Re-Entry of Space Vehicle Fragments

PETER M. TWISS*
Weapons Research Establishment, Salisbury, South Australia

A light metal sphere found in a remote part of Australia is described. To test the hypothesis that the sphere came from a space vehicle, an analysis is made of the likely re-entry history of the sphere during decay from circular orbit. It is concluded that the sphere originated in a U. S. space vehicle in orbit, and it is shown that the sphere would survive re-entry whether or not it were shielded by additional material burnt or melted off during re-entry. Further analysis is required to decide whether this particular sphere was in fact shielded during part of the re-entry.

Nomenclature

A = cross-sectional area of sphere
B = Stefan-Boltzmann constant, 0.48×10^{-12} Btu/ft^2 sec°R^4
c = specific heat, Btu/lb°R
C_D = drag coefficient
g = acceleration due to gravity, 32.2 ft/sec^2
K_1 = q/q_s
K_n = Knudsen number
q = convective heat-transfer rate per unit area, Btu/ft^2 sec
q_s = convective heat-transfer rate at stagnation point, Btu/ft^2 sec
$\bar{q}$ = dimensionless function proportional to heat-transfer rate[4]
R = radius of sphere, ft
S = surface area of sphere, ft^2
T_w = temperature of sphere surface, °R
$\bar{u}$ = ratio of velocity component normal to radius vector to circular orbital velocity
W = weight of sphere, lb
ϵ = emissivity of sphere surface
φ = flight-path angle relative to local horizontal

Introduction

INSTANCES of the successful re-entry of fragments of space boosters[1] and at least one example of the successful re-entry of fragments from a decaying satellite vehicle[2] have been reported. Gallaher and Sibulkin[1] have shown that steel disks may generally be expected to survive re-entry. So far as is known, all fragments reported have been irregularly shaped and subject to considerable melting and erosion during re-entry.

On April 8, 1963, a light sphere, 14.75 in. in diameter and weighing 11.5 lb, was discovered in a remote part of Australia; the location was approximately latitude 30° 03′ S, longitude 141° 50′ E. The sphere was lying on the surface of sandy country that is broken up by some rocky areas. It is not known how long the sphere had been there, since it was found in an infrequently visited portion of a 35,000 acre grazing area, and investigations of the many reported sightings of falling objects which were received following subsequent publicity revealed no relevant information. On June 29, 1963, a second sphere was found approximately 40 statute miles NNW of the first sphere, at latitude 29° 32′ S, longitude 141° 34′ E. The first sphere, which has come to be known as the Boullia Ball, since it was found on Boullia Station property, has been examined by staff of Weapons Research Establishment (WRE). The second sphere has received only a cursory examination by WRE; it is approximately 16.6 in. in diameter and weighs 21.6 lb.

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* Principal Research Scientist, Trials Wing. Member AIAA.

Description of the Boullia Ball

The Boullia Ball is shown in Fig. 1, and a dimensioned sketch is given in Fig. 2. The ball is spherical within 0.006 in. except for the small, slightly flattened area shown and consists of two hemispheres welded together. Considering the weld as the equator, the two bosses are at the poles. One of the bosses is a mounting or locating lug integral with the sphere, whereas the other (also integral) provides access to the interior and carries a threaded portion with a nut. Both bosses carry small amounts of fused metal; the fused metal in the hole through the surface effectively seals the sphere. The thread on the boss and nut conforms to 1 in. 14 turns per inch (TPI) American National Fine; in the condition as found, the nut turned quite freely on the boss but is prevented from turning right off by the fused metal at the end. In the course of examination, the sphere was sectioned through the poles in a plane at right angles to equatorial weld. The pressure inside was below atmospheric; tests for halogen gases were negative.

Analysis of the sphere material carried out by the Defence Standards Laboratories (DSL) revealed that it is composed of 90% titanium, 4% vanadium, and 6% aluminium; this corresponds to the American Society for Testing Materials (ASTM) B265/58T grade V. The fused metal on the bosses at the poles of the sphere is the same alloy with traces of magnesium, aluminium, iron, copper, and nickel. The sphere is covered with a nonuniform surface residue, mainly black in

Fig. 1 The Boullia Ball.

color, which is visible in Fig. 1, and it gives the appearance of having been subjected to high temperatures. Microscopic examination of the structure of the material bears out the belief that the sphere has been exposed to high temperatures. The ASTM B265/58T grade V is an alpha-beta titanium alloy with beta transformation temperature of 1825 ± 20°F.[3] The distinct change in structure of the alloy when heated to or beyond the beta transformation temperature makes it possible to determine whether this temperature has been reached. Examination by DSL of sections of two diametrically opposite specimens (remote from the weld) confirmed that the beta transformation temperature has been exceeded at the sphere surface. The transformed structure penetrates to a depth of only 0.0005 in. approximately, indicating that the majority of the sphere wall has not exceeded a temperature of 1825°F. The examination revealed some local areas of blistering on the outer surface, also, possibly, local areas of melting and surface combustion, although the last two characteristics are not well defined. There is no significant difference in the structure observed in the diametrically opposite specimens. Specimens taken from the skin near the bosses gave similar results except where the fused metal has actually flowed on the boss material; in this latter case the transformed structure penetrates to a depth of approximately 0.02 in. The fused metal on the bosses shows a coarse grained acicular structure typical of recrystallization after melting. The fused zone contains some massive occlusions, probably oxides and nitrides. The uniformity of the skin crystal structure indicates that the sphere was rotating during re-entry and was thus subjected to fairly uniform heating over its surface.

Radiation examination proved negative, showing only the normal background count. No detailed tests have been conducted for the radioactive isotopes that are likely to be formed from the bombardment by the high-energy corpuscular radiations in space. As has been pointed out,[2] the positive identification of certain isotopes provides the strongest evidence for believing that an object has spent some time in space, and, in certain circumstances, the concentrations can be used as a crude measure of the period of exposure. In this instance, the long period that has ensued since the finding of the ball, together with the unknown length of time between re-entry and discovery, will strongly influence the conclusions that can be drawn from an isotope survey. In contrast, the laboratory examination[2] of fragments of Satellite 1960 ϵ 1 was begun only 50 hr after re-entry.

Analysis of the hexagonal nut showed it to be of an austenitic stainless steel of the 18% chromium, 8% nickel type, and containing approximately 0.6% molybdenum and 0.4% copper.

The over-all impression of a very high quality piece of fabrication in a modern material found in these circumstances led to the suggestion that the sphere came from a space vehicle, and an analysis has been made of the likely re-entry characteristics of such a body to test this belief.

Estimated Re-Entry History

The analysis follows generally the method given by Chapman.[4] The ratio W/C_DA is basic to all re-entry calculations, so that is is necessary to fix a value of C_D appropriate to this sphere during re-entry; if the major phenomena occur during the free-molecule flow period then C_D will be[5] about 2.2, whereas if continuum flow prevails C_D will be[6] about 0.92, hence W/C_DA may range from 4.4 to 10.5. The Reynolds number at peak heating[4] is approximately 10^4 for both values of W/C_DA occurring at an altitude of approximately 240,000 ft. For the sphere at these altitudes, the Knudsen number $K_n < 0.01$, so that continuum flow will prevail during the most critical heating period. In view of the Reynolds number, laminar flow may be expected. With the value of W/C_DA thus established at 10.5 lb-ft^{-2}, the re-entry history of the sphere may be computed from the generalised functions developed by Chapman.[4] The terminal flight path angle is 90°, and with $C_D = 0.1$ in the subsonic flow region, the impact velocity is 280 fps.

In estimating the wall temperature rise for the sphere, account is taken of the laminar convective heat input and the surface radiation output; the radiant input from the gas cap is neglected.[7] The sphere is assumed to be rotating during the re-entry period, so that the heat input is uniformly distributed over the surface, likewise the entire surface is assumed to radiate. Reismann and Jurney[8] have shown that relatively low rotation rates are adequate to attain the surface temperature reductions that accompany the rotation. The sphere shell is assumed to be thermally thin, thus radial temperature gradients are neglected. The total heat stored in the shell is equated to the resultant inward heat flow, giving

$$WcdT_w/dt = q_{\text{in}} - q_{\text{out}} \tag{1}$$

where c is the specific heat of the sphere material. The specific heat of ASTM B265/58T grade V varies[3] with temperature; a constant value of $c = 0.23$ is adopted here, and this value corresponds to a temperature of 2000°R.

The laminar convective heat transfer to any point on the sphere may be written

$$q = K_1 q_s \tag{2}$$

where q_s is the convective heat transfer at the stagnation point, and K_1 is the factor that takes into account the variation in heat input over the sphere surface.

Using the expression developed in Ref. 4

$$q_s = 590(W/C_DARg)^{1/2}\bar{q}/\cos^3\varphi \text{Btu/ft}^2 \text{ sec} \tag{3}$$

The variation of K_1 adopted for the windward hemisphere is that attributed to Lees,[9] and K_1 is assumed constant over the leeward hemisphere at its value at 90° to the flow. In evalu-

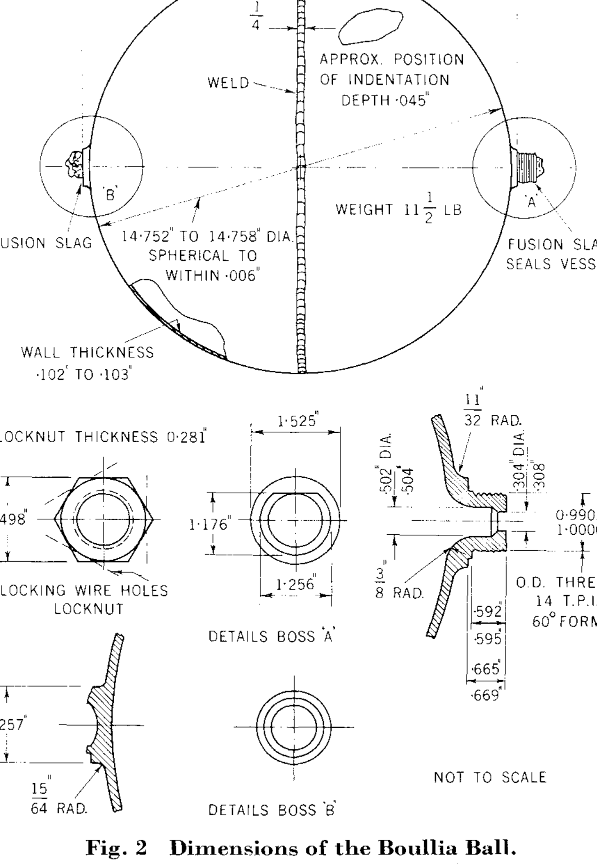

Fig. 2 Dimensions of the Boullia Ball.

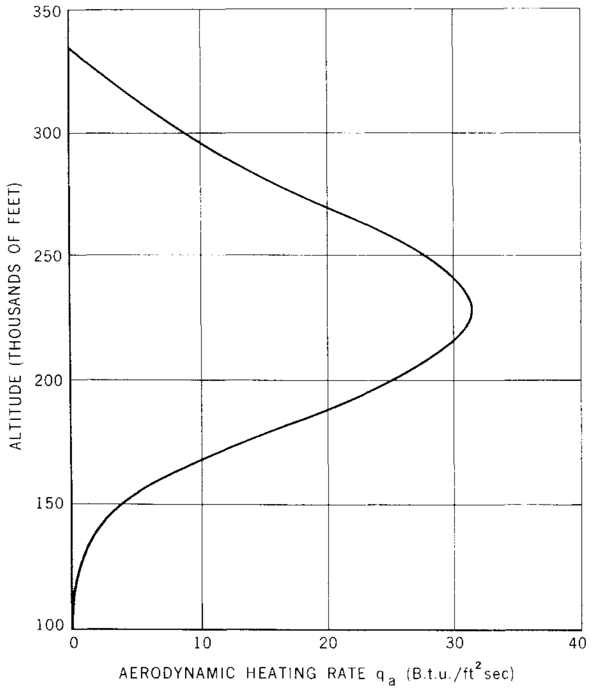

Fig. 3 Variation of aerodynamic heating rate with altitude.

ating $\bar{q}$ from Chapman's Z functions, it is assumed that $\bar{q}$ and hence q_{in} are zero at $\bar{u} = 0.995$. The variation of the aerodynamic heating rate with altitude from Eqs. (2) and (3) is shown in Fig. 3.

The total surface radiated heat output is given by

$$q_{out} = BT_w^4S \tag{4}$$

The emissivity is taken to be that of pure titanium oxidised grey,[3] hence $\epsilon = 0.55$, and is roughly constant above 1000°R. This value for ϵ is probably conservative, so that results are also given for $\epsilon = 0.7, 0.8$.

Substitution in Eq. (1), together with appropriate values of the constants yields the following differential equation for sphere wall temperature:

$$dT_w/dt = 259\bar{q}/\cos^3\varphi - 0.86 \times 10^{-12}T^4 \tag{5}$$

On the assumption that the sphere is rotating before re-entry, the initial temperature can be estimated by the method of Schmidt and Hanawalt[10]; the initial temperature derived is 500°R. Equation (5) has been integrated for $\epsilon = 0.55$, 0.7, and 0.8 using the values of φ in Ref. 4; the resulting wall temperatures are shown as functions of altitude in Fig. 4.

Subsequent to this analysis, the results of Gazley and Masson[11] for the spinning Vanguard satellite were discovered in Ref. 12, (the original source is unavailable). Their results are compared with the present ones for $\epsilon = 0.8$ in Fig. 5 where results from the present analysis are shown for initial temperatures of 500°R and 1280°R, the latter value being the one derived by Gazely and Masson for Vanguard. It is apparent that the re-entry temperature histories are roughly comparable.

Discussion and Conclusions

It is immediately apparent from Fig. 4 that the sphere may be expected to survive re-entry by decay from circular orbit, as the skin temperature never reaches the melting temperature. It is felt that a surface emissivity of at least 0.7 would apply because of the blackened oxide coating on the skin surface, hence the peak temperature reached during re-entry would be about 300°F below the temperature at which melting first occurs with this material. It is not known what units were connected to the bosses, but if, as seems likely, these were comparatively thin pipes or structural members, then melting of these units could quite easily occur owing to their small heat capacity, whereas the main sphere remained solid.

Study of the material structure shows that temperatures of the order of those indicated in Fig. 4 have been reached on the outer surface of the sphere. However, it seems likely that with such a good heat conductor as the sphere alloy, the high temperatures would penetrate further into the skin than the microanalysis shows. This would appear to indicate that the sphere was shielded during at least part of the re-entry, and that after the shield was burnt off the sphere was subjected to a heat pulse of shorter duration than that indicated in Fig. 3. The discovery of the second sphere so close to the Boullia Ball is strong evidence that break-up of the main vehicle structure carrying the balls occurred after re-entry, rather than at some earlier time during orbit. The lack of significant radiation count reported earlier could also be construed as being due to the sphere being well shielded by the space vehicle structure until late in the orbit life; however, the paucity of the radiation evidence, and the unknown length of time between re-entry and discovery preclude much weight being given to this evidence. An attempt is being made to answer this question as to whether or not the sphere was shielded during part of its re-entry by solution of the equations for temperature gradient in the skin when subjected to the transient heating rate shown in Fig. 3. If, as seems likely, the solution indicates a deeper penetration of the beta transformation temperature than the micro structure demonstrates, it may be concluded that shielding did occur during part of the re-entry. It will not be possible to work back from the measured penetration of the beta transformation temperature to determine the point at which the shielding disintegrated because of the impossibility of fixing the sphere temperature when initially exposed to the stream. Also, the velocity and trajectory history of the shielded sphere would be markedly different from those calculated here for the sphere, so that these further initial conditions for computation of the sphere temperature history following loss of the shielding would be unavailable.

Although all the evidence is circumstantial, there can be little doubt that the Boullia Ball and its companion were once part of a space booster or a space craft. That the balls are of U. S. origin seems certain also, particularly as there are many published photographs and descriptions of U. S. rocket

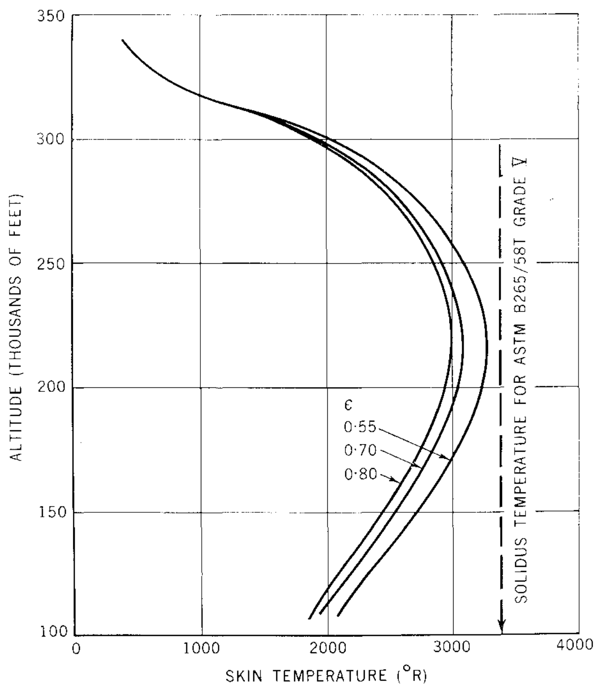

Fig. 4 Skin temperature variation with altitude.

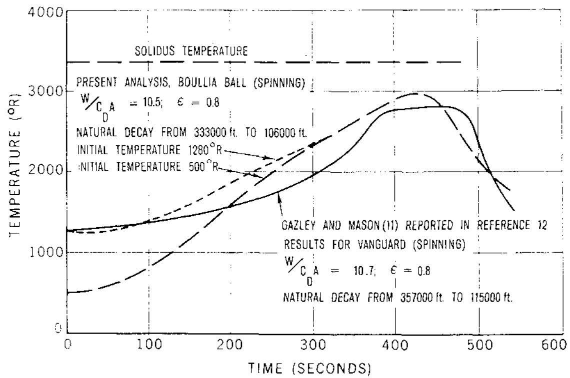

Fig. 5 Comparison of Boullia Ball and Vanguard satellite re-entry histories.

vehicles showing similar titanium spheres on board. To have reached their final impact points by ballistic suborbital flight from the major U. S. launching sites on the east and west coasts of U. S. A. would have required flight path angles at re-entry which would have resulted in almost certain destruction of the balls. Re-entry at an angle of only 4° would result in an increase in peak heating rate of more than 50% over that experienced during orbital decay, and even though the flight time from re-entry to impact is considerably reduced when re-entry occurs at a finite angle, the temperatures induced would be sufficient to destroy an unprotected sphere of this type. Most probably, destruction would also occur with shielding present during part of the re-entry, unless very special shields were used.

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