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SPACECRAFT MICROBIAL BURDEN REDUCTION DUE TO ATMOSPHERIC ENTRY HEATING – JUPITER*

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Abstract

Planetary quarantine analyses performed for recent unmanned Mars and Venus missions assumed that the probability of contamination by a spacecraft given accidental impact was equivalent to one. However, in the case of the gaseous outer planets, the heat generated during the inadvertent entry of a spacecraft into the planetary atmosphere might be sufficient to cause significant microbial burden reduction. This could affect navigation strategy by reducing the necessity for biasing the aim point away from the planets. An effort has been underway at Jet Propulsion Laboratory to develop the tools necessary to predict temperature histories for a typical spacecraft during inadvertent entry. In order that the results have general applicability, parametric analyses are performed. The thermal response of the spacecraft components and debris resulting from disintegration is determined. The temperature histories of small particles and composite materials, such as thermal blankets and an antenna, are given special attention. Guidelines are given to indicate the types of components and debris most likely to contain viable organisms, which could contaminate the lower layers of the Jovian atmosphere (~1 atmosphere of pressure).

1.0 Introduction

With missions to the planets, an unmanned spacecraft has a finite probability of accidentally impacting the planet due to inherent errors and uncertainties in the spacecraft navigation system [1]. This assertion is valid not only for missions to Venus and Mars but also to missions beyond Mars. In performing planetary quarantine analysis for Mars missions, it has been assumed that impact of the planet by an unsterilized spacecraft would lead to a probability of contamination equal to one. However, due to the relatively large inertial entry speed of 61 km/s for Jupiter, the heat received by a body entering the planet's atmosphere will be significant. Thus, the burden reduction due to entry heating may be large enough such that the probability of contamination due to inadvertent entry may be significantly less than one. As a result of this possibility, a study was initiated to determine if the spacecraft and spacecraft debris receive sufficient thermal heating which could result in a significant reduction of microbial burden.

This paper presents the preliminary results of these investigations. After describing a typical Jupiter flyby spacecraft, the background and method of analysis is presented. Then the results of a parametric analysis of selected components of the sample spacecraft and representative particle debris are discussed.

2.0 Technical Discussion

2.1 Background

An artist's conception of a typical Jupiter flyby spacecraft used in this study is shown in Figure 1. The spacecraft consists of a nine-sided frame assembly (1.5 m across by 0.5 m high), to which nine electronic chassis are attached. The frame assembly provides primary structural attachments for a high-gain antenna (3.7 m in diameter), propulsion assembly, radioisotope thermoelectric generator (RTG), science instruments, science platform, celestial sensors, attitude control assembly, and thermal blankets.

A body entering the atmosphere of a planet first encounters the rarefied portion of the atmosphere, called the "free-molecular regime." In this regime, the energy transfer to the body results from exchanges of kinetic energy of colliding gas molecules with the body. The body then enters the denser regime of the atmosphere where the gas behaves like a homogeneous, continuous matter; this regime is referred to as the "continuum." Continuum flow regime entries are characterized by a strong high-density shock ahead of the body which results in the body surface becoming exposed to very high convective and radiative heat fluxes.

Accidental biological contamination of the atmosphere of Jupiter by an encountering spacecraft can be caused from three sources: (1) the spacecraft itself, (2) ejecta released during flight from Earth, and (3) disintegration debris (i.e., fragments and particles) released as the spacecraft passes through the atmosphere. The general survivability of these three sources has previously been determined for Jovian entry assuming simple configurations -- spheres, circular disks, and cylinders -- and homogeneity in the configuration material [2] [3]. This investigation concentrates on determining the thermal responses of selected components of the spacecraft -- consisting of complex geometries and several different materials -- and ejecta and disintegration debris as they pass through the free-molecular flow regime and early continuum.

2.2 Method of Analysis

Classical thermodynamic equations were used to determine the heat input to spacecraft debris and components in the free-molecular regime.

Particles smaller than 1000 μm were assumed to come to thermal equilibrium instantaneously, while thermal response computer routines were used to determine the time-temperature histories of components.

The significant particle parameters relating to the debris analyses are size, density, drag coefficient, accommodation coefficient, and surface emittance. The accommodation coefficient involves the amount of gas kinetic energy absorbed by the particle and depends on the body surface material as well as the gas molecular weight. The emittance determines the amount of energy radiated away. A limiting value of the ratio of accommodation coefficient to emittance of 0.39 was used, based on engineering judgment and a review of the literature [4]. Analyses were performed for three atmospheric models [5], and a range of entry angles. A spherical shape was used in view of the fact that supportive analyses indicated that it represented the most conservative case.

The spacecraft component free-molecular regime analyses involved additional thermal response calculations of the structure being considered. An example of thermal modeling that was required is that used for the antenna as shown in Figure 2, where a simplified antenna geometry with the nodal subdivisions is presented. The antenna dish structure is made up of the aluminum honeycomb core and two very thin graphite epoxy face sheets, one bonded to the front and the other to the back of the core by means of an epoxy resin. Since inadvertent entry may occur at any spacecraft attitude with respect to the velocity vector, the thermal response analyses were performed in two orientations: "face on" (along the z-axis) and "edge on" (along the y-axis).

It is assumed that the thermal responses of intermediate orientations are bounded by these two cases. The thermal model nodal subdivisions were based on the selected orientations. The thickness of the antenna was divided into eight layers conforming to the shape of the dish (see cross-sectional nodes sketch). Each quadrant was divided into 36 sectors, thus forming 288 nodes per quadrant. For clarity, only the first and last two sectors in the (+Y, +X) quadrant are shown.

The analysis in the "face on" case required consideration of the heat flow in the "A" direction only because of concentric symmetry. In the "edge on" case, both heat flow modes -- normal ("A") and tangential ("B") -- were considered; thus all 288 nodes in the quadrant were used to obtain the actual temperature distribution. Only one-half of the dish was modeled because of circumferential symmetry. In the "edge on" case, part of the dish is exposed to the heat flux while the other part is in the shadow (no heating), and thus represents a heat sink. An appropriate number of nodes to account for this is used in the "edge on" analysis.

Similar analyses were performed for the thermal blankets which consisted of layers of aluminized Mylar. In addition, the temperature responses due to entry heating on the aluminum strut structure supporting the spacecraft appendages were determined.

2.3 Results

2.3.1 Ejecta and Disintegration Debris

The results of the particulate analyses indicate that ejecta released in the free-molecular regime, or prior to entry, may survive depending on particle properties, entry angle, and atmospheric model used.

Figure 3 illustrates the results obtained for spherical plastic particles as a function of entry angle for the three model atmospheres. It also indicates that there is a minimum angle below which a particle will skip out of the atmosphere and not return. The area to the right of the shaded area represents the region where microbial "kill" would be achieved based on the lethality model [6] used in this analysis. In general, chances of survival increase as: (1) the particle size decreases, (2) the entry becomes "shallow," and (3) as the scale height of the assumed atmospheric models increases (i. e., warm atmosphere model).

2.3.2 Spacecraft Components

Analyses for the entire spacecraft, as it traverses the free-molecular regime and enters the early continuum, have shown that the thermal insulation blankets and the antenna dish disintegrate before entering the continuum flow, and that their disintegration should be completed in the early continuum. Also, the aluminum strut structure will melt away rapidly as soon as continuum flow is established.

Figure 4 illustrates the identified disintegration stages of the outer planet spacecraft described in Figure 1. The first stage, on the left, represents the spacecraft in outer space approaching the atmosphere of the planet. The spacecraft is still undisturbed but its flight may be stable or tumbling (dashed line indicates oscillation). The major parts of the spacecraft are identified in the figure. The second stage, in the middle, shows the spacecraft status when leaving free-molecular regime, i. e., at the continuum regime boundary. Here, the antenna is shown as partially disintegrated with the blankets also beginning to disintegrate. Small debris and particles, entrapped in these parts during manufacture, may be released at this time. These are indicated by a dotted shower. The third stage, on the right, portrays the situation in the early continuum. At this time, the aluminum strut structure has melted away, the antenna and other appendages have completely disintegrated, and the blankets are in the final stages of disintegration. In conclusion, what is left for the continuum flow entry analyses are the spacecraft science platform and the bus. The RTG has been eliminated from consideration, since its operational temperature is about 1000°C in the center and over 350°C on the outside; hence it was assumed to be inherently sterile. The disintegration described was caused primarily by thermal effects, because the maximum flow pressure generated on any part of the spacecraft did not exceed 0.01 atm; thus, the flow pressure could not contribute perceptibly to the spacecraft breakup.

Figure 5 shows the typical results of thermal response of blankets during entry into the nominal Jupiter atmosphere. Ordinates are temperatures in degrees Celsius and the abscissa is time from entry. The temperature histories for three angles are presented, and the limit temperature at which the blanket plastic evaporates is indicated. These data are representative of stage two of disintegration as depicted in Figure 4. It is seen that the deeper the entry angle the shorter is the time of thermal response and the steeper is the temperature rise. The 90° (-90° using standard convention) entry angle means that the spacecraft is heading straight in toward the center of the planet.

The results have shown that the antenna will only partially disintegrate before the continuum flow is reached, primarily due to relatively high heat resistance of the graphite epoxy face sheets. However, once disintegration has started, it will proceed rather rapidly in the continuum flow thermal environment.

3.0 Summary

This study has applied classical aerothermophysics techniques to determine the thermal responses of selected components of a typical Jupiter flyby spacecraft as well as ejecta and disintegration debris as they pass through the free-molecular flow regime and early continuum. Analyses for the entire spacecraft have shown that the thermal insulation blankets and the antenna are completely disintegrated by the early continuum. Large components, such as the spacecraft main support structure with the attached electronics and the science platform, will not receive sufficient heating in the free-molecular regime to cause major disintegration. However, complete disintegration is expected to occur in the continuum regime; analyses are being performed to determine the thermal response of these structures in the continuum. The analysis of spherical plastic particles indicates the existence of "survival corridors" which indicate that small diameter particles are the most likely to survive entry heating.

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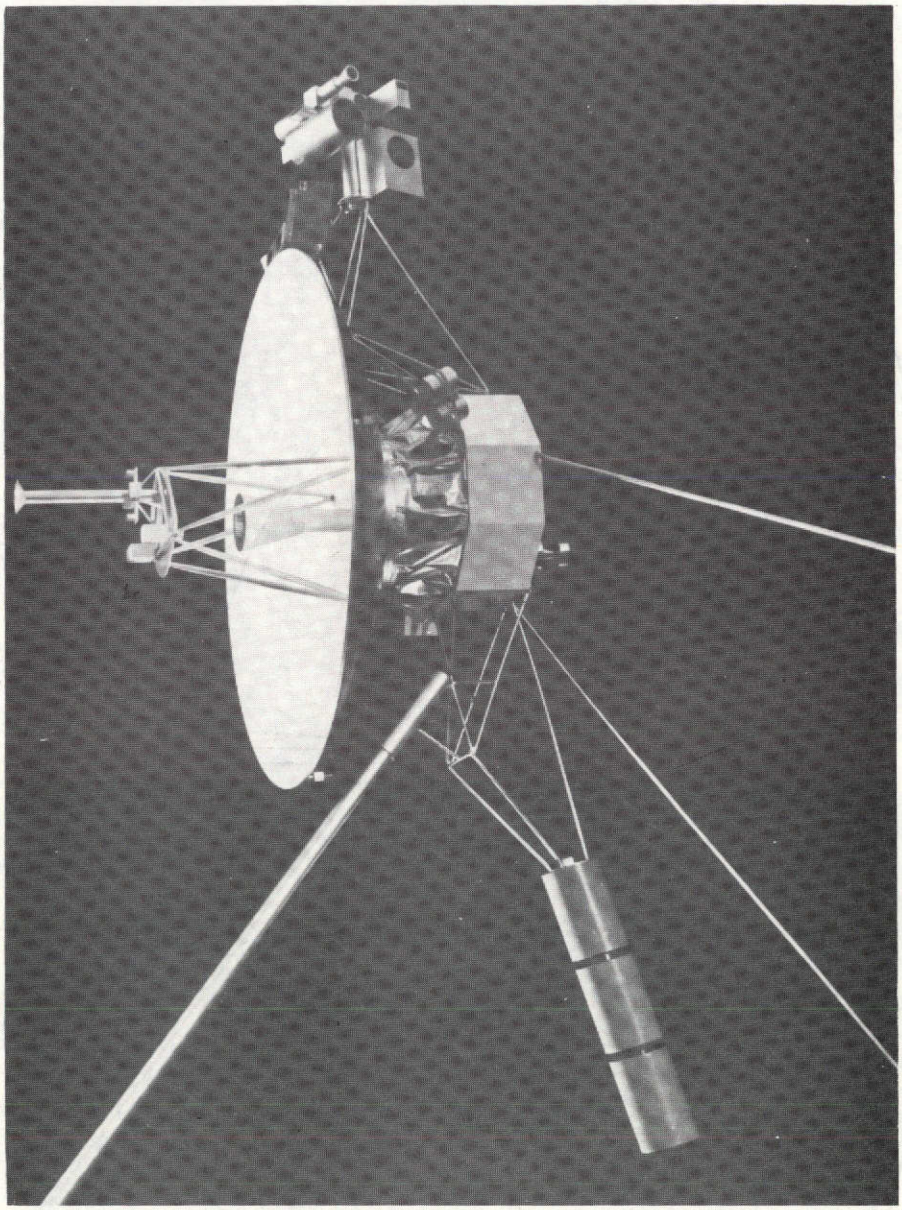

Figure 1. Typical outer planet spacecraft

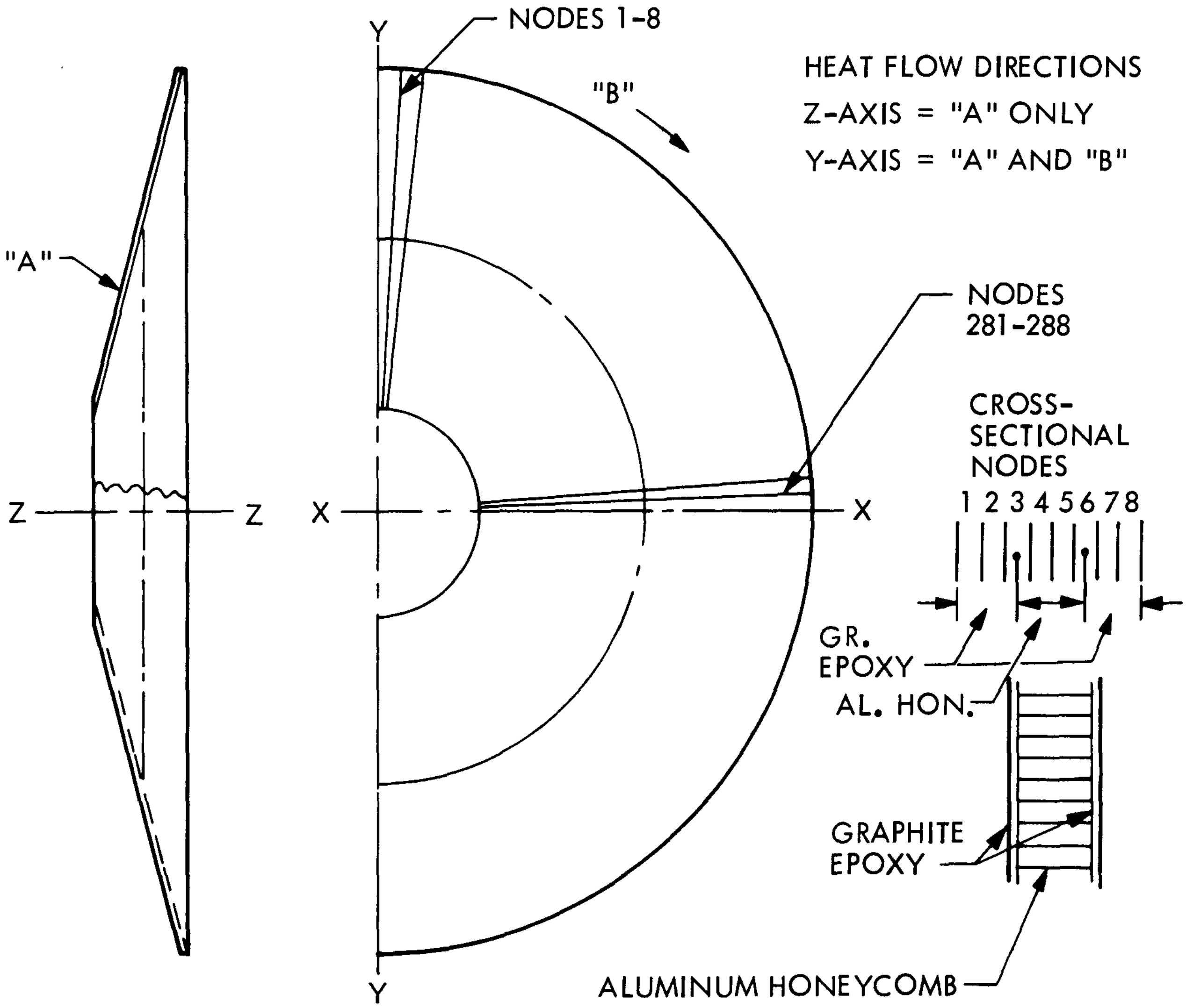

Figure 2. Antenna geometry

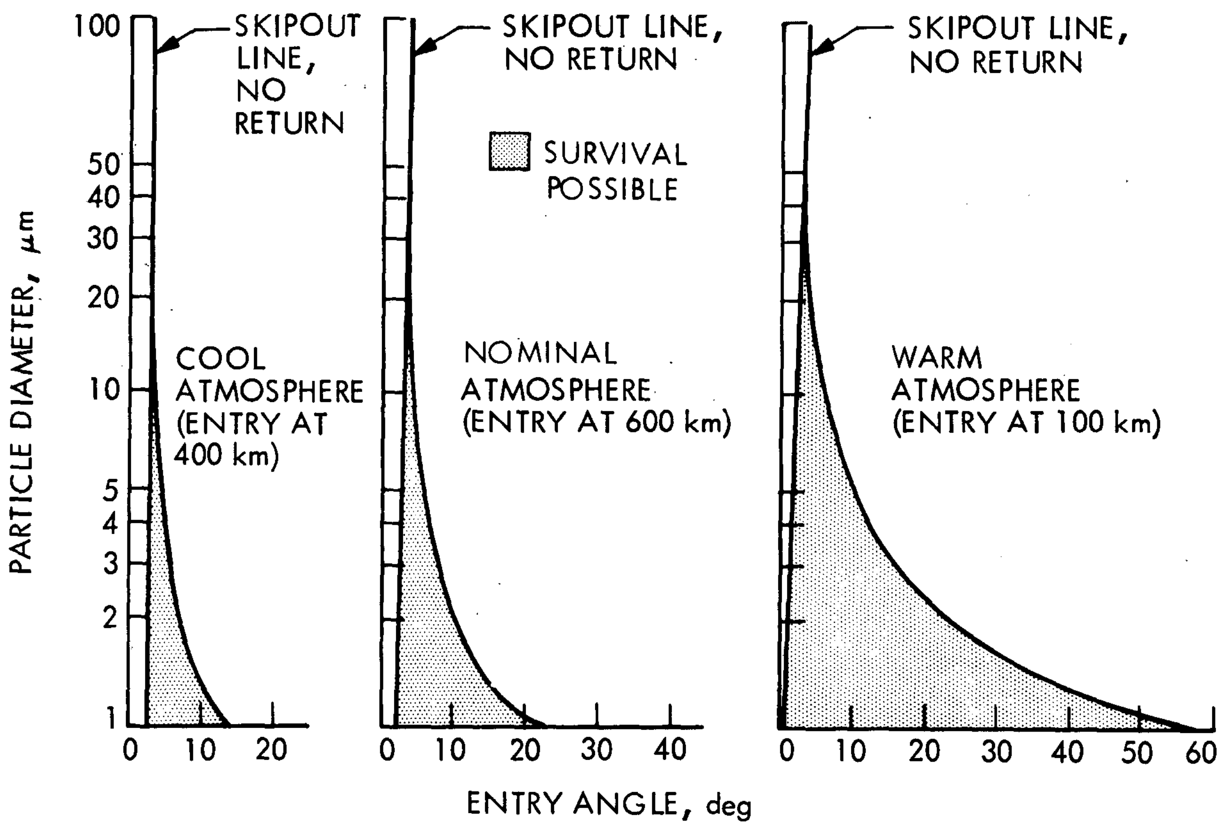

Figure 3. Thermal corridors for plastic particle

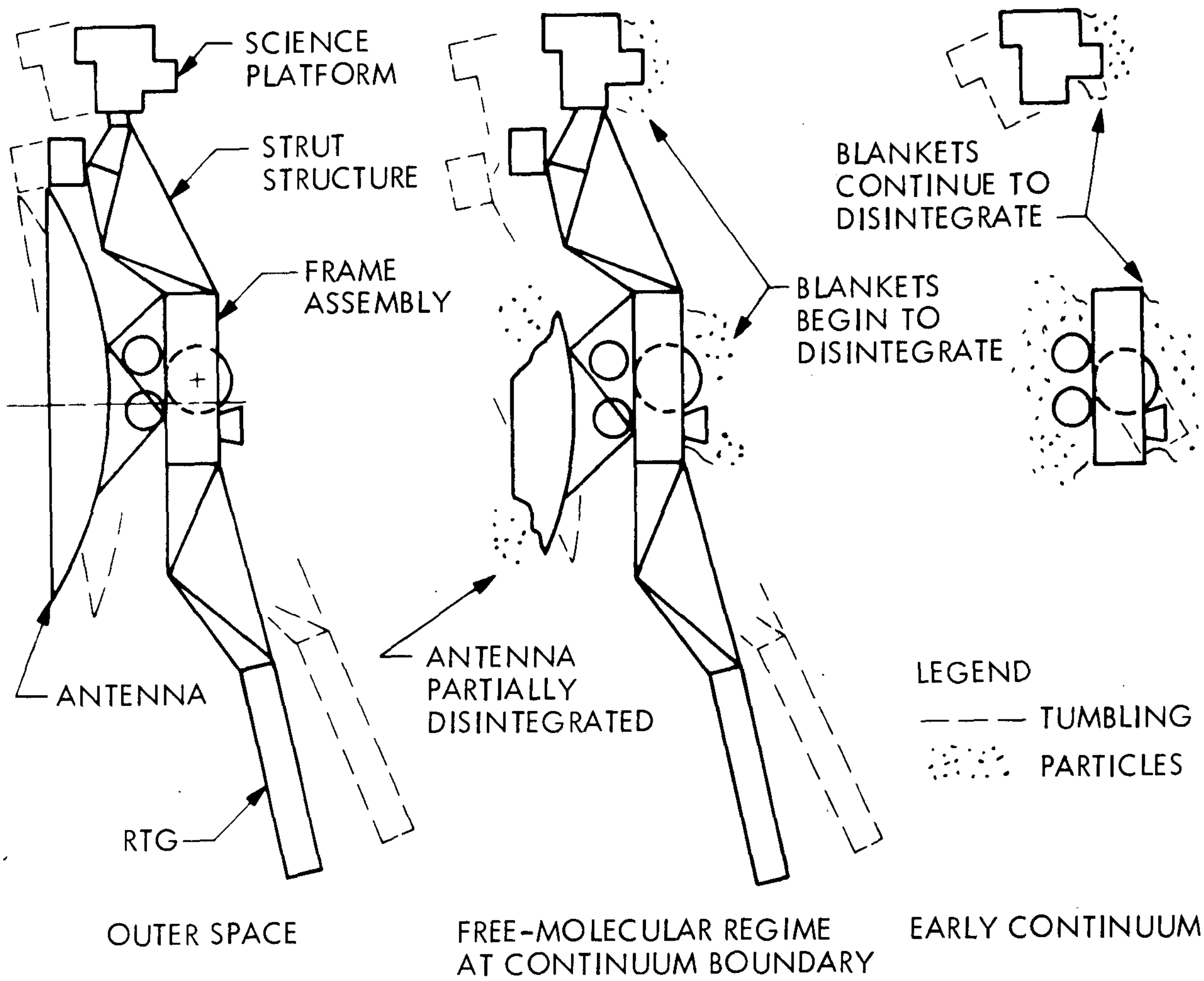

Figure 4. Disintegration stages of outer planet spacecraft

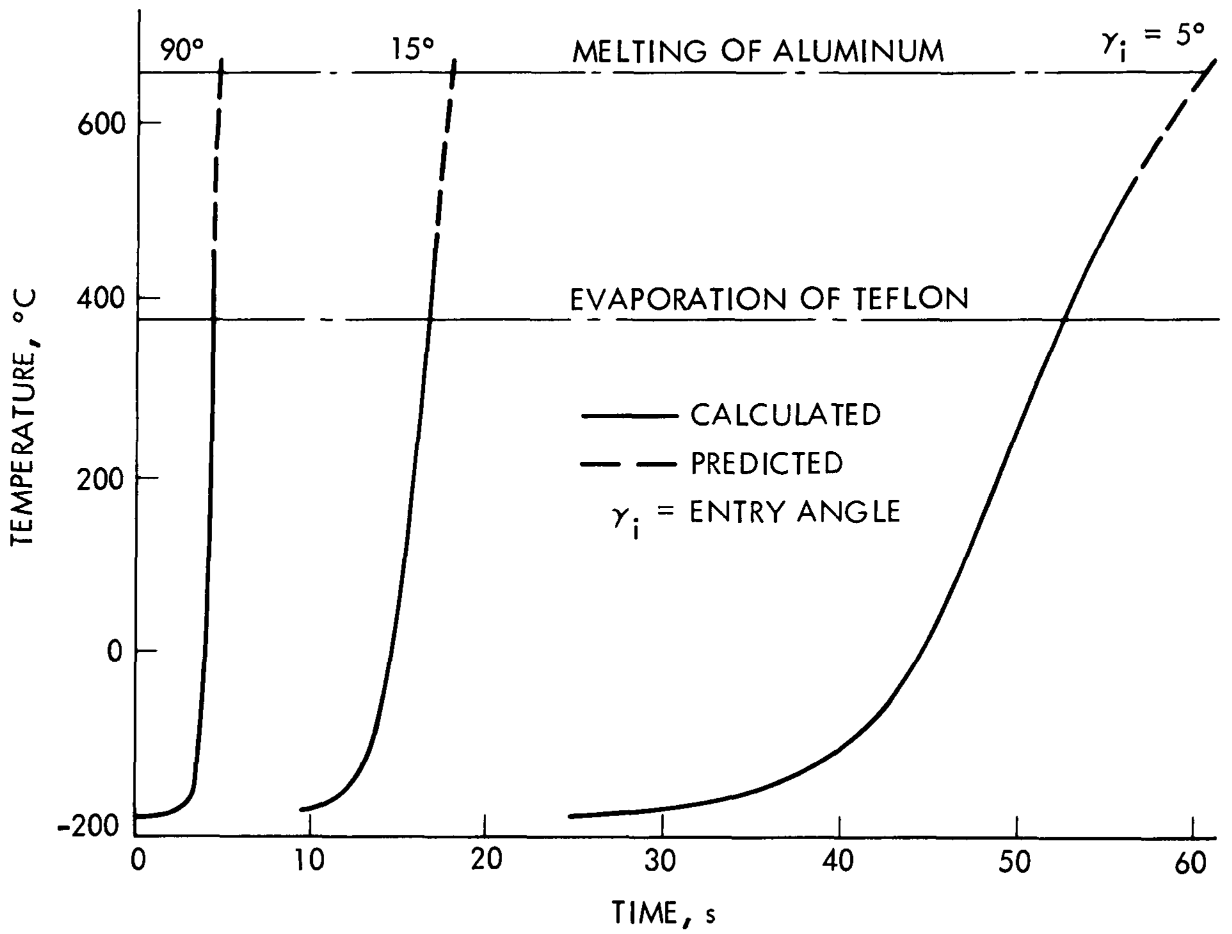

Figure 5. Typical thermal response of blankets and struts of outer planet spacecraft -- nominal atmosphere