FIN STRUCTURAL DESIGN FOR HIGH PERFORMANCE SOUNDING ROCKETS

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Abstract

Design of the Bristol Aerospace "Black Brant" sounding rocket family had, as its main objectives, provision of vehicles of low cost, high efficiency, and low wind sensitivity. These requirements resulted in use of relatively short burning-time solid propellant motors, and acceptance of design peak dynamic heads approaching 1,000 KN/m^2 (21,000 p.s.f.). In consequence, vehicle stability is significantly influenced by aerothermal-elastic effects, and the more conventional solutions to the associated problems of fin thermal control and structural design were rejected. Instead, an inexpensive form of ablative insulation is employed and lightweight bonded sandwich structures were evolved. These solutions are together considered to represent a significant extension to the state of the art, as applied to the low-cost sounding rocket field. They are also extensively flight proven. Vehicles employing such fin structures have repeatedly demonstrated that fin effectiveness and structural integrity are entirely satisfactory. Achieved roll rates and vacuum coning motion have closely conformed with predicted values with a complete absence of vibration or lateral acceleration during low-altitude roll-yaw resonance. Altitude performance is in no way degraded by the ablation process.

I. Introduction

The continuing need to improve the efficiency and utility of the high-performance sounding rocket has resulted in adoption of progressively more sophisticated design techniques. Customer requirements have also become more exacting, as experimental payloads increase in complexity and cost. However, if the aeronomy rocket is to remain a truly useful scientific tool, it must meet these new demands and yet stay a simple, highly reliable, inexpensive device, capable of being launched without fuss from a minimal facility.

To resolve these often conflicting requirements, Bristol Aerospace Limited have developed the "Black Brant" family of rocket vehicles, using design techniques and manufacturing processes which are, in part, radical in application, yet still compatible with the overall design objectives. These techniques and precesses are well illustrated in the structural design of the fins, which have solved new aerothermal-elastic problems by use of ablative materials and bonded sandwich structures.

This paper will describe the design and test programs associated with the development of these fin structures, with an outline of how the structural properties are related to the design and performance of the complete vehicle.

II. Ablative Insulation

Design Considerations

Bristol Aerospace Limited entered the sounding rocket field with the single-stage Black Brant III - See Figure1. This is a 25.9 cm (10.2 in.) diameter, 5.5 metres (18 ft.) long vehicle, which lifts a 23 Kg (50 lb.) useful payload to a nominal apogee altitude of 170 Km (105 statute miles). To minimize impact dispersion, a radial burning propellant geometry was adopted, with a total burning time of approximately 12 sec. Achieved trajectory properties are given in Figure 2, and include a peak dynamic head of 900 KN/m^2 (18,900 lb./sq. ft.) coincident with a Mach. No.

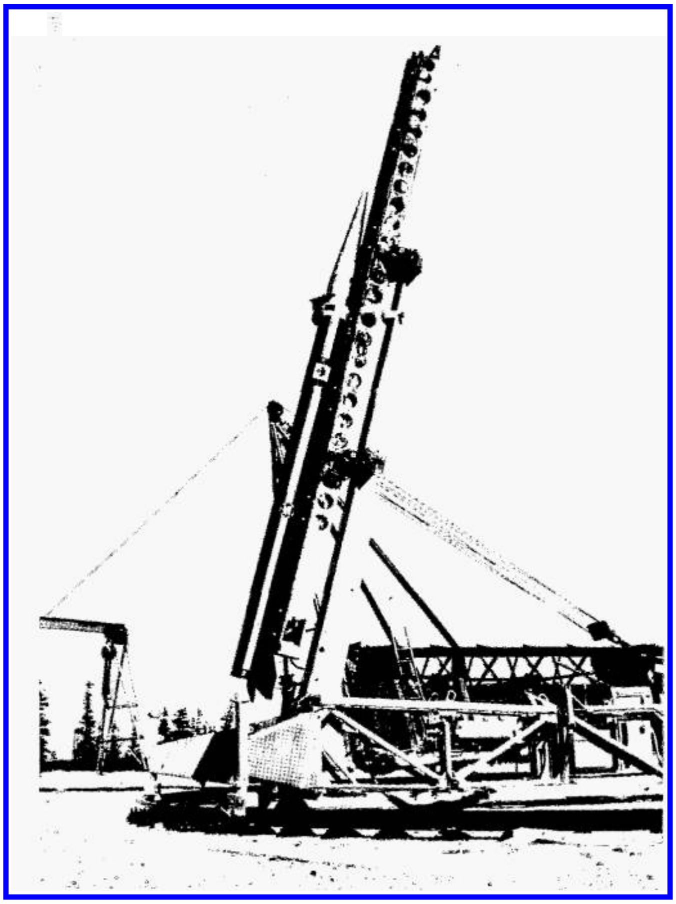


Figure 1 Black Brant III

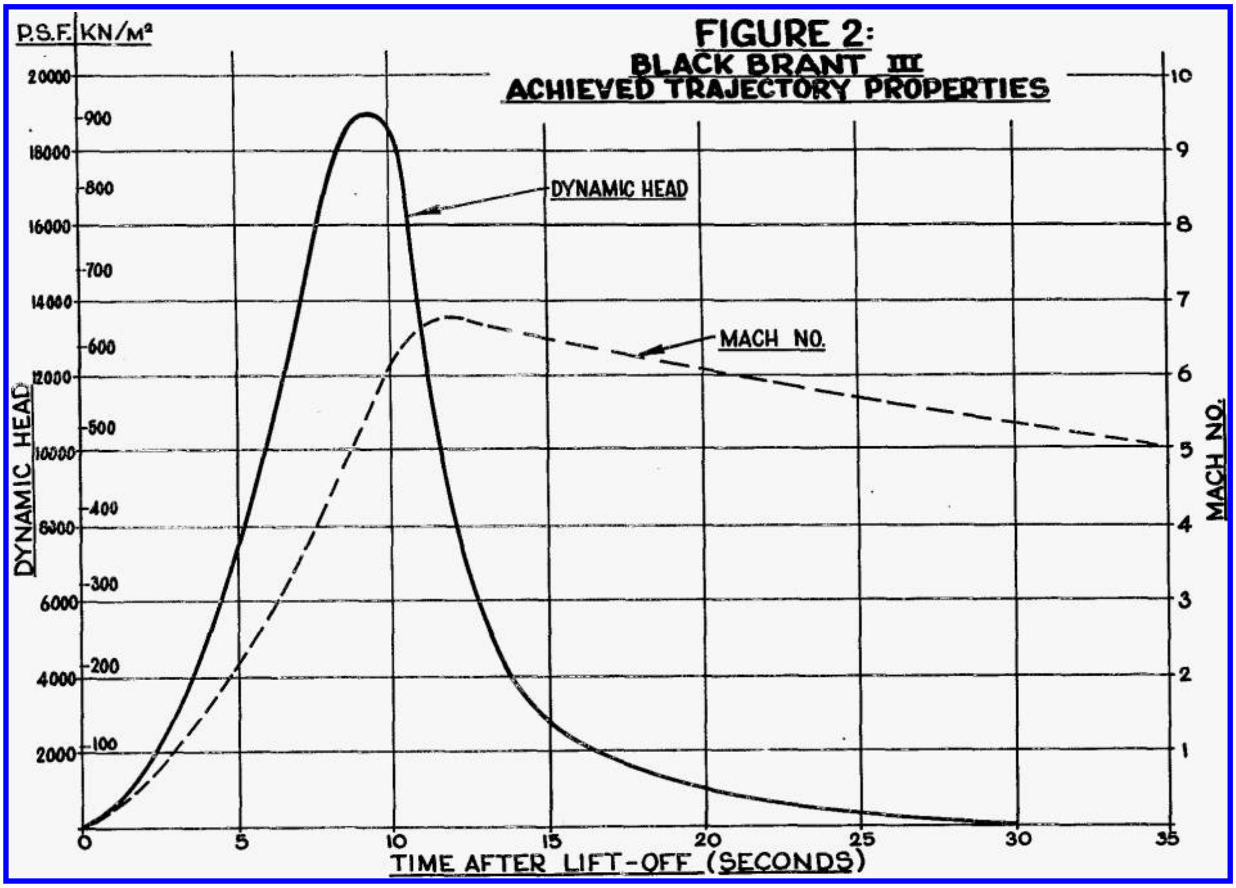


FIGURE 2:
BLACK BRANT III
ACHIEVED TRAJECTORY PROPERTIES

of 5.5. Super-position of the effects of fin elastic deflection upon the decay of "rigid-body" C_{n_α} with increasing Mach. No. , and inclusion of the influence of elastic modulus reduction due to aerodynamic heating, presents stability problems which dictated a new look at fin design. The more conventional sounding rocket solution, i.e., a steel and/or titanium heat sink, was shown to result in a fin structure of unacceptably high weight and planform area. Therefore, it was decided to examine in detail the application of an ablative insulation to a relatively light-weight load carrying fin "blade".

The problem was to select an insulant which provided high fin efficiency without an unrealistic cost penality. Laboratory tests of a wide range of materials were run to establish relative insulation properties under the anticipated heat flux history, the more promising configurations being inserted into a representative high-dynamic head, high temperature gas flow, The fin structure thus evolved initially into:-

i) a thorium-magnesium structural fin "blade"
ii) an erosion-resistant titanium leading edge sheath
iii) a surface covering of ablative insulation, comprising 1.14 mm (0.045 inch) thick "Stanpreg" phenolic reinforced fiberglass.

The first four Black Brant III vehicles to be launched used fins of this design. While generally successful, the flights were all marred by a transient build-up of lateral acceleration prior to thrust tail-off, coincident with the instant of peak dynamic head. Studies were therefore directed towards obtaining a more accurate assessment of aerothermal-elastic effects, and to further examine the integrity and behaviour of the Stanpreg insulation.

Aerothermal-elasticitv

Using a flight-standard fin, loaded by air bags simulating the fin pressure distribution at the maximum dynamic head point in the trajectory, the fin lateral deflection distribution was experimentally determined. This data was then integrated to assess the effective normal force coefficient of the flexible fin, by use of the simple relationship:-

$$\frac{C_{n_{\alpha}\,\text{Rigid}}}{1+\delta F}$$

Where δ = an inverse stiffness (fin incidence change per unit fin normal force)

α ="rigid" vehicle incidence

F = fin normal force at incidence α

The theoretical data were compared with wind-tunnel measurements made on model fins by the Canadian National Aeronautical Establishment. In the latter tests (1) Cn_α was measured over a limited dynamic head and Mach. No. range, using fins fabricated from steel, titanium and Scotchply plastic. It can be shown that, for a thin elastic solid wing of arbitrary planform and slowly varying thickness in a uniform airflow, the local aeroelastic rotation is proportional to: -

$$(1 - \nu^2) \times \frac{q}{E} \times \frac{(L)^3}{(t)^3} \qquad (2)$$

Where E = elastic modulus of the fin material

3 = Poission's ratio

t = root thickness

L = characteristic dimension

q = dynamic head

Using the wide variation in elastic modulus afforded by the three test fins, the wind tunnel results were extended to cover the dynamic head range of Black Brant III. These data are then generalized by a presentation of the movement of aeroelastic centre of pressure with q/M, and theoretical values (based on equation 1) superimposed. Reference Figure 3, excellent correlation is noted, particularly at the point of minimum aeroelastic static margin (q/M = 150 KN/m^2, or 3150 p.s.f.).

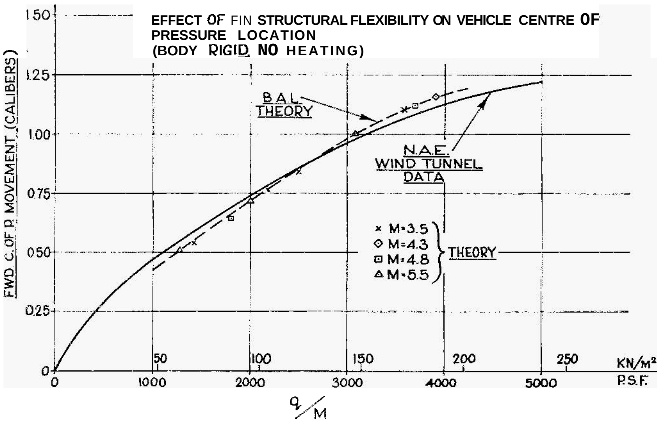


Figure 3 Black Brant III

To complete the refined analysis, an iterative mathematical process was developed in which fin and body flexibility, corrected for elastic modulus loss due to aerodynamic heating, are included in a final calculation of the static margin. The results indicated that the aeroelastic loss was significantly higher than predicted in any earlier, more approximate analysis.

Insulation Studies

It was established that if asymmetric ablation occurred, the differential loss of fiberglass insulation would lead to significant fin torsional deflections.

This condition was not so much the result of differential heat inputs to the fin blade, as it was the loss of the stiffness contribution from the fiberglass itself. Clearly, the process of ablation could not be permitted to affect fin blade properties - i.e. use of a very low elastic modulus thermal insulant became mandatory.

Final Production Configuration

The foregoing dictated two modifications to the fin design, viz:-

i) a switch from magnesium to aluminum, to provide a structural substrate of improved stiffness/weight ratio at peak operating temperatures

ii) use of Avcoat insulation in lieu of fiberglass, thus providing an ablative coating of approximately equal efficiency but of negligible elastic modulus. This change also improved the insulant-fin blade bond, and reduced production costs.

The Avcoat is cast into 1.52 mm (0,060 inch) thick sheets, and attached to the parent material by liquid Avcoat, bonded under pressure, and finally post-cured at elevated temperatures. Very accurate control of fin profile is achieved.

Flight Characteristics

Thirteen vehicles have been flown with fins of the final production configuration. All have exhibited excellent aerodynamic characteristics, in particular: -

i) the previous large transient lateral maneuver at peak dynamic head point was eliminated.

ii) the ability of the fin to accurately provide a predefined finite roll rate history has been repeatedly demonstrated.

iii) roll-yaw resonance has been intentionally incurred at low altitude and high dynamic head, with virtually zero associated lateral acceleration build-up.
The subsequent vehicle in-vacuum coning motion has had a maximum half-angle amplitude of 14° , during a total of five such flights

iv) it has been proven that use of ablative insulation in no way degrades vehicle altitude performance

v) impact dispersion. for apogees of from 110 Km to 200 Km (70 to 122 statute miles) has never exceeded 11 Km (7 statute miles), compared with a predicted 3σ dispersion radius of 48 Km (30 statute miles).

vi) the fin production process have proved inexpensive and capable of accurate quality control, and the need fox on-range fin measurements or setting adjustments have been completely eliminated.

III Bonded Sandwich Structures

Concept Development

The Bristol Aerospace Limited Black Brant V (see Figure 4) evolved as a logical development of the older Black Brant IIA rocket. However, in order to meet a wide range of customer performance requirements, the new vehicle was designed to use either a new 26KS20000 motor, or the existing 15KS25000 propulsion unit of the Slack Brant IIA. With the 26KS20000, 114kg (250 lb.) useful payloads can be lifted to 365 Km (227 statute miles) apogees, and design peak Mach. No. is 9.0. Using the 15KS25000, the same payload will reach 156 Km (97 statute miles), and design peak dynamic head is 670 KN/m^2 (14,000 p.s.f.).

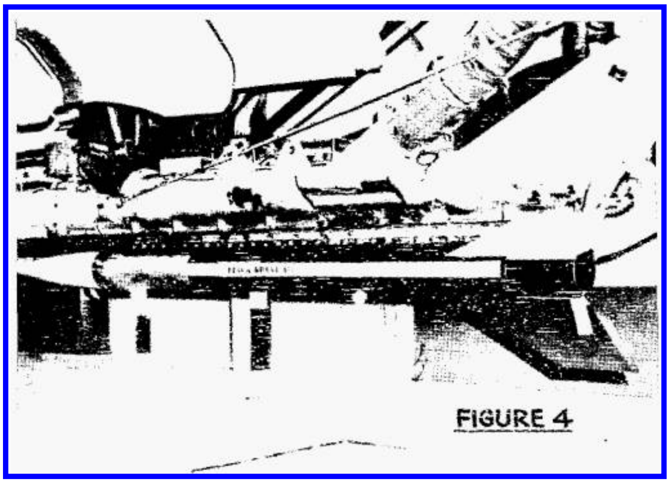


FIGURE 4

To obtain the desired performance and still cater for the wide range in operational environmental conditions resulting from use of two different motors, it was decided that the fin design should combine the now-proven ablative thermal insulation technique with a light-weight bonded sandwich structure. This form of construction, while dimensionally impractical on the smaller Black Brant III, promised to provide significant overall benefits due to the sizeable decrease in both weight and weight/stiffness ratio, compared with that obtainable from relatively homogeneous fin structures.

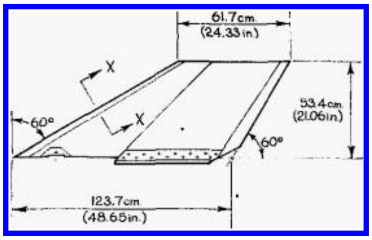
Initially, fin core studies encompassed:-

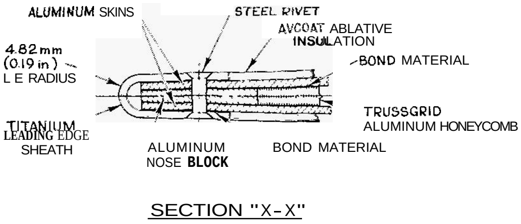
i) a machined aluminum slab with a multitude of small lightening holes. This was quickly rejected as being Excessively heavy and costly.

ii) application of one of the various "improved woods". This initially appeared an attractive solution, but was eventually rejected since the complete structure would be of questionable integrity when associated with high heating rates

iii) use of an aluminum honeycomb. This was the chosen solution, the selected product being Trussgrid (8.1 lb. cu. ft. razed density].

FIGURE 5: BLACK BRANT V FIN STRUCTURAL DETAILS





The fin structure thus became a shaped block of Trussgrid (the honeycomb "grain" being suitably aligned with respect to the mean spanwise flexural axis), to which was bonded sheet aluminum skin facings and an aluminum nose block. Thermal protection was identical to that of Black Brant III, i.e., a titanium leading edge sheath and an Avcoat ablative coating (See Figure 5). The structural concept has also been applied to the booster fins of the two-stage Black Brant, IV. This latter vehicle (See Figure 6) combines the Slack Brant III with a 15KS25000 motor, to lift a 23 kg (50 lb.) useful payload to 1000 Km (622 statute miles); and as such, utilizes an identical fin supporting structure as the Black Brant V. To optimize the fin design of Black Brant IV and V, numerous small photo-elastic models were built, the resulting stress and deflection data being reviewed in conjunction with aerodynamic properties. It was thus possible to arrive at a fin design which afforded maximum aeroelastic stiffness with no meaningful loss in aerodynamic efficiency.

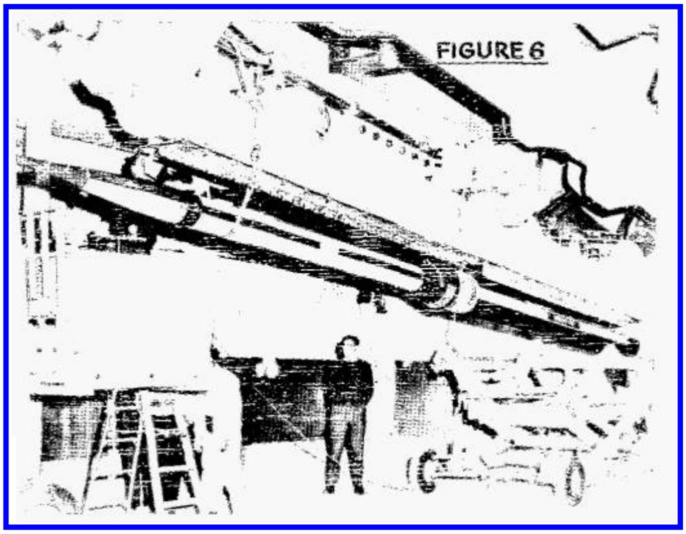


FIGURE 6

Aeroelastic Tests

To confirm the predicted aeroelastic characteristics, the National Aeronautical Establishment performed similar wind tunnel tests to those carried out on the Black Brant III (1). The results are shown in Figures 7 and 8. K is a stiffness parameter, defined as:-

$$K = \frac{4q}{(M^2-1)^{1/2}} \times \frac{b}{100} \times \frac{E_o}{E} \qquad (3)$$

Where:- q = dynamic head
M = Mach. No.
b = fin span
E_o = elastic modulus at room temerature
E = elastic modulus of heated structure

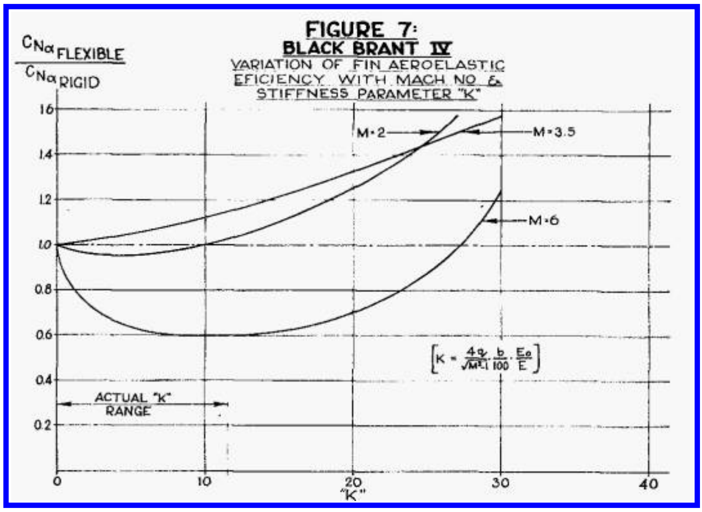


FIGURE 7: BLACK BRANT IV VARIATION OF FIN AEROELASTIC EFICIENCY WITH MACH NO & STIFFNESS PARAMETER "K"

The actual K-range of each vehicle is also shown. Note that the aeroelastic efficiency of the Black Brant IV fin remains very high until about M=4.5. Since the Mach No. at maximum dynamic head is 4.0, and at stage separation is 5.0, no problem exists. However, at still higher Mach Nos., the tip Mach cone creates an adverse aeroelastic condition, due in part to use of a very low aspect ratio, overall constant thickness "slab" fin. Postponing the loss beyond the booster stage operating Mach No. envelope permitted the design to take advantage of a separate cost-effectiveness study, which had shown the drag penalty of "slab" fins to be negligible, while cost savings are significant. For the much higher Mach number single-stage Black Brant V application, increased aspect ratio, modified double-wedge aerofoil section and spanwise thickness taper were mandatory; therefore the Mach cone effect is not experienced and fin aeroelastic efficiency remains high.

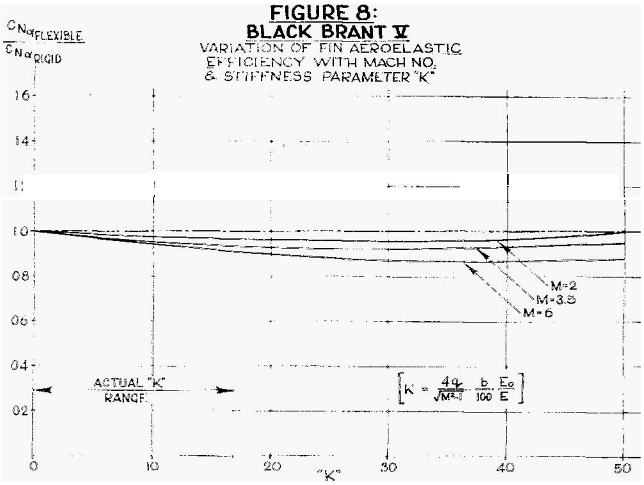


FIGURE 8: BLACK BRANT V VARIATION OF FIN AEROELASTIC EFFICIENCY WITH MACH NO. & STIFFNESS PARAMETER "K"

Structural Tests

To ensure the integrity of the skin-Trussgrid bond, control bend tests of heated beam assemblies were performed. Applied bending moments were determined from data obtained from previous tests on photo-elastic fin models. To confirm the final design, a full-size structural prototype was then built for measurement of overall stress and deflection distributions. The latter data could then be converted into influence coefficient format, applicable to flutter calculations.

Fabrication

In quantity production, the bonded sandwich structure has posed few problems, while proving to be an economic concept. For the Black Brant IV fin, Trussgrid is purchased in the finished thickness, and rework confined to cutting the sheets to planform shape. The modified double-wedge section and spanwise thickness taper of the Black Brant V fin is achieved by machining the Trussgrid surface to approach the required thickness distribution, and then crushing to the final overall contour.

When complete, both fin designs are dimensionally accurate to a high degree. All fin "blade" surfaces are flat to ± 0.39 mm (0.915 inches), thickness is everywhere controlled to ± 0.13 mm (0.005 inches), and root-io-tip twist never exceeds ± 0.003 radians. As with the Black Brant III fin, no on-range fin measurements or setting adjustments are required.

Flight Characteristics

A total of eleven Black Brant IV, VA, and VB vehicles have been flown to date, and without exception, have all demonstrated that fin design is satisfactory. Both the Black Brant IV and VB have been intentionally rolled, and achieved spin rates remained close to the predicted values. Roll-yaw resonance has been induced at low altitude and relatively high dynamic head: no significant lateral acceleration build-up occurred. Measured apogees have been within ± 5% of theory, and a rolled Black Brant VB exhibited a steady vacuum coning half angle of only 2°.

IV Conclusions

Manufacturing experience and extensive flight testing have demonstrated that ablative insulation and sandwich structures may be successfully applied, both separately and in conjunction, to the design of low-cost, high-efficiency sounding rocket vehicles. Use of these techniques results in significant cost and flight performance benefits, without introduction of any adverse characteristics.

V References

(1) "An aeroelastic investigation of three rocket fins at high Mach. Nos.", by R. C. Dixon and L. H. Ohman.
NRC (National Aeronautical Establishment) Report No. LR-447'