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Development of the Astrobee F Sounding Rocket System

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Introduction

THE Astrobee F sounding rocket vehicle was developed from a dual-thrust, long-burning, solid propellant rocket motor developed for the NASA Office of Aeronautics and Space Technology to demonstrate new propulsion technology. The concept for a dual-thrust extended burning solid rocket motor grew out of earlier studies performed for NASA-OAST. The first application of these concepts was the development of the 6-in. diameter dual-thrust Astrobee D which has previously been reported.[1] The Astrobee F propulsion system was an extension of the design concept utilizing hydroxyl-terminated polybutadiene (HTPB) propellant designed to have very low burning rates. A relatively neutral pressure history is maintained during the sustain portion of burning by use of a one piece molded plastic ablating nozzle.

An abbreviated static test program included four static firings augmented by a well-instrumented flight test which featured an attempt to recover the motor as well as the payload. Thus, the first flights of the vehicle became "high altitude static tests." Upon successful demonstration of the Astrobee F propulsion system, a vehicle design and flight test program was initiated by NASA Goddard Space Flight Center for the demonstration of the propulsion system as part of a complete sounding rocket vehicle (Fig. 1).

Motor Development

The general concept of the Astrobee F was similar to that of the Astrobee D, in that the motor provides a dual-thrust level; a short, high-thrust level boost-phase followed by a relatively long, low-thrust level sustain phase. The extended sustain phase was to provide the advantages of a low level of drag, aerodynamic heating, and dynamic pressure, all of which have a significant effect on payload design and environment. The Astrobee F environment is similar to the liquid Aerobees.

There was concern that a one piece molded plastic nozzle similar to that used on the Astrobee D might not be scalable for use on a significantly larger size Astrobee F motor. Variations in molding technique, materials preparation and post cure were tried. These tests resulted in the largest known single piece molded nozzle. The nozzle, which is of a 13.5-in.-diam, uses 49 lb of glass phenolic material. The nozzle section thickness tapers from 3.5 in. to 0.5 in.

The first Astrobee F motor was fired on Dec. 2, 1970. The motor achieved the desired propulsion parameters and burned for a duration of 50 sec. Examination of the motor after firing, showed the internal insulation had eroded at a localized area in the aft section of the motor and that the case material had been heated to the point of distortion. Examination of the liner revealed that material remained through approximately 270° of the aft portion of the chamber, but that all material had been removed in a portion of one quadrant. A number of potential causes for this asymmetrical erosion were considered and what appeared to be a reasonable hypothesis was formulated.

The second unit was fired on Feb. 18, 1971. Propulsion-wise, it appeared to be nearly identical to FF01 with a smooth transition between the high-pressure boost and the low-pressure sustain portion, as predicted. Operation was normal through approximately 42 sec when the chamber pressure took a sharp drop. Upon examination, the motor was found to have burned through in one quadrant in the aft portion of the chamber. Subsequent examination of the linear system revealed an identical erosion pattern to that of FF01. That is, adequate insulation through three quadrants with one quadrant having been reduced to zero insulation. It became apparent from the results of this

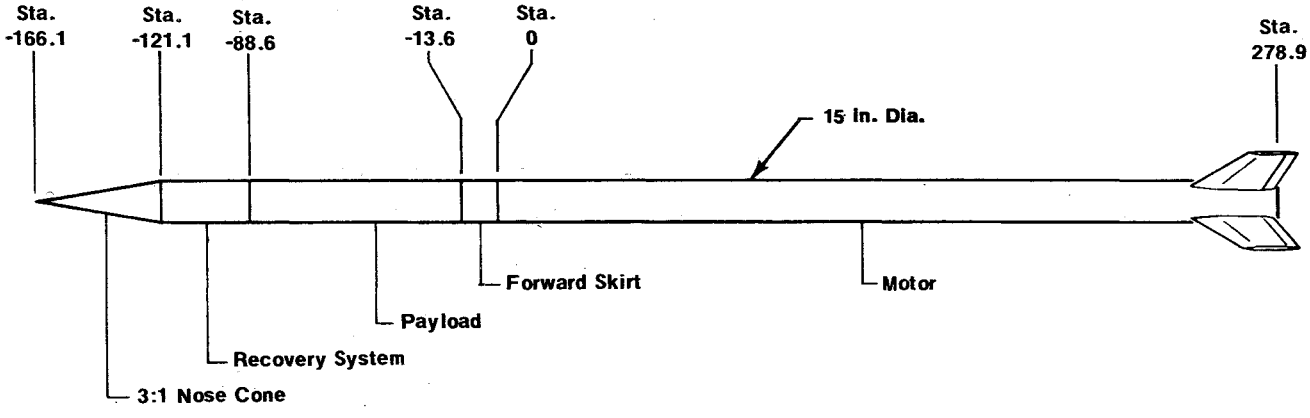

Fig. 1 Astrobee F flight test vehicle.

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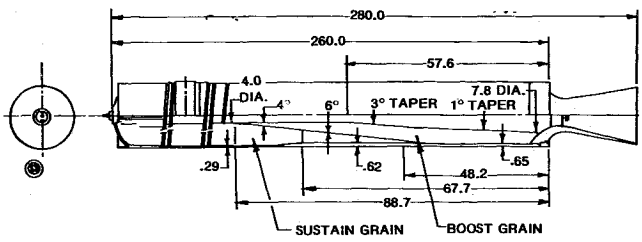

Fig. 2 Astrobee F motor grain configuration.

test that the previous explanations were inadequate to explain the observed phenomenon.

Extensive efforts were made by both Aerojet and NASA personnel to determine the flow mechanism that might result in the asymmetrical erosion. Numerous flow tests were run at the NASA Langley facility with various grain interface and flow simulations. It was determined that the vertical interface between the sustain and boost grain resulted in a condition that caused a high Mach number jet exiting from the sustain grain port into a plenum formed by the removal of the boost grain. This jet, because of the abrupt interface, did not fully expand but rather attached itself to the chamber wall in a preferred position. This fluid dynamic phenomena is referred to as the Coanda effect.[2]

The design was changed to provide for a low angle expansion from the sustain grain into the boost plenum. This revised configuration is shown in Fig. 2. The sustain grain was cast in place with a long tapered section. The boost grain was then cast over the sustain grain giving a tapered interface.

For the third motor the liner was augmented by the addition of a 0.3-in. thick rubber insulator, similar to that used for the forward release boot. The FF03 motor with the new grain configuration was successfully fired on Sept. 23, 1971. Examination of the motor case indicated that the erosion resistance of the liner was not as great as had been anticipated from results obtained from the Astrobee D program.

To compensate for this lower erosion resistance, a tapered insulator of V-45 rubber was installed in the aft section of the chamber. This rubber insulation was then overlined with the liner material.

Motor FF04, which had originally been designated for flight test, was static fired in March 1972 to demonstrate this revised configuration. Adequate insulation was found to remain in all areas of the motor.

In all firings there was no evidence of combustion stability problems. Transitions from the boost phase to the sustain phase, an abrupt 4:1 decrease in operating pressure, were remarkably smooth in all cases.

Motor FF05 was then fabricated in the same configuration as FF04 and was subsequently used for flight test (Fig. 3).

The following propulsion technology developments were successfully demonstrated during the motor development phase of the Astrobee F program: 1) tandem dual grain boost/sustain operation; 2) extended burning time for radial burning grain (50+ sec for 15-in.-diam motor); and 3) net molded large plastic nozzle without inserts.

Vehicle Design and Development

The Astrobee F vehicle design concept results directly from a conscious effort to duplicate the highly desirable features of the standard Aerobee vehicle system. The dual thrust level motor yields a single stage vehicle having a relatively low wind sensitivity and a relatively mild flight environment, in terms of both dynamic pressure level and aerodynamic heating. The nominal performance design goal was placement of a gross payload of 225 lb at 215 statute miles apogee altitude, for an 87°, no wind, launch from sea level (Fig. 3). The relatively long burn time of the motor, approximately 54 sec, and the mass properties of the vehicle result in minimum stability near burnout at altitudes of 175,000 ft, thus elastic effects on minimum static margin are negligible. Where elastic effects are significant, near-maximum, dynamic pressure, static margin is very high. Since the dynamic pressure environment, about 2400 psf max, is less than that of the Aerobee system, the vehicle loads environment is similar.

Flight Test

Wallops Island was selected for the first flight of the Astrobee F Sounding Rocket System designated NASA Flight 12.020 GT. The entire vehicle was to be recovered, excepting the empty nose cone.

A new recovery system was designed to function in a dynamic pressure up to 250 psf, in the normal Aerobee recovery mode. As a result of failure of the fin severance subsystem, the flight test vehicle failed to achieve the desired re-entry attitude. The vehicle re-entered in a stable mode thus producing excessively high dynamic pressure (1900 psf) and an unacceptable nosedown attitude for chute deployment. Yet, recovered fragments and telemetry data indicate the system went through proper sequencing and ejected the cover plate and drogue chute.

The flight was successful except for final recovery. The following conclusions can be drawn:

1) Operation of the motor appeared completely normal. Average boost phase chamber pressure was 1160 psia for $2\frac{1}{2}$ sec and average sustain phase chamber pressure was 250 psia with "tail-off" beginning at $t+38$ sec and burnout at $t+54$ sec (Fig. 4).

2) The vehicle angle of attack, in the sensible atmosphere, never exceeded $\frac{1}{2}°$.

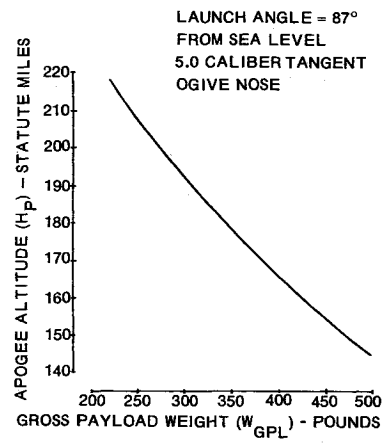

Fig. 3 Astrobee F normal vehicle performance.

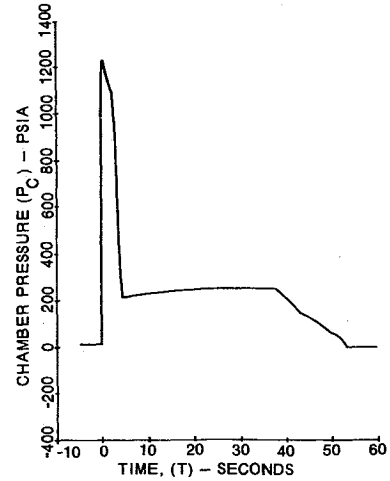

Fig. 4 Motor chamber pressure.

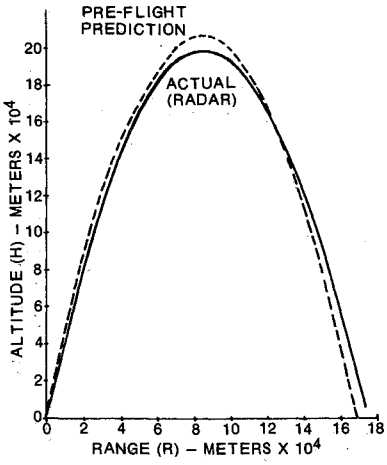

Fig. 5 Flight test vehicle trajectory.

3) Burnout roll rate was 3.4 rev/sec; the fins were set to produce a theoretical 2.5 rps. However, fin conduit facing interference effects were unaccounted for.

4) Burnout velocity was 1737 m/sec at an altitude of 48 km; predicted values were 1772 m/sec and 46 km. Performance was near predicted (Fig. 5).

5) Longitudinal acceleration averaged about 11.5g during boost phase, dropped to about 1g at boost phase burnout, then rose to a sustain phase maximum of about 6.3g at $t+38$ sec.

6) No significant temperature rise occurred anywhere on the motor during burn. Payload temperature was of the order of magnitude expected (Fig. 6).

7) Vibration input to the payload, once the vehicle was out of the tower, varied from about 1.2g to about 4g, peak to peak, at about 1 kHz in the lateral planes and from about 1.5g to 3g, 1 kHz in the thrust direction.

8) The vehicle exited the tower at $t+0.96$ sec with a velocity of 84.5 m/sec.

9) The two lateral accelerometers in the tail show a peak to peak vibration of 10g–12g at moderate frequencies. The apparent correlation between the amplitude-time characteristic of this vibration and the dynamic pressure vs time curve suggests that the observed vibration is influenced by, perhaps dominated by, aerodynamics rather than the motor and is most likely due to interactive flow phenomena between the conduits and the fins which were not aligned with each other.

10) The recovery of the vehicle failed because the fins were not jettisoned.

The main parachute, its bag, the flotation bag and its bag, and portions of the drogue chute bag were recovered. Entangled in the mass of nylon and webbing were a number of fragments from the recovery system itself and from the payload, indicating that the vehicle payload section of the vehicle disintegrated at impact.

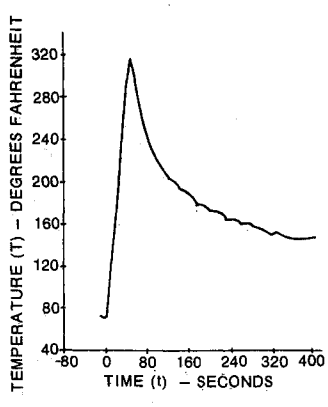

Fig. 6 Forward skirt door temperature.

Summary

A successful program for the demonstration of a new propulsion system with the stated new technology features and the integration of this motor into a flight vehicle was accomplished.

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Blowing Simulation of Asymmetric Transition Effects on Slender Ablating Vehicles

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THE effects of aft body asymmetric transition on slender vehicle aerodynamics as measured by Martellucci and Neff,[1] using blowing to simulate ablative mass addition, seem to be in sharp contrast to what has been presented in Ref. 2 (see Fig. 1). The negative aerodynamic loading induced by asymmetric transition should have the highest slope at $\alpha = 0$ and not at some intermediate value like $\alpha = 0.5°$.

In order to understand the peculiar behavior of the transition-induced characteristics in Fig. 1, the author consulted the data source.[3] As sketched in the insets in Fig. 2, there are two important α-parameters in a test simulating asymmetric transition effects on an ablating model using blowing. The blowing area was shaped to conform to the free transition front measured on the nonblowing solid model (with smooth surface) at a certain angle of attack $\alpha = \alpha_{AT}$. The aerodynamic loads for various blowing rates were then measured as a function of α for three blowing geometries, i.e., those with blowing fronts corresponding to the transition lines for $\alpha_{AT} = 0°$, 1°, and 2°. The freestream unit Reynolds number was kept constant at the value used when defining the transition front geometry on the solid model.

Even when the transition front is far upstream of the base, thereby minimizing the sting interference which (otherwise) can be large for models with boundary-layer mass addition,[4] one faces several problems when attempting this type of simulation of asymmetric transition effects, as is discussed by Martellucci and Neff.[1] Using an impervious forward section for the laminar flow region may give the turbulent blowing rate increment a larger effect than it has in presence of forebody blowing (at laminar levels). At low blowing rates the breathing and tripping effects of the porous surface itself also have to be considered.[5–8]

In spite of these simulation difficulties, one can postulate that at some angle of attack close to $\alpha = \alpha_{AT}$ the free† transition effect is indeed simulated. With this in mind the author went

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† "Free" means with transition free to move with α, as is the case on the ablating flight vehicle.