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**AEROSPACE
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AEROTHERMODYNAMIC ANALYSIS OF THE SNAP-27 FUEL CASK

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SNAP-27 FUEL CASK

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ABSTRACT

An aerothermodynamic analysis of the SNAP-27 LEM fuel cask is presented for each of three mission aborts. Aerodynamic models for point mass and six degree-of-freedom trajectories are used, and the fuel cask heating rates and temperature responses are predicted for these trajectories. A survey of analytical and experimental studies of separated flow is related to the fuel cask, and a shock tunnel test program is outlined for further fuel cask analyses.

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SUMMARY

Sandia Corporation is responsible for providing independent safety assessments of space isotope power systems. In fulfilling this responsibility, Sandia conducts studies of contractor-submitted systems in order to determine if the design submitted meets all the safety requirements.

It is necessary that the fuel capsule for the SNAP-27 system be capable of intact reentry in case of a mission abort. The SNAP-27 fuel cask has been designed as a reentry body to protect the fuel capsule and thus meet the requirement of an intact reentry. It is therefore necessary to analyze the aerodynamic and thermodynamic characteristics of the fuel cask to determine if the design is capable of providing the fuel capsule with a safe reentry from various mission aborts.

Three mission aborts were analyzed, one at orbital decay velocities and two at supercircular velocities, to determine if the fuel cask would meet its design requirements. Aerodynamic models for point mass and six-degree-of-freedom trajectories were used to obtain reentry flight conditions. Fuel cask local heating rates were determined from AEDC wind tunnel tests on the cask configuration, and these heating rates were used to determine the temperature response of the system. This information predicted fuel cask failure for all reentry conditions, so a survey of various experimental and analytical studies of separated flow was made to determine the validity of applying the AEDC data to actual flight conditions. This study indicated that additional experimental work should be performed at near flight conditions before any definite conclusions could be reached. Therefore, a test program for the Cornell Aeronautical Laboratory Hypersonic Shock Tunnel was outlined in order to provide more applicable heat transfer rates in the fuel cask separated flow region.

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AEROTHERMODYNAMIC ANALYSIS OF THE SNAP-27 FUEL CASK

I. Introduction

As part of a continuing effort to provide independent safety assessments of space systems employing isotope power supplies, Sandia Corporation has conducted a series of aerodynamic and thermodynamic analyses of the SNAP-27 fuel cask. The fuel cask studies include definition of aerodynamic models, three- and six-degree-of-freedom trajectory computations, derivation of local heating rates, prediction of the cask thermal response to reentry environments, and assessment of flow re-attachment in the cavity. Response of the fuel cask center body has been calculated for exposure to environments resulting from mission aborts where potential hazards due to failure of the cask may be anticipated. In scope, the reentry environments considered include both those due to earth orbital decay and to entry into the earth's atmosphere at supercircular speeds. In order to survive these environments, it is necessary that the fuel cask be released from the LEM or other spacecraft components and be allowed to perform as a "free body" near the start of reentry. Aerodynamic and thermodynamic characteristics have been included by the contractor in the cask design to provide aerodynamic damping to low angles of attack and low heating rates through promotion of separated flow at altitudes of cask peak heating. It is the purpose of the Sandia analyses to independently assess the ability of the fuel cask to meet the intended design performance.

II. Results of Sandia Calculations

Trajectory Analyses

Point Mass Trajectories -- The point mass option of the Sandia Corporation theoretical trajectory program A (TTA) was used to calculate trajectories for the SNAP-27 fuel cask when decaying from an earth parking orbit and also when entering the earth's atmosphere at supercircular speeds. The results of these calculations were used to define the environment associated with each reentry mode, and the output of the trajectory computations was used in subsequent thermal analyses of the fuel cask. Zero degree angle of attack continuum hypersonic flow drag data were used to evaluate the ballistic coefficient ($B = 32.54 \text{ lb/ft}^2$). Initial conditions used in the trajectory computations and results of the computations are shown in Figures 1, 2, and 3.

Six-Degree-of-Freedom Trajectories -- The effect of initial angular rates on the angle of attack convergence was determined by using the six-degree-of-freedom aerodynamic model of the SNAP-27 fuel cask without flap; two six-degree-of-freedom earth orbit decay trajectories were calculated to define the effect of the initial angular rate on the angle of attack convergence of the fuel cask. The initial conditions used were:

- (1) 179 degrees angle of attack, no angular rate; and
- (2) 179 degrees angle of attack, 5.74 degrees per second pitch rate.

The results of these trajectories are presented in Figure 4. Thus, at peak heating, the angle of attack for no initial pitch rate is 12 degrees, and for 5.74 degree/sec, the angle of attack is 21 degrees.

In addition, Figure 4 includes information provided by General Electric in the Stage II Release. Thus, for no initial angular rate the Sandia and General Electric curves are in good agreement for peak heating conditions.

The six-degree-of-freedom option of TTA was also used to compute a trajectory for the SNAP-27 fuel cask without flap using an initial angle of yaw of 90 degrees with an initial yaw rate of 0.1 radian/sec. The angle of attack history predicted by this calculation is shown in Figure 5.

It is apparent that a relatively small angular rate at the start of reentry significantly increases the angle of attack at peak heating. These trajectories will be run for the modified cask configuration (with flap) as soon as the mathematical model is completed.

Definition of Fuel Cask Local Heating Rates

The nondimensional heating-rate ratio, F_q , which is defined as the ratio of the cask local heat transfer rate to the stagnation point heat transfer rate on a one-foot radius sphere, was determined from the AEDC wind tunnel data.

The AEDC wind tunnel tests were conducted in a free stream Reynolds Number range from 1×10^6 to $3.4 \times 10^6/\text{ft}$ and at a Mach Number of 8.0. For all these conditions, the test results showed flow attachment in the fuel cask cavity. The resultant heat transfer data were used in thermal analyses of the fuel cask. The measured local rates on the cylinder were averaged over the circumference for a rotating vehicle. Several points along the cylinder were analyzed at various angles of attack. Heating rate distributions are shown in Figures 6 and 7 for angles of attack from 0 to 20 degrees. Figure 7 indicates that as the angle of attack increases, the flow reattachment point moves forward on the cylinder, as expected. On the rear portion of the cylinder, the heating ratios decrease with increasing angle of attack due to the self-shielding of the cylinder. Sandia calculations, described later in this report, show that a heating rate ratio of 0.10 on the cask

center body is sufficient to cause cask failure. Figures 6 and 7 show that a prohibitively high heat transfer rate exists on a portion of the cylinder for all angles of attack considered.

Fuel Cask Thermal Analysis

A two-dimensional heat transfer model of the beryllium cylinder of the fuel cask and the fuel capsule was constructed for use in Sandia's HERMAN heat transfer program.

The nose and flare are not included in the model because construction of the cask is such that heat conduction and radiation to the ends of the capsule and cask cylinder are a small fraction of the radiant heat transfer through the capsule and the cask cylinder. The ends are assumed to be insulated and the model is believed to be an accurate approximation of the cylindrical section of the cask.

A sketch of the model defining the node placement is shown in Figure 8. To account for a possible nonuniform axial distribution of aerodynamic heating, the cylinder and cask were divided into 2-inch segments. Uniform heating was then assumed over each segment, and each segment was assumed to be isothermal for computing the radiant heat transfer between cask and capsule.

In order to assess the validity of this model, a one-dimensional segment was extracted, and the initial temperature and heating rate for the cylinder near the flare, as specified in G.E.'s Stage II Release, was applied. A comparison of this calculation with that presented by G.E. is shown in Figure 9. Both the magnitude and time of occurrence of the maximum temperature are essentially the same as those predicted by G.E. There is a discrepancy during the earlier portion of the trajectory which must be due to a difference in thermal capacity between the two thermal models. The results of this comparison show that any difference between temperatures reported here and those to be reported by G.E. will be substantially due to the different aerodynamic heating rates applied to the cask cylinder.

Convective heating rates to a unit radius sphere for the earth orbital decay trajectory and the superorbital trajectories with initial entry angles of -6.4 and -90 degrees are shown in Figures 10, 11, and 12, respectively. These curves represent the actual heating rates applied for computations utilizing the two-dimensional model. Heating ratios over the cask cylinder are shown in Figure 13. The average heating ratio for each cylinder segment is assumed to apply uniformly over the segment. These heating ratios represent the aerodynamic heating to the cylinder for turbulent separated flow which reattaches to the cylinder upstream from the flare. Initial temperatures used throughout the computations were 950°F for the beryllium cylinder, and 1200, 1240, and 1300°F for the Haynes 25 cladding and inner and outer fuel nodes, respectively.

Results of the heat transfer calculation of the cask cylinder temperature for the orbital decay trajectory are shown in Figure 14 for node 5, which is the segment of cylinder between 7.25- and 9.25-inches downstream from the beginning of the cylindrical centerbody. Results for this node are presented in order to avoid possible end effects. Temperatures of nodes 6 and 7 are higher than the temperature of node 5. It can be seen that the temperature at this position reaches 1600°F at approximately 245 seconds before peak heating for the heating ratios shown in Figure 13.

Temperatures of node 5 for the superorbital trajectories are shown in Figures 15 and 16; the figures show that temperatures of 1600°F are reached at 31 and 2 seconds before peak heating for the trajectories with initial entry angles of -6.4 and -90 degrees, respectively.

III. Analytical and Experimental Studies of Separated Flow with Application to the Fuel Cask

References 1 through 7 are typical of the literature available about separated flow. These references cover both analytical and experimental studies of separated flow and include the prediction of heating rates in the separated region, the location of flow reattachment, and heating rates in the reattached region. Numerous correlation parameters are used:

1. Mach number
2. Reynolds number
3. The ratio of boundary layer thickness at separation to the longitudinal body radius of curvature at the point of separation
4. The ratio of pressure in the separated flow region to free stream pressure
5. The ratio of wall temperature to adiabatic wall temperature
6. The ratio of boundary layer thickness at separation to step height
7. Geometry ahead of the separation (blunt body, slender body, or virtual infinite forebody)
8. Cavity geometry (length to depth ratio and shape)
9. The ratio of radius of curvature perpendicular to flow to step height
10. Laminar or turbulent flow
11. Closed or open flow
12. Amount of mass injection from the body surface
13. Angle of attack.

From the standpoint of comparing data for a specific shape such as the LEM fuel cask, this list of parameters can be reduced to the following:

1. Mach number
2. Local Reynolds number based on conditions at the point of separation and wetted length ahead of separation
3. Geometry ahead of separation
4. Geometry of the separated region
5. Geometry of the reattachment region
6. Angle of attack
7. Ratio of wall temperature to adiabatic wall temperature.

Figure 17 shows the ratio of separated length to step height versus local Reynolds number, based on wetted length ahead of the separation point as predicted by several of the references. The flow reattachment point for the 800 psia AEDC LEM fuel cask tests is also shown for comparison. This point was taken from Schlieren photos (Figure 18) and from the heating ratio plot (Figure 19). The step height on the LFC is 2.5 inches. Figure 17 shows a definite dependence of separation distance on Reynolds number, but the shape of the vehicle is equally important. There is also some discrepancy between the references as to the magnitude and slope of the curves. References 2 and 6 show increasing separation distance with increasing Reynolds number, whereas Reference 3 shows a decreasing separation distance with increasing Reynolds number. Figure 17 also shows the inability of many of the references to predict the reattachment point for the LEM fuel cask under the conditions of the AEDC tunnel tests. The fact that one reference predicted the reattachment point for this one condition is no assurance that it will be accurate at other Reynolds numbers or that the ratios of separated to attached flow heating rates will be correct.

Figure 20 gives the free stream Reynolds numbers for an orbital decay trajectory of the LFC and for lunar return trajectories with reentry angles of -6.4 and -90 degrees. The three Reynolds numbers of the AEDC tunnel test are seen to be higher than the peak heating Reynolds numbers for the orbital decay and shallow lunar return trajectories. Since the reattachment point and the heating ratios in the separated region are functions of Reynolds number, the AEDC data may only apply for a small portion of the LEM fuel cask thermal analysis. The literature search summarized in Figure 17 indicates that there is no way of analytically predicting the heating rates along the cylindrical section of the cask and that there is no way of correcting the AEDC data for actual flight conditions.

IV. Description of Heat Transfer Test of the SNAP-27 Reentry Configuration in the Cornell Aeronautical Laboratory 48-Inch Hypersonic Shock Tunnel

The studies presented in Section II of this report show that for heating rate ratios based on separated cavity flow, the cask will survive entry from an earth orbital decay at zero angle of attack (Figure 9). For heating rate ratios based on attached cavity flow, the cask fails to survive an earth orbital decay trajectory (Figure 14). Because of the importance of the heating rates to the cylindrical center section of the cask and the uncertainties of predicting them analytically (Section III), it was concluded that the cask should be subjected to further experimental tests in which the seven critical parameters described in Section III are matched as closely as possible for trajectories of interest. A description of tests, currently underway at Cornell Aeronautical Laboratory, follows.

Purpose of the Test Program

This test program is scheduled to experimentally study flow reattachment by measuring heat transfer distribution on a one-half scale model of the SNAP-27 fuel cask while it is in a flow regime which simulates, as nearly as possible, conditions encountered during reentry. The points of primary interest on this test are as follows.

1. Heat transfer over the cylindrical portion of the model
2. Visual evaluation, by means of Schlieren photographs, of the flow in the region extending from the cylindrical section back to as much of the aft flared section as is possible to get in the field of view of the Schlieren system
3. The effect of Mach number on heat transfer distribution
4. The effect of Reynolds number on heat transfer distribution
5. The effect of angle-of-attack on heat transfer distribution.

Model Description

The fuel cask configuration (one-half scale) and a hemisphere cylinder calibration model will be tested during each run. Thirty-one heat transfer gages will be mounted on the cylindrical portion of the fuel cask model and four heat transfer gages on the hemisphere cylinder model. Gage location has been selected to determine flow reattachment location and circumferential heat transfer rate distribution.

Test Procedure

Table I lists the conditions for the tests.

TABLE I
Test Conditions

<u>Run Number</u>	<u>Conf. Number</u>	<u>Mach Number</u>	<u>Reynolds Number (ft)</u>	<u>Angle of Attack (deg)</u>	<u>CAL Nozzle</u>
1	1	10.8	2×10^6	0	D
2	1	15.4	2×10^4	0	D
3	1	9.3	2×10^5	0	D
4	1	17.1	2×10^5	0	D
5	1	17.1	3×10^4	0	D
6	1	17.1	3×10^4	8	D
7	1	17.1	3×10^4	16	D
8	1	17.3	5×10^4	0	D
9	1	17.3	5×10^4	6	D
10	1	17.3	5×10^4	12	D
11	1	9.0	6×10^4	0	D
12	1	17.4	6×10^4	0	D
13	1	9.2	1.4×10^5	0	D
14	1	18.4	1.4×10^5	0	D
15	1	10.3	1×10^6	0	D
16	1	18.0	1.4×10^5	0	E
17	1	11.0	2×10^6	0	E
18	1	19.9	4×10^3	0	E
19	1	20.7	7×10^3	0	E
20	1	21.2	1.2×10^4	0	E
21	1	21.2	1.2×10^4	10	E
22	1	21.2	1.2×10^4	20	E
23	1	18.0	2×10^3	0	E

It is anticipated that experimental data from this test will remove many of the uncertainties in predicting the behavior of separated flow in the fuel cask cavity.

V. Conclusions

The Sandia aerothermodynamic analyses of the SNAP-27 fuel cask presented in this report have attempted to assess the behavior of the cask in reentry environments resulting from mission aborts where potential hazards due to cask failure may be anticipated. While some discussion of cask behavior resulting from entry into the earth's atmosphere at supercircular speeds is presented, primary emphasis has been placed on assessment of the ability of the fuel cask to meet the intended design performance in an earth orbital decay trajectory. The following conclusions have been reached.

1. The ability of the fuel cask to damp to small angles of attack at the altitude of peak heating is affected by initial angular rates imparted to the cask at the start of reentry. Results of six-degree-of-freedom trajectory calculations have shown the cask to damp to a 12 degree angle of attack for zero initial angular rate. For an initial angular rate of 0.1 rad/sec the cask damped to an angle of attack of 21 degrees.
2. The location of flow reattachment in the fuel cask cavity moves forward with increasing angle of attack.
3. For the attached flow considered in this study, a prohibitively high heating rate exists over a significant portion of the cask center body for angles of attack from 0 to 20 degrees.
4. For the attached cavity flow and the heating rate ratios based on AEDC test data used in this study, the cask center body will not survive either an earth orbital decay trajectory or entry into the earth's atmosphere at supercircular speeds.
5. For detached flow and the heating rate ratios presented in the G.E. Phase II release, the cask will survive an earth orbital decay trajectory.
6. Based on the results of a literature survey, behavior of the fuel cask cavity flow cannot be predicted with confidence for either the AEDC test conditions or the expected flight conditions.
7. The importance of the heating rates to the fuel cask center section (cask survivability) requires that the cask be subjected to further experimental tests in which the seven critical parameters described in Section III are matched as closely as possible.
8. A final safety assessment of the fuel cask should not be made until results of the Cornell tests become available and a final set of heating rate ratios are mutually agreed upon.

Figure 1. Velocity and altitude versus time for earth orbit reentry of SNAP-27 shipping cask

Figure 2. Velocity and altitude versus time for supercircular reentry ($\gamma_e = -6.4^\circ$) of SNAP-27 shipping cask

Figure 3. Velocity and altitude versus time for supercircular reentry ($\gamma_e = -90^\circ$) of SNAP-27 shipping cask

Figure 4. Maximum angle of attack variation with altitude for SNAP-27 fuel cask, with and without an initial angular rate

Figure 5. Maximum angle of attack variation with altitude for SNAP-27 fuel cask

Figure 6. Heat transfer ratio from AEDC data

Figure 7. Heat transfer ratio from AEDC data

Figure 8. Heat transfer model for fuel cask cylinder and fuel capsule

Figure 9. Temperature of a 0.1 inch cask cylinder for an orbital decay trajectory

Figure 10. Stagnation point heating to a 1 ft radius sphere for an orbital decay trajectory from 400,000 ft

Figure 11. Stagnation point heating to a 1 ft radius sphere for a superorbital trajectory from 400,000 ft

Figure 12. Stagnation point heating to a 1 ft radius sphere for a superorbital trajectory from 400,000 ft

Figure 13. Heating ratio for the cask cylinder

Figure 14. Temperature of node-5 for orbital decay trajectory

Figure 15. Temperature of node-5 for superorbital trajectory

Figure 16. Temperature of node-5 for superorbital trajectory

Figure 17. Ratios of reattachment distance to step height for backward facings steps

Figure 18. Schlieren photograph showing beginning of flow reattachment for 800 psia AEDC LEM fuel cask tests

Figure 19. Heat transfer ratio from AEDC data

Figure 20. Freestream Re_∞/ft for LFC reentries and for AEDC aeroheating tests

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