) Tare weights and dimensions.

(2) Camera.

(3) X-ray.

b. *Limitations.*

(1) Isothermal surfaces not flat.

(2) Transient effects.

c. *Special problems.*

(1) Model drive system.

(2) Contamination effects from electrode and gas.

(3) Lateral motion of material along surface.

5. ***Photographic records of surface phenomena.***

(1) Roughness effects.

(2) Lateral flow.

(3) Erosion-irregularity records.

XII. Flight Test

Earth flight tests can hardly ever be made to completely duplicate planetary-entry flight trajectories. Differences in atmospheric-universe scale height could be adequately handled, except that atmospheric-composition variations make it impossible to duplicate the actual chemical kinetics of the material response. Mars out-of-orbit entry is an exception to this because heat loads are low and combustion kinetics do not play a significant part. On the other hand, the degree (or range) of severity can mostly be simulated without regard to the relative balance of energy-absorbing mechanisms (except in the case of direct Jupiter entry). In this way, the analytical techniques can be exercised to increase confidence in their use for predicting performance in severe, nonearth-simulatible environments without an exact simulation of the hypothesized flight.

A. Earth Simulation of Mars Entry

1. ***Out of orbit.***

a. *Matching of all parameters possible.*

2. ***Direct entry.***

a. *Convective heating and pressure good.*

b. *Radiative duplication possible with shape manipulation.*

c. *Combustion duplication poor.*

B. Earth Simulation of Venus Entry

1. ***Lower-energy entries.*** These are not simulated because of the large dependence of material performance upon combustion.

2. ***Higher-energy entries.*** These are somewhat more simulatible because most of the ablation response is in the sublimation regime, which is not greatly dependent upon external species.

3. ***Degree of severity.*** This can always be tested to exercise analytical techniques and to increase confidence.

C. Earth Simulation of Jupiter Entry

1. ***Difficult to impossible at this time.***

D. Special Problems

1. ***Scale vs full size.***
   a. *Size contribution.*
   b. *Shape contribution.*
2. ***Flight instrumentation.***
   a. *Thermocouples and thermistors.*
   b. *Heat pipes.*
   c. *Break wires.*
   d. *Radioactive recession gages.*
   e. *Calorimeter.*
   f. *Pressure transducers.*

XIII. Rocket-Nozzle Testing

This area is discussed primarily because of the close relationship in technology utilization between entry heat shields and rocket-nozzle heat shields. Planetary uses of the rocket-nozzle heat shield are primarily centered around smaller systems for midcourse guidance, orbital or planetary injection, attitude control, or soft-landing touchdown. This section is not nearly as complete as the other sections, and is not intended to be. Its inclusion is meant, again, to emphasize the technology application to both fields.

A. Motor Liner or Combustion Chamber

1. ***Material systems.***
   a. *Structures for solids.*
      (1) Molded.
      (2) Tape-wrapped.
      (3) Filament-wound.
   b. *Structures for liquids.*
      (1) Metallic.
      (2) Molded carbon.
      (3) Composite.
   c. *Insulations.*
      (1) Foam.
      (2) Multilayer.
      (3) Powder with container.
2. ***Performance limits.***
   a. *Total heat load.*
   b. *Pressure containment.*
3. ***Special problems.***
   a. *Injector-erosion pattern.*
   b. *Chamber-design effects.*
      (1) Standard.
      (2) Submerged nozzle.
      (3) Solid-hole pattern.

B. Throat and Throat Inlet

1. ***Material systems.***
   a. *Ablative.*
      (1) Molded-glass or carbon-cloth laminate.
      (2) Tape-wrapped laminate.
      (3) Graphite.
      (4) Prepyrolyzed composites.
      (5) Special fillers.
      (6) Silica-impurities effects.
      (7) High and low silica–carbon ratios.
      (8) Three-dimensional reinforcements.
   b. *Metallic.*
      (1) Coated or uncoated.
      (2) Filled porous.
2. ***Performance limits.***
   a. *High pressures.*
   b. *Long times.*
   c. *Fuel dependence.*
3. ***Special problems.***
   a. *Minimizing shape changes.*

b. Restart.

c. Submerged nozzles.

C. Exit Cone

1. *Materials.*

a. Metallic or graphite, radiation cooled.

b. Ablative.

(1) Molded.

(2) Tape-wrapped.

2. *Special problems.*

a. Nozzle-expansion ratio.

b. Turbulent tripping.

D. Test Stands

1. *Liquid.*

a. Dimensions.

b. Fuel-to-oxidizer ratio.

c. Chamber-pressure control.

d. Injector pattern.

e. Run duration and restart.

2. *Solid.*

a. Dimensions.

b. Fuel.

(1) Polymeric.

(2) Metallized.

c. Chamber-pressure control.

d. Propellant configuration.

e. Run duration.

3. *Plasma arc.*

a. Working fluid simulates combustion-produced gases.

XIV. Resin Development

Resin systems can be tailored to a wide variety of requirements by combining complementary systems or by building molecules to provide specific properties. Although it is possible to use existing polymers, new resin systems can potentially provide a wider variety of design solutions for future needs.

A. Clean-Characterized Polymer Standards

1. *Polymers.*

a. Silicone elastomer.

b. Phenolic.

c. Epoxy.

d. Epoxy Novalac.

e. Polyimide.

f. Polybenzimidazole.

2. *Characteristics.*

a. Variations. Two or three variations of each type are desirable, as follows:

(1) One should be the simplest, most reproducible molecule possible of its type.

(2) One should be representative of a common-usage variety.

(3) One should be representative of a high-temperature, high-performance variety.

b. Reproducibility in time should be stressed.

c. Amount of testing necessary to characterize each resin must be determined rigorously.

B. New High-Temperature Resin

1. *Improved phenolics.*

a. 2,7-Naphthalenediol: Formaldehyde.

b. p-Phenylphenol: Formaldehyde.

c. o,o′-Biphenol: Formaldehyde.

d. Other.

2. *Silicones.*

a. Glass resins.

b. Metacarborane: dimethyl silane.

c. Rigid silicones—phenyl T related.

d. Quinone based.

e. Epoxy: Siloxane.

f. Phenolic: Siloxane.

- *g. Polysilphenylene Siloxanes.*
- *h. Polyarylorysilanes.*
- *i. Fluorinated silicones.*
- *j. Others.*

3. ***Polyimides.***
   - *a. Flexibilized.*
   - *b. Other.*

4. ***Polybenzimidazoles.***
   - *a. Low-volatile version.*
   - *b. Flow control at high temperatures.*

5. ***Ladder polymers.***
   - *a. Pyrrones.*
   - *b. Other.*

6. ***Polyperfluoroalkyltriazine.***

7. ***Polybenzothiazole.***

8. ***Polyquinoxaline.***

9. ***Polyphenyl oxides.***

10. ***Semiorganic or inorganic polymers.***

11. ***Other.***

C. New Foams

1. ***Polymeric systems.***
   - *a. Polytetrafluorethylene.*
   - *b. Cross-linked polycarbonate.*
   - *c. Polyurethanes.*
   - *d. Polyphenylene oxide.*
   - *e. Polyethylene.*
   - *f. Diphenyl oxide.*
   - *g. Polyimide.*
   - *h. Epoxy.*
   - *i. Isocyanurate.*
   - *j. Other.*

2. *Characteristics.*
   - *a. Low density.*
   - *b. Rigidity.*
     - (1) Stiff with reasonable structural strength.
     - (2) Flexible.
   - *c. Homogeneous and fine void distribution.*
   - *d. Tough.*

D. Tailoring Resin Systems for Particular Needs

1. ***Good low-temperature flexibility.***
   - *a. High chemorheological temperature.*
   - *b. High heat-distortion temperature.*
   - *c. Low brittle temperature.*

2. ***Good low-temperature toughness.***

3. ***Good high-temperature toughness.***

4. ***High char yield.***
   - *a. High char strength.*
   - *b. High degradation-zone strength.*
   - *c. Uniform char surface.*
   - *d. High emittance and absorptance.*
   - *e. Chemically unreactive.*
   - *f. Low shrinkage.*

5. ***High-temperature stability.***

6. ***No unreacted or reactive sites after cure.***
   - *a. Stoichiometric balance of reactive components.*
   - *b. Capping of chain ends.*

7. ***RF transparency.***
   - *a. Virgin state.*
   - *b. Char.*
     - (1) Nonconductive.
     - (2) Hot or cold.

8. ***Single or multiple degradation reactions.***

9. ***Endothermic decomposition.***

10. *Specific specie concentration in evolved gas.*
   a. *Low molecular weight.*
   b. *Wake quenching.*

11. *High specific heat.*

12. *Low conductance.*

13. *Thermally stable char in presence of fillers.*

14. *Easy processing.*
   a. *A liquid system in uncured state.*
   b. *Low-temperature and low-pressure processing.*
   c. *Good filler wetting and bonding.*
   d. *Addition polymerization rather than condensation polymerization.*
   e. *Low cure shrinkage.*

15. *Low thermal expansion coefficient.*
   a. *Isotropic.*
   b. *Anisotropic.*

16. *Space stable.*

17. *Ground-storage stability.*
   a. *Fungus.*
   b. *Humidity.*
   c. *Sunlight.*
   d. *Smog.*

18. *High strain capability.*
   a. *Elastomers.*

19. *Controlled Poisson's ratio.*

20. *Good adhesion.*

21. *Impact-energy absorption.*

22. *Inertness to sterilization.*
   a. *Chemical.*
   b. *Dry heat.*

XV. Filler Development

Filler development is important to widen the scope of design solutions for capsule heat-shield problems.

A. Clean-Characterized Filler Standards

1. *Filler materials.*
   a. *Glass, silica, and quartz.*
      (1) Fiber.
      (2) Yarn.
      (3) Eccospheres.
   b. *Carbonaceous.*
      (1) Fiber.
      (2) Yarn.
      (3) Powder.
   c. *Organic.*
      (1) Nylon.
         (a) Powder.
         (b) Fiber.
      (2) Phenolic–microballoon.
   d. *Cork.*
2. *Characterization.*
   a. *Uniformity.*
   b. *Cleanliness.*
   c. *Reproducibility.*

B. New Filler Development

1. *Materials.*
   a. *Oxides.*
      (1) Aluminum.
      (2) Titania.
      (3) Zirconia.
      (4) Aluminum, silica, and chromia.
   b. *Other refractories.*
      (1) Nitrides–boron nitride.
      (2) Borides.
      (3) Silicates.
      (4) Carbides.

c. High-temperature metals.

d. Organic.

(1) Nomex powder.

(2) PBI.

(a) Fiber.

(b) Microballoons.

(3) PI.

(a) Fiber.

(b) Microballoons.

(4) BBB.

(a) Fiber.

e. Wood.

(1) Balsa.

f. Asbestos.

2. Special additives.

a. Antioxidants.

b. Decomposing salts.

c. Fire retardants.

d. Additives to control chemical cracking.

3. New forms.

a. Submicron particles.

C. Improved Fabrication Techniques

1. Fiber.

a. Drawing.

b. Controlled fiber lengths.

c. Single crystal.

d. Finishes.

e. Diameter control—small diameters.

f. Size distribution.

g. Placing additives in spinning dope prior to fiber formation.

2. Yarn.

a. Multifilament twisted vs single-strand yarn.

b. Surface condition.

c. Surface area.

d. Fiber finishes.

e. Smaller diameters.

3. Cloths.

a. Three-dimensional.

4. Powder.

a. Uniformity.

b. Size distribution.

c. Cold grinding.

5. Microballoons and eccospheres.

a. Uniformity.

b. Size distribution.

6. Wetting and bonding additives.

D. Tailoring Properties to Needs

1. High-temperature stability.

2. Control of melt viscosity at high temperatures.

3. Resin stabilization.

4. High-temperature strength.

5. High-temperature modulus.

6. High-temperature toughness.

7. Low-temperature strength.

8. Low-temperature flexibility.

9. Low-temperature toughness.

10. Density control.

a. Virgin composite.

b. Char.

c. Pyrolysis zone.

11. High char strength and erosion resistance.

12. Endothermic decomposition.

13. Controlled sublimation energy.

14. ***Controlled melting temperature.***

15. ***Thermal-expansion control.***

16. ***High specific heat.***

17. ***Space resistance.***

18. ***Ground-environment resistance.***

   a. *Fungus.*

   b. *Humidity.*

   c. *Sunlight.*

   d. *Smog.*

   e. *Salt spray.*

19. ***Sterilization resistance.***

   a. *Chemical.*

   b. *Dry heat.*

20. ***Low conductivity.***

21. ***Char-oxidation protection.***

22. ***Char dimensional stability.***

23. ***Good wetting and adhesion with resin.***

24. ***Easily dispersed in resin matrix.***

XVI. Composite Development and Fabricability Investigations

The development of application techniques is a vast area of activity that is too often left until the formal design of a vehicle has been completed. A good deal of the potential reliability, weight, and cost savings are tied up in this area.

A. Standard Ablative Composites

1. ***High-density standards.***

   a. *Phenolic silica.*

      (1) Resin content.

      (2) Silica form.

   b. *Phenolic carbon.*

      (1) Resin content.

      (2) Carbon form.

   c. *Phenolic nylon.*

      (1) Resin content.

      (2) Nylon form.

   d. *Other.*

2. ***Low-density standards.***

   a. *Phenolic nylon.*

      (1) Resin content.

      (2) Nylon form.

      (3) Microballoon content.

   b. *Other.*

B. Special Preparation of Resins

1. ***Viscosity changes.***

   a. *Temperature control.*

   b. *Solvent dilution.*

2. ***Filler wettability.***

   a. *Additives.*

   b. *Viscosity.*

3. ***Extraction of low-molecular-weight fragments.***

   a. *Solvent.*

   b. *Vacuum thermal.*

C. Special Preparation of Fillers

1. ***General filler–reinforcement pretreatment.***

   a. *Thermal.*

   b. *Vacuum thermal.*

   c. *Surface modification.*

      (1) Roughening.

      (2) Coupling agent.

   d. *Moisture control.*

   e. *Storage.*

   f. *Solvent cleaning.*

2. *Low-density filler processing.*

a. Homogeneity.

(1) Dense inclusions.

(2) Fiber clumping.

b. Microballoon breakage.

c. Bulk density.

3. *Specific forms.*

a. Chopped fiber or cloth.

(1) Length and size distribution.

(2) Uniformity.

b. Unidirectional tape.

(1) High-strength filaments.

(2) Tape-winding procedures.

(3) Preparation for winding transition.

(4) Areas around sharp edges or corners.

(5) B-staging.

c. Bias-cut tape.

(1) B-staging.

(2) Splicing.

(3) Prestretching.

d. Cloth weaves.

(1) Open mesh.

(2) Tight.

(3) Three-dimensional.

e. Braid.

D. Fabricability Investigations

1. *Mixing.*

a. Semidry.

b. Flocculation.

(1) Particle size.

(2) Dispersion.

c. Settling.

d. Dispersion of low-density fillers.

e. Potlife and mixing time.

f. Mixing sequence.

g. High- vs low-shear equipment.

2. *Application techniques.*

a. Foaming.

(1) Chemical foaming agents.

(2) Open-cell foams.

(3) Closed-cell foams.

(4) Density control.

(5) Cell size and structure.

(6) Density gradients.

(7) Foam in place.

(8) Sprayup and foaming techniques.

(9) Fillers.

b. Compression molding.

(1) Large laminates.

(2) Flow control.

(3) Pressure optimization for:

(a) Density control.

(b) Porosity control.

(c) Mechanical behavior.

(d) Ablative performance.

(4) Part-size effect on optimum pressure.

(5) Vacuum-bag pressure applications.

(6) Autoclave pressure applications.

(7) Hydroclave pressure applications.

(8) High-pressure molding in matched metal dies.

(9) Pressure effect on materials selection.

(10) Compatible-cure cycle.

(11) Mosaic shaking and fitting.

(12) Microballoons or eccospheres.

c. Spraying.

(1) Tailoring ablator system.

(2) Handling of dry and filled mixture.

(3) Viscosity control by solvent additive.

(4) Spraying in layers.

(5) Thickness control.

(6) Thixotropic properties.

(7) Large-structure economics.

(8) Settling or floating in supply lines.

(9) No viscosity reduction during cure.

(10) Complete solvent removal during cure.

(11) Sprayup and foaming techniques.

d. Extrusion.

(1) Continuous.

(2) Edge-member fabrication.

e. Roller coating.

(1) Reproducibility.

(2) Tailoring ablator system.

(3) Viscosity control.

(4) Thickness control.

(5) Large-structure economics.

(6) Homogeneity.

(7) Trapped air.

(8) Vacuum-bag curing.

f. Trowelling.

(1) Reproducibility.

(2) Homogeneity.

(3) Trapped air.

(4) Packing density.

(5) Vacuum-bag curing.

(6) Honeycomb reinforcements.

g. Gunning.

(1) Void elimination.

(2) Lower-density materials.

(a) Eccospheres.

(b) Microballoons.

(3) Cell sealing and priming.

(4) Increase in cell-filling rate.

(5) Homogeneity.

(6) Shallow honeycomb.

h. Cloth layup.

(1) Curvature distortion.

(2) Orientation.

(3) Bias cutting.

(4) In-place vs mandrel.

(5) Isotropy.

(6) With compression molding.

i. Tape wrapping.

(1) Bidirectional laminate.

(2) Unidirectional vs bias-cut tapes.

(3) Conformation to contours.

(4) Application to complex shapes.

(5) Optimum tape wrap angle.

(a) Aerodynamic shear.

(b) Conductance.

(6) Speed.

(7) Tension.

(8) Compaction pressure.

j. Filament winding.

(1) Application to complex shapes.

(2) Bidirectional laminates.

(3) Conformation to contours.

(4) Speed.

(5) Tension.

(6) Compaction pressure.

k. Three-dimensional weaves.

(1) Impregnation.

(a) Vacuum.

(2) Supplementary pressure.

(3) Weaving equipment.

3. Use of honeycomb reinforcement.

a. Application methods.

(1) Trowelling.

(2) Gunning.

b. Materials.

(1) Resins.

(a) Phenolic.

(b) Polyimide.

(2) Cloth.

(a) Glass.

(b) Silica.

(c) Carbon.

(d) Nylon.

(3) Film.

(a) Nomex.

c. Honeycomb properties.

(1) Cell shape.

(2) Cell size.

(3) Density.

(4) Open- vs tight-weave fabric.

(5) Saddling effects in two directions.

(6) Number of cloth dips.

d. Special problems.

(1) Structure-to-honeycomb bond.

(2) Cell-wall-to-ablator bond.

(3) Thin sections.

(4) Thickness control.

(5) Joints.

4. Adhesive compatibility.

a. Properties.

(1) Chemical.

(2) Thermal expansion.

b. Surface-preparation requirements.

(1) Cleanliness.

(2) Roughness.

(3) Primer.

c. Type of adhesive.

(1) Self-adhering.

(2) Rigid.

(3) Flexible.

d. Special problems.

(1) Minimum bond weight.

(2) High-temperature adhesives (to 800°F).

(3) Honeycomb bonding.

5. Cure.

a. Temperature.

(1) Room temperature desirable.

(2) Must be sufficient to advance resin and control flow.

(3) Should be at least as high as sterilization temperature to drive off volatiles.

b. Atmosphere.

(1) Inert.

(2) Vacuum.

(3) Air.

c. Cycle properties.

(1) Heat-up rate.

(2) Cooldown rate.

(3) Post cure.

d. Special problems.

(1) Vacuum–thermal treatment for removal of low-molecular-weight species.

(2) Oxidative degradation.

(3) Minimization of residual stresses.

(4) Effect of part size on cure cycle.

6. Machining.

a. Methods.

(1) Hand finishing.

(2) Machine cutting.

(3) Grinding.

b. Special problems.

(1) Foams.

(2) Rough surface.

(3) Fillers.

(4) Finishing to fixed outer contour.

(5) Finishing to fixed thickness.

(6) Tooling.

(7) Reference dimensions.

7. *Repair and refurbishment.*

a. *Flaws.*

(1) Surface.

(2) Local interior.

(3) Cracks.

(4) Wide area of imperfection.

b. *Methods.*

(1) Trowelling.

(2) Gunning.

(3) Section replacement.

(4) Spraying.

E. Special Problems

1. *Continuous processing.*

2. *Scale-up studies.*

3. *Abrasion resistance.*

a. *Friability.*

b. *Toughness.*

c. *Coatings.*

d. *Laboratory test method.*

4. *Transpiration cooling techniques.*

5. *Coatings.*

a. *Aerodynamic smoothness.*

b. *Temperature control.*

(1) Paint.

(2) Film.

(3) Vapor deposition.

(4) Porosity effects.

6. *Joints.*

a. *Gap sealants.*

b. *Similar vs dissimilar materials.*

c. *Filled or bonded.*

7. *Radar cross section for tracking in transit.*

8. *Process-control procedures.*

9. *Dual-density ablators.*

XVII. Nondestructive Testing

Necessary for quality control of actual hardware, nondestructive testing can also be useful in characterizing samples before destructive tests. Major limitations are sensitivity and contamination from surface-contact agents.

A. Methods and Limitations

1. *Infrared radiometer scanning.*

a. *Measures thermal gradients due to heat flow.*

(1) Static.

(2) Dynamic.

b. *Detects flaws affecting heat flow.*

(1) Voids.

(2) Delaminations.

(3) Cracks.

(4) Inclusions.

(5) Chemical inhomogeneity.

c. *Advantages.*

(1) Sensitive to small defects.

(2) Full-size mapping.

(3) No surface contact or contaminant.

d. *Problems.*

(1) Defect must affect heat conduction.

(2) Does not necessarily distinguish between voids, inclusion, and chemical inhomogeneity.

(3) Slow.

(4) Nonuniform heat flow.

2. *X-ray radiography.*
   a. *Measures X-ray attenuation.*
   b. *Detects:*
      (1) Chemical inhomogeneity.
      (2) Voids.
      (3) Inclusions.
   c. *Advantages.*
      (1) Noncontaminating.
      (2) Fast.
   d. *Problems.*
      (1) Insensitive.
      (2) Flaw-size detection dependent on thickness.

3. *Neutron or gamma-ray radiography.*
   a. *Measures neutron or gamma-ray attenuation.*
   b. *Detects:*
      (1) Chemical inhomogeneity.
      (2) Voids.
      (3) Inclusions.
   c. *Advantages.*
      (1) Noncontaminating.
      (2) Fast.
   d. *Problems.*
      (1) Expensive.
      (2) Complex.

4. *High-intensity light source.*
   a. *Allows visual inspection if material sufficiently transparent.*
   b. *Advantages.*
      (1) Fast.
      (2) Inexpensive.
      (3) Noncontaminating.

5. *Microwave energy.*
   a. *Measures attenuation.*
      (1) Transmission.
      (2) Scattering.
      (3) Reflection.
      (4) Absorption.
      (5) Phase change.
      (6) Pulse shifts.
      (7) Pulse echo.
   b. *Detects:*
      (1) Voids.
      (2) Delaminations.
      (3) Cracks.
      (4) Material inhomogeneity.
   c. *Advantages.*
      (1) Noncontaminating.
   d. *Problems.*
      (1) Insensitive.
      (2) Erroneous defect indications.

6. *Ultrasonic energy.*
   a. *Measures attenuation.*
      (1) Transmission.
      (2) Reflection scattering.
      (3) Pulse echo.
      (4) Resonance.
      (5) Surface wave.
   b. *Detects:*
      (1) Voids.
      (2) Delaminations.
      (3) Cracks.
   c. *Advantages.*
      (1) Sensitive to small defects.
      (2) Full-size mapping.
      (3) Indirect measure of mechanical response.
         (a) Modulus.
         (b) Poisson's ratio.
   d. *Problems.*
      (1) Couplant contaminates surface.

(2) Signal attenuation can be too great or too small with certain materials.

(3) Transmission methods require access to both sides of material.

XVIII. Design Criteria and Parametric Studies for Design

A systematic method is needed for establishing the system constraints and anticipated environments for particular planetary-entry missions. The combined uncertainties in environments, material parameters, and modeling techniques can then be subjected to parametric studies delineating heat-shield problems and solutions for particular classes of missions.

A. Definition of Heat-Protection System Requirement and Constraints

1. *Shape change.*
2. *Structural configuration and materials.*
3. *Allowable temperature rise in structure.*
4. *Signal transmission.*
5. *Blackout alleviation.*
6. *Mission-reliability goals.*
7. *Planetary atmospheric sampling.*
8. *Contamination of optical surfaces.*
9. *Interference with scientific experiments.*

B. Definition of Anticipated Environments

1. *Fabrication.*
   - a. *Elevated-temperature cure.*
   - b. *Handling.*
   - c. *Inspection.*
   - d. *Storage.*
   - e. *Fuel spillage.*
2. *Decontamination and sterilization.*
   - a. *ETO–Freon 12 surface decontamination.*
   - b. *Dry-heat sterilization.*
3. *Launch.*
   - a. *Acceleration.*
   - b. *Vibration.*
   - c. *Shock.*
   - d. *Rapid pressure change.*
4. *Space vacuum.*
   - a. *Vacuum of 10–16 torr.*
   - b. *Solar radiation.*
   - c. *Space radiation.*
   - d. *Micrometeoroids.*
5. *Cold soak.*
   - a. *Temperature extremes.*
   - b. *Temperature cycles.*
   - c. *Vibration.*
6. *Entry.*
   - a. *Convective heat flux.*
   - b. *Radiative heat flux.*
   - c. *Dynamic pressure.*
   - d. *Aerodynamic shear.*

C. Procedures for Applying Analysis Methods and Material Performance Data to Anticipated Exposure Conditions

1. *Uncertainties in materials performance.*
2. *Uncertainties in environmental levels.*
3. *Uncertainties in mathematical modeling techniques.*
4. *Combined uncertainties.*

D. Design Procedures

1. *Nominal or modified trajectory parameters.*
2. *Nominal or modified materials properties.*
3. *Safety factors on heating rate, duration of heat pulse, and shear forces.*

4. *Safety factors on allowable temperatures, surface recession, and thermal stress.*

5. *Combination of extremes in input quantities.*

6. *Methods for updating procedures as better materials properties and analysis techniques become available.*

E. Parametric Studies

1. *Mars.*

2. *Venus.*

3. *Jupiter.*

Appendix B

Contents

Appendix B

A List of Heat-Shield R&D Tasks for Extraterrestrial Atmospheric-Entry Missions

The R&D tasks outlined in this appendix were produced from a systematic review of heat-shield technology; they represent the total scope of effort possible with a reasonable expectation of successful advancement of this technology. It is unlikely that any one agency could or would desire to fund all of these tasks. Within each subcategory, the listed tasks are preceded by a symbol in parentheses to indicate their estimated relative value. Starred items (*) are considered key or critical. Items marked (1) are expected to have a large effect on mission success, reliability, weight, or cost. Items marked (2) have implications towards technology growth or long-range research, whereby the magnitude or timing of the output is not immediately obvious. (Some funding in this latter area is important, but the selection is arbitrary.)

I. Ablation Theory

A. Internal Processes

1. (*) Develop a new mathematical model for internal degradation processes, accounting for heating rate as well as temperature, pressure, species, and shape factors.
2. (*) Develop an internal flow model that accounts for the actual thermochemical state of the gases with the accompanying pressure gradients, diffusion coefficients, chemical erosion, etc.
3. (1) Develop a char-conductance model as a function of temperature, temperature history, microordering, and density changes (relate to IV-H and IV-I).
4. (1) Develop a new mathematical model for phase-change and degradation processes, accounting for volume changes.
5. (1) Develop a conductance model that differentiates between conduction and internal radiation transfer in porous materials (relate to IV-J).
6. (1) Develop a diffusion model to replace the model based on Darcy's law.
7. (1) Develop a conductance model for nonhomogeneous and anisotropic materials with filler, porosity, and honeycomb reinforcements (relate to IV-K).
8. (1) Develop an internal flow model that represents cracking and redeposition reactions.
9. (2) Develop a conductance model as a function of pressure and gas species—air, N_2, CO_2, CO, CH_4, H_2, and He (relate to IV-G).
10. (2) Develop a silicone–elastomer liquid-layer model with vaporization.
11. (2) Develop a silica or glass reinforcement liquid-layer model with vaporization.
12. (2) Develop a conductance model representing the changes caused by cracking and pyrolytic deposition (relate to IV-C-4).
13. (2) Develop a model for silicone–carbide formation and other char-reinforcement reactions.
14. Investigate photochemical reactions from incident radiation.

B. External Processes or Surface Interactions

1. (*) Develop an absorptance, emittance, and transmittance model that accounts for surface roughness, pore geometry, temperature gradients, and wavelength.
2. (*) Develop a high-blowing-rate model.
3. (*) Develop a radiative-heating model for representative combinations and pressures of N_2, O_2, Ar, H_2O, H_2, He, LH_2, and NH_3 in various equilibrium and nonequilibrium states and with self-absorption.
4. (*) Develop an improved turbulent-heating model with turbulent transition on the cone.
5. (1) Develop a model for mass-addition changes in shock shape and radiative heating, accounting for absorption in the evolved gaseous species (including upstream effects).
6. (1) Develop a boundary-layer-combustion model, including upstream influences and effects on heating.

7. (1) Develop a combustion model for CO_2-C.

8. (1) Develop a combustion model for H_2-C.

9. (1) Develop a sublimation model accounting for temperature, pressure, species, diffusion, and vapor-pressure effects.

10. (1) Develop a shear and thermomechanical erosion model, accounting for aerodynamic shear, external pressures, internal pressures, thermal stresses, inertial stresses, and pre-stresses (upstream transpiration).

11. (1) Develop a model for surface roughness and catalysity effects on convective and radiative heating.

12. (1) Develop a laminar convective-heating model for representative combinations and pressures of N_2, O_2, CO_2, Ar, H_2O, H_2, He, CH_4, and NH_3 in various equilibrium and frozen states and for free molecular and continuum flow.

13. (1) Develop a model for convective- and radiative-heating distribution around an entry body, including base heating, angle-of-attack effects, and improved transition criteria.

14. (1) Develop an improved model for mass-addition changes in flow-field and convective heating, including upstream effects.

15. (2) Develop a combustion model for N_2-C.

16. (2) Develop a vaporization model for oxide reinforcements that is consistent with the sublimation model (I-B-9).

17. (2) Develop a combustion model with inhibitors.

18. (2) Investigate turbulence effects on radiation-heat transfer.

C. General

1. (2) Develop a model for joints, windows, and feed-throughs (geometrical discontinuities).

2. (2) Develop a conductance model for honeycomb-sandwich materials.

II. Computer Program Development

A. Computer Processes

1. (1) Establish techniques for feeding entry-simulator calibration and test data directly into, and getting finished plots directly out of the computer.

2. (1) Establish techniques for computer reduction of basic material-property data.

3. (2) Investigate computer processes in depth to improve accuracy, decrease computer time, and provide multidimensional capability.

4. (2) Establish standards for notation, coordinate systems, units, common subroutines, and input and output handling.

5. (2) Establish a practical data-storage and -retrieval system.

B. Computer Programs

1. (1) Establish a set of preliminary design programs for a Venus-entry heat shield.

2. (1) Establish a set of preliminary design programs for a Jupiter-entry heat shield.

3. (1) Develop a sophisticated, one-dimensional, uncoupled-ablation computer program including:

   a. An improved conductance model with hysteresis, pressure, and radiation effects.

   b. An improved radiation-absorptance model with surface-roughness effects.

   c. An improved internal-degradation model.

   d. Allowance for swelling and shrinking.

   e. An improved internal-flow model with realistic diffusion, thermochemical equilibrium, cracking, redeposition, and silicon–carbide formation.

   f. An improved combustion model for oxygen and carbon dioxide.

   g. Nitration reactions in the proper temperature regime.

   h. An improved sublimation model.

   i. A combustion model for hydrogen.

   j. An improved thermomechanical-erosion model with pressure, shear, thermal gradient, and evolved gas stresses.

   k. An improved liquid-layer model.

4. (2) Develop a fully coupled boundary-layer–ablation-response computer program.

5. (2) Develop a multidimensional uncoupled-ablation computer program.

6. (2) Establish a set of preliminary design programs for a Mars-entry heat shield.

7. (2) Establish a standard program for back-calculating materials properties from thermocouple-response data.

III. Characterization and Physical Properties

A. Characterization

1. (1) Adapt specific-density model to account for deposition.

2. (1) Investigate sample representativeness for any laboratory testing.

3. (1/2) Adapt specific-density model to account for swelling and shrinkage.

4. (1/2) Develop methods of determining percent of each major component in virgin materials and chars.

5. (2) Develop elemental-analysis techniques that allow identification of full realm of species anticipated.

6. (2) Develop a method of measuring permeability in typical porous heat-shield material.

7. (2) Measure permeability of representative heat-shield materials as a function of temperature, permeant, and porosity.

8. (2) Compare methods of measuring specific density and porosity; establish density and porosity model that should actually be used in computations.

9. (2) Investigate application of reflectance measurements to char profiling.

B. Physical Properties

1. (2) Develop a method of measuring vapor pressures under extreme temperature and pressures.

2. (2) Measure vapor pressures of carbon through its triple point.

IV. Thermal and Optical Properties

A. Thermal Expansion

1. (*) Measure thermal-expansion coefficients of typical ablation materials.

2. (1) Develop a high-temperature (to 7000°F) thermal-expansion apparatus suitable for graphites and chars with and without exotic fillers or reinforcements.

   a. Determine thermal-expansion model that is used by each of the existing expansion facilities.

   b. Determine biases that remain in expansion measurements, providing that care is taken to minimize facility error, from the different facilities.

   c. Determine facility that best represents expansion for use in computer modeling and provides the best accuracy in obtaining experimental data.

   d. Determine how this facility can be modified or replaced to improve accuracy and computer-model representation.

   e. Make the modifications and automate the operation.

3. (2) Develop a low-temperature thermal-expansion technique (−200 to +800°F) to handle inhomogeneous ablative composites.

4. (2) Investigate effects of high heating rates on thermal expansion of ablative materials.

B. Specific Heat

1. (*) Measure specific heat of typical ablation materials.

2. (2) Compare alternate methods of measuring specific heat of solids from −200 to +7000°F and select the simplest, most accurate, most reproducible method for each temperature range.

3. (2) Establish methods of measuring specific heat of evolved ablation gases.

C. Thermal Conductance

1. (*) Measure conductance of typical ablation materials.

2. (1) Develop a high-temperature conductance apparatus suitable for graphites and chars.

a. Determine conductance form that is modeled by each of the existing conductance facilities.

b. Determine biases that remain in conductance measurements, providing that care is taken to minimize facility error, from the different facilities.

c. Determine facility that best represents conductance, as used in computer models, and provides the best accuracy in obtaining experimental data.

d. Determine how this facility can be modified or replaced to improve accuracy and computer-model representation.

e. Make the modifications and automate the operation.

3. (1) Investigate conductance from -200 to $+7000\,^\circ$F of carbonaceous chars varied in known fashion as to char structure, time at temperature, and pyrolytic deposition; establish a standard char-conductance-characterization test matrix.

4. (1) Investigate conductance from -200 to $+7000\,^\circ$F of silaceous chars (from silicone elastomer resins or silica or glass reinforcements) and establish a standard char-conductance-characterization test matrix.

5.(1/2) Devise an experiment to separate out the radiative-transfer component in high-temperature conductance and establish a realistic mathematical model for its representation (may or may not be attached to the study in IV-C-8, above).

6. (2) Investigate effect of pressure or vacuum on conductance of porous ablators.

7. (2) Develop an apparatus for accurately measuring conductance of honeycomb–sandwich composites in both directions.

8. (2) Devise an experiment to determine conductance anisotropy in ablative materials caused by fillers, porosity, reinforcements, or honeycomb.

9. (2) Develop an apparatus for accurately measuring conductance of superinsulation with joints and attachments.

10. (2) Develop an apparatus to measure the effects on composite conductance of joints, feedthroughs, windows, etc., in ablators.

D. Optical Properties

1. (*) Measure optical properties of typical ablation materials.

2. (1) Investigate absorption coefficient and transmittance of chars as functions of char structure, surface roughness, and temperature (may or may not be attached to the study in IV-D-7, below).

3.(1/2) Develop a high-temperature reflectance or emittance apparatus suitable for graphites and chars.

a. Determine optical theory that is modeled by each of the existing conductance facilities.

b. Determine biases that remain in optical measurements, providing that care is taken to minimize facility error, from the different facilities.

c. Determine facility that best represents absorptance and emittance as they are used in the numerical processes of computer models and provides the best accuracy in obtaining experimental data.

d. Determine how this facility can be modified or replaced to improve accuracy and computer-model representation.

e. Make the modifications and automate the operation.

4.(1/2) Develop a technique to measure reflectance or absorptance at lower (<0.2 μm) wavelengths (may or may not be attached to IV-D-3, above).

5.(1/2) Investigate effects of lateral and in-depth temperature gradients on surface temperature and optical-property measurements as functions of surface roughness and temperature level.

6.(1/2) Develop higher temperature sources for reflectance measurement plus sources with a wider range of wavelength capability.

7. (2) Investigate reflectance and emittance of carbonaceous and silaceous carbon chars as functions of char structure, time at temperature, surface roughness, pressure, wavelength, and pyrolytic deposition.

8. (2) Develop an apparatus for measuring optical properties of hot gases.

9. (2) Investigate why three quite different emittance facilities give the same emittance value, and three quite different reflectance facilities give the same absorptance value, but—for the same wavelength—emittance can appear to be unequal to absorptance for chars while showing adequate equivalence for high-density carbons or graphites.
10. (2) Identify spectral and diffuse components of reflectance and delineate lobing.
11. (2) Investigate light-pipe effects in porous chars.

V. Mechanical Properties

A. General Mechanical Properties

1. (*) Measure tensile, compressive, flexure, and shear strength of typical ablation materials.
2. (1) Develop a high-temperature (room temperature to 7000°F) tensile–compressive apparatus, suitable for graphites and chars, with automated operation and data recording, improved load-cell sensitivity, and adaptations for controlled atmosphere testing and high-heating-rate—high-loading-rate testing.
3. (1) Develop a high-temperature (room temperature to 7000°F) shear apparatus, suitable for graphites and chars, with automated operation and data recording and with adaptations for testing under controlled atmospheres, high loading rates, and high heating rates.
4. (1) Investigate effect of inert gases and vacuum on tensile, compressive, flexure, and shear strength of heat-shield materials and their chars.
5. (2) Develop a low-temperature (−200 to +1000°F) tensile–compressive apparatus suitable for both rigid and elastomeric heat-shield materials, with automated operation and data recording and adaptations for testing in controlled atmospheres and at high loading rates.
6. (2) Develop a low-temperature (−200 to +1000°F) flexure apparatus suitable for both rigid and elastomeric heat-shield materials, with automated operation and data recording and with adaptations for testing in controlled atmospheres, under high loading rates, and for fatigue under cycling.
7. (2) Develop a low-temperature (−200 to +1000°F) shear apparatus suitable for both rigid and elastomeric heat-shield materials, with automated operation and data recording and adaptations for testing under controlled atmospheres.
8. (2) Investigate applicability of normal analytical concepts for representing the mechanical behavior of heat-shield materials and their chars.
9. (2) Investigate effect of high heating rates and temperature gradient through the thickness on the tensile, compressive, flexure, and shear strength of heat-shield materials and their chars.
10. (2) Investigate flow and fracture behavior of heat-shield materials, including such factors as high loading rate, strain sensitivity under high compensation, creep at high and low temperatures, cycling loads, stress concentrations, and anisotropy.
11. (2) Investigate effect of bidirectional loading on tensile, compressive, and shear strength of heat-shield materials.

B. Special Mechanical Properties

1. (*) Develop a simple method of determining low-temperature brittle transition of nonhomogeneous heat-shield composites that will be a true indicator of low-temperature mechanical performance.
2. (1) Develop a simple method of determining resistance of heat-shield materials to thermal shock, using both sudden cooldown of a hot specimen and sudden heating of a cold specimen.
3. (1) Determine micrometeoroid-penetration resistance of typical heat-shield materials as a function of temperature, pressure, impact rate, impact direction, material density, reinforcement, and previous history.
4. (1) Develop a method of measuring mechanical properties of ablator-structure composites with superimposed temperature gradients and pressure forces for development of better analytical models of combined performance.
5. (1) Develop a meaningful thermal-stress measurement technique.

6. (2) Establish appropriateness of standard notch-impact tests for analyzing performance of heat-shield materials.

7. (2) Develop a micrometeoroid-penetration apparatus with a wide variation of particle size and velocity, low-vacuum capability, and capability of bombarding reasonably large specimen areas with simulated interplanetary radiation.

8. (2) Investigate relationship between impact resistance of typical heat-shield materials and the area under the stress–strain curve.

9. (2) Investigate effect of penetrations on thermal performance of typical heat-shield materials as a function of hole size and shape.

10. (2) Develop a method of determining peel strength of an ablator-structure interface that will be meaningful in relation to the singly and doubly curved shapes typical of real fabrications.

11. (2) Investigate methods of improving peel strength at both high and low temperatures.

12. (2) Develop a method of measuring strength of a virgin-char interface both during ablation and after cooldown.

13. (2) Develop a meaningful set of fatigue tests for ablators, including both low-cycle–high-strain and high-cycle–low-strain tests.

VI. Electrical Properties

A. Signal Attenuation

1.(1/2)Measure signal attenuation of typical heat-shield materials before, during, and after ablation to determine the effects of pressure, atmospheric species, ablator thickness, pyrolyzed thickness, heating rate, shape, wavelength, incident angle, and time at temperature.

2. (2) Develop an improved apparatus for determining attenuation of various signals passing through typical classes of heat-shield materials before, during, and after ablation.

3. (2) Evaluate possibility of calculating transmission properties from temperature profiles and dielectric data as a function of temperature.

B. Dielectric Properties

1. (2) Measure dielectric properties of typical heat-shield materials.

VII. Degradation Kinetics Investigations

A. Primary Degradation Kinetics

1. (1) Identify exo- and endothermic processes inherent in different classes of heat-shield composites as a function of temperature, temperature change rate, pressure, gaseous species, sample size and state, and thermocouple biases.

2. (1) Adapt TGA methods for high heating rates and measure differences in kinetics for typical heat-shield materials.

3. (2) Improve DTA facility capabilities by expanding temperature limits, increasing environmental-simulation capabilities, and automating operation and data recording.

4. (2) Improve DSC capabilities by expanding temperature limits, increasing environmental-simulation capabilities, expanding heating-rate capability, and automating operation and data recording.

5. (2) Improve TGA facility capabilities by minimizing control deviations, providing better atmosphere control, and automating operation and data handling.

6. (2) Investigate differences between isothermal, constant-temperature-rise, and constant-heating-rate TGA methods for deriving kinetic parameters.

7. (2) Investigate effects of size, shape, form, holder, buoyancy, diffusion, pretreatment, and view temperature of sample on TGA kinetic constants.

8. (2) Compare TGA data with DTA and DSC results.

9. (2) Investigate appropriateness of gas chromatographs, mass spectrometers, time-of-flight mass spectrometers, and infrared spectrometers for identifying evolved species and specific reactions during polymer degradation and their representativeness in relation to species actually evolved during entry or in rocket nozzles, including:

   a. Postcracking on adjacent hot wall.

   b. Repolymerization transients.

   c. Condensation.

   d. Heating-rate effects.

e. Specimen-configuration effects.

f. Heating-method effects.

10. (2) Improve gas-chromatograph capabilities.

11. (2) Improve mass-spectrometer capabilities.

12. (2) Improve infrared-spectrometer capabilities.

B. Secondary Reactions

1. (1) Develop equipment to investigate cracking and deposition of gases in graphites and chars.

2. (1) Investigate effect of cracking and deposition on conductance.

3. (1) Investigate cracking in silica-reinforced chars as compared with completely carbonaceous chars.

4. (1) Investigate mechanisms and kinetics of cracking and deposition, including temperature and pressure effects, species, gas-flow rate, porosity, facility biases, specimen representativeness, and catalysity.

5. (1) Develop a computer model for cracking and deposition.

6. (2) Establish magnitude of the effect of cracking on heat balance.

7. (2) Investigate effect of cracking and deposition on porosity of typical chars.

8. (2) Investigate effect of cracking and deposition on mechanical strength.

9. (2) Develop equipment to study carbon–silica reactions in chars.

10. (2) Investigate carbon–silica reactions in chars as to their effect on material removal, mechanical strength, and conductance.

11. (2) Develop equipment to study carbon–CO_2 and carbon–H_2O reactions in chars, and investigate their effect on ablator performance.

C. Other Parameters

1. (1) Measure heat of combustion for typical heat-shield materials.

2. (2) Develop an apparatus to measure heat of combustion of graphites and chars, using different planetary atmospheres.

3. (2) Develop a technique to determine flammability of ablative materials in planetary atmospheres.

4. (2) Measure flammability of different heat-shield materials.

5. (2) Develop equipment for measuring diffusion constants of typical ablation gases and planetary atmospheres, and measure the constants.

VIII. Pre-entry Environmental Compatibility Tests

A. Prelaunch Environments

1. (1) Carry out a test program to determine effect of spilled fuel or long-time exposure to fuel vapors on thermal and mechanical performance of typical ablation materials.

2. (1) Investigate effect of chemical surface decontamination and dry-heat sterilization on thermal and mechanical performance of typical heat-shield materials.

3. (1) Investigate alternate carrier gases to replace Freon 12 in chemical surface decontamination.

B. Launch Environments

1. (1) Shake and shock typical heat-shield materials at different temperatures.

2. (1) Investigate compatibility of low-density materials with rapid evacuation.

C. Transit Environments

1. (1) Determine vacuum stability of typical heat-shield materials.

2. (1) Determine volatile condensable material content of typical heat-shield materials.

3. (2) Investigate effect of space radiation on typical heat-shield materials.

4. (2) Investigate effect of nuclear power plant radiation on typical heat-shield materials.

D. Combined Environments

1. (2) Measure flexure and tensile strength of typical ablators after consecutive *in situ* exposure to sterilization, launch vibration, launch pump-down, and long-time exposure to vacuum.

IX. Entry-Simulator Development

A. Plasma-Arc Facilities

1. (1) Investigate control systems capable of pulsing both power and working-fluid flow rate simultaneously.

2. (1/2) Investigate methods of increasing heating rate and pressure simultaneously.

3. (2) Investigate arc processes such as energy-transfer mechanisms, arc-column studies, radiation loading, and transport properties of gases.

4. (2) Develop arc heads for high-flow-rate, high-pressure, high-power systems.

5. (2) Develop arc heads for reactive working fluids such as oxygen, carbon dioxide, hydrogen, and methane.

6. (2) Develop scaling techniques for increasing the sizes of various classes of arcs toward 500-MW capability.

7. (2) Investigate differences in energy distribution in gases heated by dc current, ac current, and inductive coils, respectively.

8. (2) Develop improved electrode materials and configurations.

9. (2) Develop simple starting techniques.

10. (2) Develop power sources with low ripple, low power-factor correction, wide power range, instantaneous control response, and rapid control-change capability for large short-time power pulses.

11. (2) Develop power-source controls for multiple-arc systems.

12. (2) Develop diodes and rectifiers with longer life.

13. (2) Develop nozzles for higher supersonic-flow capability at high pressures.

14. (2) Develop arc-chamber, plenum-chamber, and exhaust-nozzle systems that will maximize exhaust uniformity, without contamination, while minimizing power loss.

15. (2) Develop turbulent-duct techniques.

16. (2) Develop rectangular supersonic-nozzle techniques.

17. (2) Develop high-shear exhaust systems.

18. (2) Develop high-sensitivity exhaust-pumping systems capable of fine-tuning exhaust-shock patterns and capable of varying static pressure over a wide range of pressures.

19. (2) Couple exhaust-pumping system pulsing control to the enthalpy and working-fluid pulsing controls mentioned above.

20. (2) Develop high-velocity, high-location-accuracy sample injection mechanisms with three-dimensional scanning.

21. (2) Develop a recession-compensation and rate-measuring system.

22. (2) Develop a probing system for injecting gas-sampling probes into the boundary layer of an ablating sample in an arc exhaust.

23. (2) Investigate and delineate merits and limitations of various sample configurations.

24. (2) Develop recorder–computer–plotter systems for direct conversion of diagnostic and test data to graphical or tabular results.

B. Radiant Heaters

1. (*) Develop a continuous CO_2 laser capable of producing heating rates in the 10,000-Btu/ft^2/s range.

2. (1) Investigate similar laser systems with other gas carriers.

3. (1) Investigate extension of the laser system to large sample sizes.

4. (2) Develop filament-lamp heater systems for Mars-entry simulation on large shapes.

5. (2) Develop high-pressure, vortex-stabilized, plasma-arc, radiant-heater systems with longer life, more efficient optics, brighter and larger-view-angle sources, and capability of handling a variety of working fluids.

6. (2) Develop better lens, window, and mirror materials for radiant heaters.

7. Develop high-pressure, compact-arc heater systems for Mars-entry simulation.

C. Combined Facilities

1. (1) Develop an entry-simulator system using radiant heaters and cold-gas flow for shear simulation.

2. (1) Investigate validity of using the radiant-heater cold-gas system as to wavelength effects, heating-distribution effects, surface-roughness and transmittance effects, inequivalence of local pressure and temperature gradients, and local erosion effects.

3. (1) Develop an analytical model for the flow field and surface interaction of the radiant-heater cold-gas system.

4. (1) Investigate differences and limitations in simulation between convective–radiative facilities, comparing:

   a. Plasma-arc–arc-imaging-furnace facilities.

   b. Plasma-arc–plasma-arc radiant-heater facilities.

   c. Plasma-arc facilities with specimens mounted near the arc.

   d. Plasma-arc–focused-laser facilities.

5. (1) Develop the most suitable facility (from IX-C-4) into a larger Venus-direct-entry simulator with pulsed-convective heating, radiative heating, and pressure.

6. (2) Investigate applicability and limitations of the Cornell Aeronautical Laboratory wave superheater for Venus-entry simulation.

7. Develop the most suitable facility (from IX-C-4) into a small Mars-direct-entry simulator with pulsed-convective heating, radiative heating, and pressure.

8. Investigate concepts of pebble-bed and porous-resistance heaters for Mars-entry simulation in CO_2–N_2 atmospheres.

9. Investigate applicability and limitations of nuclear-explosion data to simulation of high-energy Jupiter entry.

X. Entry-Simulator Testing

A. General Studies

1. (1) Investigate comparative oxidation capability of air and CO_2–N_2 combinations as to the CO_2–N_2 equivalent of air, reaction-rate and diffusion-rate processes, and potential effects of low-percentage contaminants; e.g., argon and water.

2. (1) Investigate sublimation processes in graphites and chars at high temperature, including heating-rate limits and pressure effects.

3. (1) Investigate dynamic blocking effects using calorimeter–ablator combinations in concentric-probe, wedge, and circular- or square-tube configurations.

4. (1) Develop techniques for scaling plasma-arc ablation results to larger body sizes.

5. (1) Investigate effects of joints, cracks, protuberances, holes, and erosion on ablation response.

6. (2) Develop an equilibrium-chemistry and boundary-layer flow model that will adequately represent boundary layers in planetary atmospheres, and compare it to the boundary layer in plasma-generator studies.

7. (2) Investigate changes in boundary-layer conditions in a plasma arc caused by surface recession in different model configurations.

8. (2) Investigate gaseous-combustion processes in a plasma-arc system by injecting separated evolved gas species into the planetary-atmosphere-simulated exhaust gas.

9. (2) Investigate nitration reactions with graphite and chars in high-temperature plasma-arc exhausts with and without the presence of oxygen or carbon dioxide.

10. (2) Develop standards in specimen shape and in minimum acceptable stream and specimen calibration.

11. (2) Investigate gas emittance and absorptance for various planetary-atmospheric species and typical ablation products.

12. (2) Investigate effects of spectral distribution on ablator response.

13. (2) Investigate radiation absorption in the boundary layers of specimens in a plasma-arc exhaust.

14. (2) Investigate contribution of regular surface roughness to ablation response in chars.

15. (2) Investigate ablation response to turbulent heating, comparing pipe, plate, and wedge flow.

16. (2) Investigate mechanisms of tripping laminar flow to turbulent flow.

17. (2) Using an arc-heated charring sample, investigate surface-roughness effects on surface-temperature measurements.

18. (2) Develop techniques for making RF-attenuation measurements during ablation.

19. (2) Investigate RF-attenuation characteristics of typical ablation materials during ablation.

20. (2) Develop techniques for ablation testing of typical heat-shield materials *in situ*:

    a. After long-time exposure to vacuum.

    b. After sterilization.

    c. After simulated micrometeoroid damage.

    d. After exposure to nuclear radiation.

    e. On cold models.

21. Investigate reactions of CH_3, NH_3, and He with graphites and chars at high temperatures.

B. Specific Mars Studies

1. Screen new low-density foams and composites relative to earlier materials for out-of-orbit Mars entry (heating rates <100 Btu/ft^2/s).

2. Test best materials from out-of-orbit Mars entry, screening for complete definition of material response within heating range, including transient effects of actual pulses.

3. Test large samples of best Mars out-of-orbit materials combined with structural members in integrated facilities, with both transit and entry environments, using radiant bulbs to heat the samples.

4. On typical classes of heat-shield materials, investigate the Mars direct-entry environment (heating rates less than 400 Btu/ft^2/s in CO_2–N_2) in depth, including CO_2 combustion equivalence, blocking effects, and pressure effects.

5. Using critical environments (defined in X-B-4, above), screen a variety of candidate low-density ablation materials for relative performance as RF-transparent and non-RF-transparent ablators.

6. Test large samples of the best Mars direct-entry materials combined with structural members in integrated facilities, with both transit and entry environments, using radiant bulbs to heat the samples.

7. Investigate scaling effects on Mars direct-entry materials in plasma-arc facilities with model sizes up to 24 in. in diameter.

C. Specific Venus Studies

1. (*) For suitable classes of heat-shield materials, investigate the Venus low-energy-entry environment (heating rates <2000-Btu/ft^2/s convective and 1000-Btu/ft^2/s radiative in CO_2–N_2), including CO_2 combustion equivalence, CO_2 combustion processes, sublimation processes, pressure effects, blocking contributions, and material response.

2. (*) Using critical environments (defined in X-C-4, above), screen a variety of candidate ablation materials.

3. (*) Investigate applicability of laser systems to simulate high-energy Venus-entry environment.

4. (*) Using available facilities, identify ground-test simulation limits for high-energy Venus-entry simulation, and test typical candidate ablative materials for their relative performance in these environments.

5. (2) Investigate applicability of direct-arc exposure to simulate the high heating rates and pressure of a high-energy Venus entry.

D. Specific Jupiter Studies

1. Correlate atomic-blast-container ablation data with Jupiter-entry material response (heating rates on the order of 1,000,000 Btu/ft^2/s).

2. Use these data to infer analytical ablation models for high-heating-rate environments on a first-cut basis.

XI. Diagnostic Instrumentation Development

A. Environmental Instrumentation

1. (*) Investigate and establish minimum environmental calibration for testing ablative samples in entry-simulation facilities.

2. (1) Establish accuracy of heating-rate limits and surface-catalysity effects for various calorimeter types, and develop standard configurations for calorimeters showing greatest promise in each convective and radiative heating-rate range.

3. (1) Establish pressure limits and accuracy of various pressure-probe concepts for plasma-arc facilities, and develop standard configurations for probes showing greatest promise for each pressure range.

4. (1) Establish enthalpy limits, accuracy, and ionized-flow biases for various enthalpy-measuring techniques, and develop standard techniques for methods showing greatest promise for plasma-arc exhaust definition.

5. (1) Develop enthalpy probes for very high enthalpies and pressures.

6. (1) Develop enthalpy probes for accurately determining coring effects.

7. (2) Investigate window-transmission limitations on radiative-heating-rate measurements.

8. (2) Investigate the difference in stream-property influence of nonablating and ablating models in plasma-arc exhaust streams and their influence on measured heating rates.

9. (2) Develop and investigate concentric-calorimeter probes wherein ablative materials could be used to replace any of the individual calorimeters for inference of blocking effects.

10. (2) Develop a contamination probe for analyzing stream contamination and its influence on heating-rate measurements.

11. (2) Investigate wall-calorimeter designs and develop standard calorimeters for insertion in nonablating and ablating systems.

12. (2) Develop methods for accurately separating static and dynamic pressure.

13. (2) Investigate pitch and yaw effects on pressure measurements.

14. (2) Develop methods for measuring pressure on ablating models.

15. (2) Differentiate between problems for subsonic and supersonic enthalpy probes.

16. (2) Establish usefulness limits, accuracy, and appropriateness of the various probe and optical techniques for analyzing plasma-arc exhaust-flow fields for velocity, temperature, and electrical distributions. Consider chemical state, shock interactions, tank and probe interference, rotational flow and vorticity, and energy state in equilibriums.

17. (2) Develop a class of wedge models with a defined and useful range of environments for ablation testing.

18. (2) Develop a class of pipe- or square-channel models with a defined and useful range of environments for ablation testing.

B. Material-Response Instrumentation

1. (1) Investigate applicability of thermocouples to measurement of internal temperatures of ablative materials, establishing the criticality of various readout parameters (e.g., wire calibration and drift, cold-junction drift, nonisothermal connections to external equipment, and sensitivity to stray currents and magnetic fields), as well as the more familiar location problems.

2. (1) Establish limitations, accuracy, surface-roughness effects, and gas-cap or arc-radiation effects on the various surface-temperature-measurement techniques, and develop standard techniques for various sample-configuration and exposure environments.

3. (1) Investigate surface-temperature measurements as they relate to surface roughness of chars and to alternate computer-node models near or at the surface.

4. (2) Develop reliable techniques to manufacture and install 1-mil or smaller thermocouples in ablation samples.

5. (2) Investigate measurement problems of using thin films to establish back-surface or interface temperatures on ablation materials.

6. (2) Develop techniques and quantify the problems of measuring internal temperatures in ablative chars.

7. (2) Investigate differences between postanalysis and transient techniques (e.g., X-rays) to measure variations in internal density during ablation, and establish the reasonableness of using these techniques to derive transient ablation models.

8. (2) Compare surface-recession and mass-loss-rate calculations from tare weights and dimensions vs transient camera or X-ray techniques for different environmental-exposure regimes.

9. (2) Establish standard techniques of measuring surface-recession and mass-loss rate for different ablative-material test configurations.

10. (2) Establish standard photographic techniques for recording surface phenomena of ablating specimens in different brightness regimes, including narrow-wavelength-regime filters, polarization, etc.

11. (2) Use photographic techniques to study the lateral surface flow of glassy fillers in ablative materials.

XII. Flight Test

A. Earth Flight-Test Simulations

1. (1) Venus low-energy-entry severity can be simulated by earth-flight test, and is desirable to prove out the high-performance heat-shield systems necessary to provide payloads on the anticipated missions.

2. (1) Venus high-energy-entry severity can be better simulated by earth-flight tests because combustion or available gaseous species play a lesser role in the overall ablation response, and such a test is desirable for the reason given in XII-A-1, above.

3. Mars out-of-orbit entry can be fully qualified by an earth-flight test, which is desirable to decrease conservatism in heat-shield and structural requirement estimates in the extremely weight-sensitive, low-ballistic-coefficient capsules under consideration.

4. Mars direct-entry severity can be closely matched in an earth-flight test, depending upon the importance of combustion processes, and is desirable for the reason given in XII-A-3, above.

5. Jupiter lower-energy-entry conditions are similar to the Venus conditions discussed in XII-A-1 and -2, above.

B. Flight Instrumentation

1. (1) Investigate available flight heat-shield-diagnostic instrumentation in depth, and establish instrument limitations, accuracy, and meaningfulness to performance diagnostics.

2. (1) Develop better temperature-history measuring systems.

3. (1) Develop better dynamic calorimeters and pressure probes.

4. (1) Develop better surface-recession indicators.

XIII. Rocket-Nozzle Testing

A. Small Rocket Tests

1. Test specific selected materials in specific subsystems of interest to particular missions.

2. Test a variety of materials with the new special high-performance propellants.

3. Investigate restart problems in nozzle-throat performance.

4. Improve and automate solid and liquid test-stand operation.

5. Investigate plasma-arc simulation of rocket-nozzle performance in depth.

XIV. Resin Development

A. Clean-Characterized Polymer Standards

1. (1) Establish phenolic standards.

2. (2) Establish silicone–elastomer standards.

3. (2) Establish epoxy and epoxy–novalac standards.

4. (2) Establish polyimides standards.

5. (2) Establish polybenzimidazole standards.

B. New High-Temperature Resins

1. (1) Investigate, theoretically and experimentally, the probable limitations or potential improvements in phenolic and epoxy resins, and establish their relative contribution to thermal stability, char properties, and low-temperature toughness.

2. (1) Repeat XIV-B-1 for polyimides and polybenzimidazoles, as well as some of the more exotic ladder and other polymers, to establish potential limitations of basic carbonaceous polymeric structures.

3. (2) Investigate contribution of fluorination on XIV-B-1 and -2.

4. (2) Repeat XIV-B-1 for silicone–elastomer-based polymers to establish potential limitations of basic siliceous polymeric structures.

5. Investigate the following:

   a. (1) Silicone–glass resins.

   b. (1) Flexibilized polyimides.

   c. (1) Noncondensation polymers of any kind.

   d. (2) Rigid silicones.

   e. (2) Aromatic silicones.

   f. (2) Fluorinated silicones.

   g. (2) New phenolic systems.

   h. (2) Ladder polymers.

   i. (2) Thiazole- and quinone-based polymers.

   j. (2) Polyphenyl oxides.

   k. (2) Fluorinated versions of carbonaceous polymers.

   l. (2) Semiorganic polymers.

   m. (2) Inorganic polymers.

C. New Foams

1. Establish density, homogeneity, toughness, rigidity, high-temperature stability, and limitations of the following:

   a. (1) Polyphenylene oxide.

   b. (1) Diphenyl oxide.

   c. (1) Polyimide.

   d. (1) PBI.

   e. (2) Polyethylene.

   f. (2) Polytetrafluoroethylene.

   g. (2) Cross-linked polycarbonate.

   h. (2) Epoxy.

   i. (2) Isocyanurate.

   j. (2) Polyurethanes.

D. Tailoring Resin Systems for Particular Needs

1. Consider a resin system for Mars out-of-orbit entry that provides the following properties or the best compromise possible within the limits of the potential catastrophic failures that are not avoidable through design (high-performance—low-density ablator):

   a. Good low-temperature flexibility or toughness.

   b. Good high-temperature stability and reasonable char-residue strength.

   c. Low conductance.

   d. Inert to fillers or strengthened by their presence.

   e. Good processability (with or without fillers) to densities in the range of 10 lb/ft^3 or lower.

   f. Easy fabrication and application to complex shapes.

   g. Low thermal-expansion coefficients.

   h. Low volatile and recondensable–volatile content in space vacuums.

   i. Space-vacuum and radiation stability.

   j. Ground-storage inertness.

   k. Compatible with reasonable adhesive systems.

   l. Inert to sterilization and surface decontamination.

   m. Low volume change during degradation.

2. Consider a resin system for Mars direct entry that provides the following properties or the best compromise possible within the limits of the potential catastrophic failures that are not avoidable through design (high-performance–low-density ablator):

   a. Good low-temperature flexibility or toughness.

   b. Good high-temperature stability and reasonably strong.

   c. Low conductance.

   d. Inert to fillers or strengthened by their presence.

   e. Good processability (with or without fillers) to densities in the range of 20 lb/ft^3 or lower.

   f. Easy fabrication and application to complex shapes.

   g. Low thermal-expansion coefficients.

   h. Low volatile and recondensable–volatile content in space vacuums.

i. Space-vacuum and radiation stability.

j. Ground-storage inertness.

k. Compatible with reasonable adhesive systems.

l. Inert to sterilization and surface decontamination.

m. Low volume change during degradation.

3. Consider an RF-transparent resin system for Mars direct or out-of-orbit entry that provides the following properties or the best compromise possible within the limits of the potential catastrophic failures that are not avoidable through design (high-performance–RF-transparent–low-density ablator):

   a. Good low-temperature flexibility or toughness.

   b. Good high-temperature stability and either no char or a nonconductive char residue.

   c. Low conductance.

   d. Inert to fillers or strengthened by their presence.

   e. Good processability (with or without fillers) to densities in the range of 20 lb/ft^3 or lower.

   f. Easy fabrication and application to complex shapes.

   g. Low thermal-expansion coefficients.

   h. Low volatile and recondensable–volatile content in space vacuums.

   i. Space-vacuum and radiation stability.

   j. Ground-storage inertness.

   k. Compatible with reasonable adhesive systems.

   l. Inert to sterilization and surface decontamination.

   m. Low volume change during degradation.

4. (*) Consider a resin system for Venus low-energy entry that provides the following properties or the best compromise possible within the limits of potential catastrophic failures that are not avoidable through design (high-performance–medium-density ablator):

   a. Good low-temperature toughness or flexibility.

   b. Good high-temperature stability.

   c. Low volume change during degradation.

   d. Good char or residue strength.

   e. Reasonable resistance to combustion by planetary gases.

   f. Reasonable resistance to combined aerodynamic-shear pressure and thermal-stress forces.

   g. Low thermal-expansion coefficients.

   h. Low conductance.

   i. High emittance.

   j. Good processability (with or without fillers) to densities in the range of 20 to 50 lb/ft^3.

   k. Easy fabrication and application to complex shapes.

   l. Compatible with reasonable adhesive systems.

   m. Inert to fillers or strengthened by their presence.

   n. Space-vacuum and radiation stability.

   o. Low volatile and recondensable–volatile content in space vacuum.

   p. Ground-storage inertness.

   q. Inert to sterilization and surface decontamination.

5. (*) Consider a resin system for Venus low-energy entry that provides the following properties or the best compromise possible within the limits of potential catastrophic failures that are not avoidable through design (high-performance–high-density ablator):

   a. Good low-temperature toughness or flexibility.

   b. Good high-temperature stability.

   c. Low volume change during degradation.

d. High char or residue strength under high-temperature, high-pressure, high-shear conditions.

e. Reasonable resistance to combustion by planetary gases.

f. Reasonable resistance to combined aerodynamic-shear pressure and thermal-stress forces.

g. Low thermal-expansion coefficients.

h. Low conductance.

i. High emittance.

j. Good processability with or without fillers.

k. Easy fabrication and application to complex shapes.

l. Compatible with reasonable adhesive systems.

m. Inert to fillers or strengthened by their presence.

n. Space-vacuum and radiation stability.

o. Low volatile and recondensable–volatile content in space vacuum.

p. Ground-storage inertness.

q. Inert to sterilization and surface decontamination.

6. Consider a resin system for small control- or injection-motor nozzles that provides the following properties or the best compromise possible within the constraint of potential catastrophic failures that are not avoidable through design (high-performance–high-density ablator):

a. Good low-temperature toughness or flexibility.

b. Good high-temperature stability.

c. Low volume change during degradation.

d. High char or residue strength under high-temperature, high-pressure, high-shear conditions.

e. High resistance to combustion by oxidizer-rich environments.

f. High resistance to failure from internal distortions.

g. Low thermal-expansion coefficients.

h. Low conductance.

i. High emittance.

j. Good processability with or without fillers.

k. Easy fabrication and application to complex shapes.

l. Compatible with reasonable adhesive systems.

m. Inert to fillers or strengthened by their presence.

n. Space-vacuum and radiation stability.

o. Low volatile and recondensable–volatile content in space vacuum.

p. Ground-storage inertness.

q. Inert to sterilization and surface decontamination.

7. (2) Develop resin systems with high endothermic decomposition.

8. (2) Investigate alternates for XIV-D-1 through -5 with high strain capability and controlled Poisson's ratio.

9. (2) Investigate alternates for XIV-D-1 through -6 with good impact-energy absorption.

XV. Filler Development

A. Clean-Characterized Reproducible Filler Standards

1. (2) Establish fiber, yarn, and eccosphere standards for glass, silica, and quartz.

2. (2) Establish fiber, yarn, and powder standards for carbon and graphite.

3. (2) Establish fiber and powder standards for nylon.

4. (2) Establish microballoon standards for phenolic resins.

5. (2) Establish standards for cork.

B. New Filler Development

1. (1) Investigate wetting and bonding additives.

2. (2) Investigate usefulness of nitrides, borides, carbides, and high-temperature metals as filler materials in high-temperature ablative composites.

3. (2) Investigate alternate organic-fiber reinforcements to replace nylon.

4. (2) Investigate higher-temperature microballoon systems than phenolic systems.

5. (2) Investigate submicron particles as fillers.

6. (2) Investigate limitations and potential improvements of special additives such as antioxidants, fire retardants, and chemical-cracking controls.

7. (2) Investigate salts that decompose endothermically yet are resistant to space vacuum and radiation.

8. (2) Investigate fiber-production techniques and methods to control the nature of the fiber, its size, and its surface properties.

9. (2) Investigate yarn-production techniques and methods to control the nature of the yarn, its size, and its surface properties.

10. (2) Investigate three-dimensional (3D) weaving techniques.

11. (2) Investigate powder-production techniques and methods to control uniformity and size distribution.

12. (2) Investigate microballoon-production techniques and methods to control uniformity and size distribution.

13. (2) Investigate eccosphere-production techniques and methods to control uniformity and size distribution.

C. Tailoring Filler Properties to Needs

1. Consider a filler system for Mars entry that provides the following properties or the best compromise possible within the limits of the potential catastrophic failures that are not avoidable through design:

   a. High temperature.

   b. Resin stabilization.

   c. High-temperature strength, modulus, and toughness.

   d. Low-temperature strength, flexibility, and toughness.

   e. Low density.

   f. Strengthens char and is highly resistant to char erosion.

   g. Endothermic decomposition.

   h. Low volume change.

   i. High specific heat.

   j. Low conductance.

   k. Char-combustion protection.

   l. Inert to space, sterilization, and ground storage.

   m. Good dispersion; wetting and adhesion with resin.

2. (1) Consider a filler system for Venus entry that provides the following properties or the best compromise possible within the limits of the potential catastrophic failures that are not avoidable through design:

   a. High temperature.

   b. Resin stabilization.

   c. High-temperature strength, modulus, and toughness.

   d. Low-temperature strength, flexibility, and toughness.

   e. Reasonable density.

   f. Strengthens char and is highly resistant to char erosion.

   g. Endothermic decomposition.

   h. Low volume change.

   i. High specific heat.

   j. Low conductance.

   k. Char-combustion protection.

   l. Inert to space, sterilization, and ground storage.

   m. Good dispersion; wetting and adhesion with resin.

   n. High sublimation energy.

3. Consider a filler system for small control- or injection-motor nozzles that provides the following properties or the best compromise possible within the limits of the potential catastrophic failures that are not avoidable through design:

   a. High temperature.

b. Resin stabilization.

c. High-temperature strength, modulus, and toughness.

d. Low-temperature strength, flexibility, and toughness.

e. Reasonable density.

f. Strengthens char and is highly resistant to char erosion.

g. Endothermic decomposition.

h. Low volume change.

i. High specific heat.

j. Low conductance.

k. Char-combustion protection.

l. Inert to space, sterilization, and ground storage.

m. Good dispersion; wetting and adhesion with resin.

n. High sublimation energy.

o. High vaporization energy.

p. High melting temperature.

q. Low viscosity at high temperatures.

XVI. Composite Development and Fabricability Investigations

A. Standard Ablative Composites

1.(1/2)Establish a high-density phenolic carbon standard.

2.(1/2)Establish a high-density phenolic nylon standard.

3. (2) Establish a high-density phenolic silica standard.

4. (2) Establish a high-density polyimide carbon standard.

5. (2) Establish a low-density phenolic nylon standard.

6. (2) Establish a low-density foam standard.

7. (2) Establish a low-density silicone–elastomer composite standard.

B. Component Preparations

1. (2) Investigate viscosity control, wettability control, and low-molecular-weight fragment-removal techniques for resin systems.

2. (2) Investigate filler–reinforcement pretreatments.

3. (2) Investigate low-density filler processing.

4. (2) Investigate unidirectional and bias-cut tape production.

5. (2) Investigate cloth-weaving techniques.

C. Fabricability Studies

1.(*/1)Develop dual-density ablator concept.

2. (1) Each resin system and filler combination that passes gross early screening should be subjected to an extensive fabricability investigation, including:

   a. Mixing problems.

   b. Alternate application techniques.

   c. Use of honeycomb reinforcement.

   d. Adhesive compatibility.

   e. Optimum cure cycle with each application technique.

   f. Machining methods.

   g. Repair and refurbishment.

3. (1) Special studies should be made of the kind of resin and filler variations necessary to improve fabricability, along with their relative effect on performance for each application technique:

   a. Foaming.

   b. Vacuum-bag or compression molding with fibers.

   c. Vacuum-bag or compression molding with microballoons or eccospheres.

   d. Spraying.

   e. Extrusion.

   f. Rollercoating.

   g. Trowelling with or without honeycomb.

   h. Gumming honeycomb.

i. Cloth layup with vacuum-bag or compression molding.

j. Tape wrapping.

k. Filament winding.

l. Three-dimensional weaves.

4. (1) Adhesive studies.

5. (1) Coating development for temperature control during transit.

6. (1) Establishment of process-control procedures.

7. (2) Continuous processing and scale-up studies.

8. (2) Joint problems.

9. (2) Radar cross-section studies for tracking in transit.

10. (2) Abrasion-resistance studies.

11. (2) Studies of compatibility with active transpiration-cooling systems.

XVII. Nondestructive Testing

A. Methods Development

1. (1) Alternate methods, along with their limitations for various classes of ablation materials, should be studied in depth.

2. (1) New techniques with theoretical promise should be pursued with vigor.

B. Applications

1. (1) The best available methods should be applied to each class of material surviving early Mars and Venus environmental screening.

XVIII. Design Criteria and Parametric Studies for Design

A. Design Criteria

1. (1) Reasonable listings of heat-protection system requirements and constraints (and their most plausible alternates) plus the best available definition of anticipated environments should be openly published following approval by NASA Headquarters, updated at standard intervals, and widely distributed.

B. Parametric Studies for Design

1. Using nominal conditions and properties, combined uncertainties, safety factors, and realistic updating procedures for reduced uncertainties, parametric studies should be made of the following:

a. Mars out-of-orbit entry.

b. Mars direct entry.

c. (*) Venus low-energy entry.

d. (*) Venus high-energy entry.

e. Jupiter lower-energy entry.

f. Jupiter higher-energy entry.

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