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Analytical Studies of Beryllium Ablation and Dispersion during Re-Entry

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Analytical studies were conducted to determine 1) re-entry ablation of beryllium in SNAP-10A reactor reflectors, and 2) toxic hazard produced at ground level by the resultant residue dispersal. Studies concluded that varying degrees of ablation will occur, depending upon re-entry attitude of reflector and point of release from the reactor. However, no ground level toxic hazard will exist, even with a reflector completely ablated at the lowest possible ablation altitude.

Nomenclature

A	=	cross-sectional area, ft^2
C_D	=	drag coefficient
C_L	=	lift coefficient
C_P	=	specific heat, Btu/lb/°R
c	=	diffusion coefficient
D	=	drag force, lb
d	=	distance, m
e	=	2.718
g	=	acceleration of gravity, ft/sec^2
h	=	height, m
ΔH	=	heat of fusion, vaporization, or combustion, Btu/lb
L	=	lift force, lb
m	=	mass, lb
n	=	stability parameter
P_s	=	surface pressure, psf
Q	=	source strength, g
$\dot{q}$	=	heat flux, Btu/ft^2-sec
r	=	radius of re-entry body, ft
$\mathbf{R}$	=	radius vector from center of earth to body, ft
R	=	distance from center of earth to body, ft
r_d	=	radius of droplet, ft (or μ)
S	=	surface tension, lbf/ft
T	=	temperature, °R
t	=	time, sec
TID_{max}	=	maximum total integrated dose, g-sec/m^3
U	=	wind velocity, m
V	=	velocity, fps or cm/sec
y	=	altitude, ft
α	=	accommodation coefficient
ϵ	=	emissivity
η	=	viscosity of air, g/cm-sec
ρ	=	density, lb/ft^3 or slugs/ft^3
ϕ	=	radius vector angle, rad
σ	=	Stefan-Boltzmann constant
θ	=	re-entry angle, deg
ψ	=	concentration, g/m^3

Subscripts

a	=	at given altitude
Be	=	beryllium
BeO	=	beryllium oxide
comb	=	combustion
conv	=	convection
D	=	drag
fus	=	fusion
L	=	lift
max	=	maximum
net	=	net
0	=	initial condition
rad	=	radiation, radial
s	=	surface, stable
SC	=	Stokes-Cunningham
st	=	stagnation
trans	=	transverse
vap	=	vaporization

THE Air Force and the Atomic Energy Commission have embarked recently on a joint program designed to launch nuclear reactor auxiliary power generators into space. The purpose of these generators is to furnish electric power to instrumented payloads for extended time periods. One of the major concerns is to assume that the reactor system will re-enter from orbit without creating a radioactive hazard from the fuel material, or a toxic hazard from atmospheric dispersion of beryllium contained in the reflector.

Analytical Procedure

Analytical studies[1] have been performed to determine re-entry ablation and ground toxic hazard resulting from atmospheric dispersion of beryllium contained in reflectors of the SNAP-10, SNAP-10A, and SNAP-2 classes. The investi-

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gation was based on the incorporation of known physical and chemical properties of beryllium into an IBM 7090 digital computer program to calculate re-entry behavior. Data output included information on trajectories, heat transfer, oxidation, and ablation during re-entry under proposed flight conditions. Initial studies were parametric in nature and assumed re-entry of spherical shapes to determine the general behavior of beryllium metal. Concluding studies postulated actual re-entry of a SNAP-10A reflector. Toxic hazards were determined by calculation of atmospheric dispersal and fallout of beryllium particles in the toxic size range. Analysis used to predict ground concentrations included molecular diffusion theory, Stokes-Cunningham sedimentation theory, and Sutton turbulent diffusion theory. The effects of re-entry into both a stationary atmosphere and an atmosphere associated with a rotating earth were studied. Also, the behavior and fate of the ablated residue from the surface of re-entering beryllium bodies was treated in detail for both continuum and free molecule flow regimes. It is believed that this is the first attempt to apply present knowledge of the properties of beryllium metal to the problem of predicting possible re-entry behavior under a given set of flight conditions. The incorporation of physical and chemical property data on specific beryllium body shapes into a computer program to determine flight trajectories, heat transfer, oxidation, ablation, and atmospheric dispersion was carried out in a step-wise procedure. The latest available information on metal properties, aerothermodynamic theory, and meteorological particle dispersion analysis was used to provide input data. Since the following presentation is an abbreviated account of a comprehensive study[1] involving a large quantity of computer data, certain statements made in the text cannot be deduced from the figures and tables contained in the paper. However, these statements are based on data contained in the original report which were not included in this paper in order to reduce the length for publication.

Analytical Results

Trajectories, Heat Transfer, and Ablation in Parametric Studies

The re-entry conditions for the SNAP re-entry studies program set forth by the Air Force Special Weapons Center and compatible with planned flight criteria are indicated in Table 1 which assumes a degenerating circular orbit and actual vehicle re-entry beginning at either of the two stated altitudes, initiated by a slight decrement of velocity below the orbital velocity.

Initial parametric studies were made on solid 3-, 6-, and 12-in.-diam beryllium spheres. These sizes were chosen to include bodies that could be expected to exhibit substantial ablation and bodies that would be likely to experience no material loss during re-entry. Spheres were selected because of symmetrical shape and relative ease of application of hypersonic re-entry theory. A spherical earth with a modified two-dimensional polar coordinate system was chosen, since re-entry angles were shallow and flight times rather long. The body was considered a mass point in space moving under the influence of gravitational, centrifugal, and tangential forces. Standard equations of motion were used in calculating re-entry trajectories. It was necessary to include terms for lift and drag forces also, and atmosphere parameters of

Table 1 Initial re-entry conditions

Symbol	Identity	Assigned value
V_0	re-entry velocity	25,600 fps
θ_0	re-entry angles	0.05°, 0.10°, 1.00°
T_0	re-entry temperature	670°R, reflector
y_0	re-entry altitudes	400,000 and 300,000 ft
m	reflector weight	58 lb

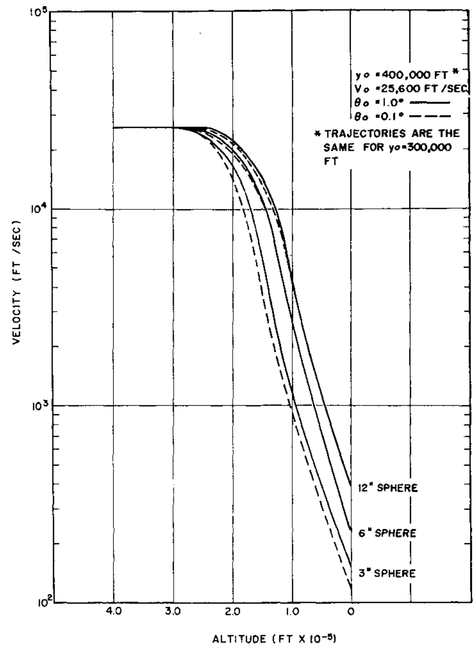

Fig. 1 Re-entry trajectories of beryllium spheres.

interest were obtained from the ARDC 1956 Model Atmosphere.[2] The basic trajectory equations then became

$$\frac{d^2\mathbf{R}}{dt^2}\,\text{rad} = \left[\frac{d^2R}{dt^2} - R\left(\frac{d\phi}{dt}\right)^2\right] + g - \frac{L}{m}\cos\theta - \frac{D}{m}\sin\theta$$

$$\frac{d^2\mathbf{R}}{dt^2}\,\text{trans} = \left[2\frac{dR}{dt} - \frac{d\phi}{dt} + R\frac{d^2\phi}{dt^2}\right] - \frac{D}{m}\cos\theta + \frac{L}{m}\sin\theta$$

where $D = (C_D\rho_a A_D V^2)/2$ and $L = (C_L\rho_a A_L V^2)/2$.

To determine the convective aerodynamic heat transfer to a body re-entering in a continuum flow regime, the method of Kemp and Riddell[3] was employed, thus leading to the following equations:

Since

$$\dot{q}_{st} = \frac{2.08 \times 10^4}{r^{1/2}}\left(\frac{\rho_a}{\rho_0}\right)^{1/2}\left(\frac{V}{V_0}\right)^{3.25}$$

and

$$\dot{q}_{conv} = \tfrac{1}{4}\dot{q}_{st}$$

while

$$\dot{q}_{rad} = \sigma\epsilon T_s^{\,4}$$

then

$$\dot{q}_{net} = \dot{q}_{conv} - \dot{q}_{rad}$$

also

$$\dot{T}_s = \frac{A_s}{mC_p}(\dot{q}_{conv} - \dot{q}_{rad})$$

Trajectory determinations included calculation of the body mass at each instant along the trajectory after the surface temperature reached the melting point, thereby including the effect of diminishing mass. Applicable equations for this calculation were

$$\dot{m}_{fus} = \dot{q}_{net}/\Delta H_{fus} \qquad (\text{if } T_s = 2800°\text{R})$$

$$\dot{r} = -\dot{m}_{fus}/\rho_{Be}$$

Table 2 Re-entry of 3-in. beryllium spheres[a]

Re-entry, type	Re-entry altitude, kft	Re-entry angle, deg	Max. stag. heat flux, Btu/ft²-sec	Change in max. stag. heat flux, %	Mass loss, %	Ablation range, mile	Ablation altitude, kft	Ablation time, sec
Nonrot.	400	1.0	302	...	70	210	230–165	70
earth		0.1	304	...	92	330	260–158	100
	300	1.0	290	...	48	169	220–155	60
		0.1	282	...	81	259	245–170	80
		0.05	280	...	84	268	248–162	90
E → W	400	1.0	384	+27	92	249	240–170	80
Rot. earth		0.1	387	+27	99	391	270–190	110
Eq. orbit	300	1.0	353	+22	80	210	235–170	70
		0.1	354	+25	97	318	255–175	100
		0.05	356	+27	97	330	260–180	100
W → E	400	1.0	249	−18	32	137	210–155	50
Rot. earth		0.1	239	−21	71	301	250–160	90
Eq. orbit	300	1.0	243	−16	3	49	180–160	20
		0.1	221	−22	50	213	225–155	70
		0.05	223	−20	53	226	230–160	70

[a] m_0 = 0.93 lb.
ϵ = 0.6.

Figures 1 and 2 show trajectories and stagnation-point heat fluxes, respectively, for 3-, 6-, and 12-in.-diam spheres re-entering at 25,600 fps to a nonrotating earth at re-entry angles of 0.1° and 1°. The results may be summarized as follows:

1) Beryllium spheres of diameter $\geq$ 6 in. would lose no mass, but 3-in. spheres would experience surface melting and liquid removal.

2) Greater deceleration due to mass loss results from a 0.1° entry angle than from a 1° angle, because the total heat input is greater, even though the peak $\dot{q}_{st}$ is slightly smaller.

3) Trajectories, and hence peak heating rates, are the same for re-entry from 400 and 300 kft, because drag is negligible above 300 kft.

4) The maximum $\dot{q}_{st}$ is near 300 Btu/ft²-sec in all cases. The velocities at which it occurs are in the range 21 to 22 kft/sec, and the altitudes vary from 230 kft for the 3-in. spheres to 180 kft for 12-in. spheres.

Table 2 summarizes ablation results for 3-in. spheres for the nonrotating earth cases just mentioned and for both westbound and eastbound re-entries from equatorial orbits over a rotating earth. Maximum $\dot{q}_{st}$ is increased by 22–27% by E → W re-entry (against earth rotation), and it is decreased by 16–22% by W → E re-entry, and mass losses vary accordingly. The horizontal ranges, altitudes, and times over which ablation occurs are also greatest for E → W re-entries.

Oxidation during Re-Entry

The parametric studies up to this point have assumed that no oxidation of the beryllium occurs during re-entry. Since aerodynamic heating will produce hot beryllium surfaces in the presence of adequate quantities of oxygen (and nitrogen), oxidation will occur. The production of a significant quantity of oxide on the metal surface could affect the heat-transfer properties of the body to an extent that behavior different from that of nonoxidizing bodies might occur. Therefore, a study was made of the probable re-entry oxidation behavior of beryllium, using available information on the mechanism and kinetics of beryllium oxidation contained in the literature. This information was formulated into a suitable computer code and programmed for re-entries of beryllium spheres under the previously studied conditions. Both stationary and moving atmospheres were postulated to obtain the best, worst, and average conditions that could be anticipated.

From a study of the data it was concluded that oxidation effects are negligible for a 3-in.-diam beryllium body re-entering the atmosphere. The maximum oxide thickness produced in any case studied was less than $\frac{1}{4}$ mil. The minimum oxide thickness under any condition was 0.028 mil. The maximum oxide film thickness predicted will be insufficient to contain the liquid mass beneath the oxide surface. Once melting occurs, aerodynamic shear will tend to sweep away the thin oxide film along with the ablating beryllium droplets. The exothermic heat of reaction of oxidation also will provide an increase to the heat input which was calculated on a drag-kinetic energy conversion basis.

Burnup of Ablated Liquid

To furnish a more complete story on ablation, there remains the task of determining what happens to the ablated residue along the re-entry trajectory. If it is assumed that the liquid on the surface of the re-entering body is removed in the form of spherical droplets, the behavior of these droplets can be studied relative to their oxidation, combustion, and vaporization characteristics in the appropriate flow regime (continuum or free-molecule). It is first necessary to predict the size range of droplets removed from the surface as a function of a set of given re-entry parameters. To determine this,

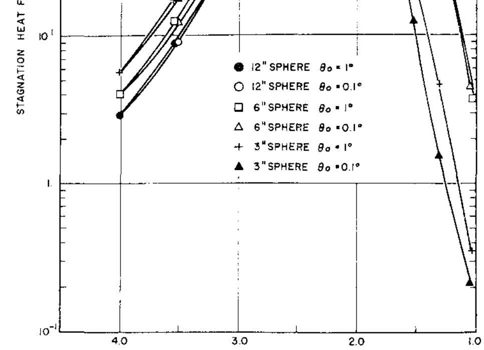

Fig. 2 Stagnation heat fluxes during re-entry of beryllium spheres.

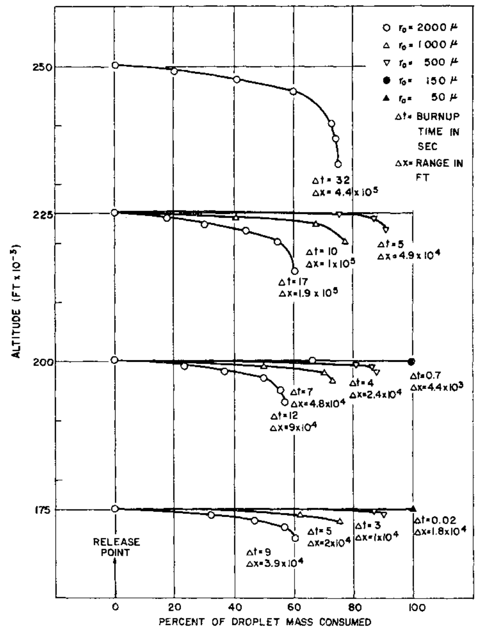

Fig. 3 Burnup of ablated beryllium droplets continuum flow regime.

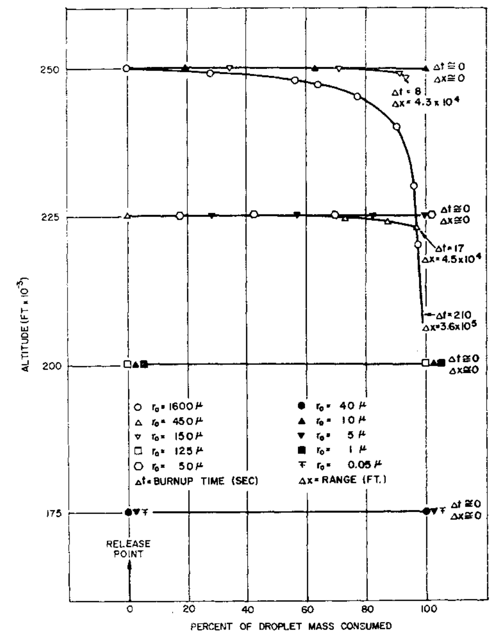

Fig. 4 Burnup of ablated beryllium droplets free molecule flow regime.

the classic theory of meteorites as treated by Opik[4] was chosen because it appears to be a simple and reasonable approach having some basis in observed fact. According to Opik's theory, the stable radius of a re-entering liquid droplet is a function of the surface tension of the liquid and the surface pressure exerted by the airstream

$$r_{d,s} = 4S/P_s$$

where $P_s = \rho_a V^2$. The surface tension of molten beryllium is not accurately known but was taken to be 1000 dynes/cm at the melting point, based on comparison with other metals of known surface tension with similar characteristics. The surface pressure P_s can be calculated at each discrete interval along the trajectory with an appropriate computer code.

To compute the change in mass and size of the droplets, it is necessary to know the net heat input. This calculation takes the form of the following equation:

$$\dot{q}_{\text{net}} = \tfrac{1}{4}\dot{q}_{st} + \Delta H_{\text{comb}}\alpha\rho_a V - \sigma\epsilon T_s^{\,4}$$

The change in mass and change in radius of the droplet may then be obtained:

$$\dot{m}_{\text{vap}} = (\dot{q}_{\text{net}}/\Delta H_{\text{vap}}) \qquad (\text{if } T_s = T_{\text{vap}})$$

$$\dot{r}_d = (-\dot{m}_{\text{vap}}/\rho_{\text{Be}})$$

The *continuum* flow results of Fig. 3 show that:

1) All droplets, regardless of release altitude, suffer at least 60% mass loss. Droplets of less than 150-μ radius will be completely consumed, but droplets of greater than 400-μ radius will not be reduced below 300 μ.

2) Burnup time (Δt) and horizontal range (Δx) increase with both drop size and release altitude, but it does not follow that mass-loss increases with release altitude, because drag and heating are smaller at high altitude. Burnup times vary from 0.02 to 32 sec, and ranges vary from 0.2 to 440 kft.

The *free-molecule* flow results of Fig. 4 show that:

1) All droplets suffer at least 90% mass loss. Droplets smaller than 125 μ are completely consumed and vary rapidly ($\Delta t \simeq 0$ and $\Delta x \simeq 0$), with ΔH_{comb} contributing significantly.

2) Burnup time increases with droplet size; 1600-μ droplets released at 250 kft give $\Delta t = 210$ sec.

In both flow regimes, droplets of initial sizes less than 150-μ radius will be reduced to toxic particle size ($\leq 5\mu$) before burnup ceases. Droplets of larger initial sizes will remain above the toxic particle size range at any release altitude in either flow regime. Unfortunately, it is not possible to predict the droplet size distribution during re-entry. For the purpose of a conservative treatment, the next section will discuss the hazards aspects of the ablated residue under the assumption that *all* droplets released will burn up to toxic particle sizes. If it can be proved that no hazard will exist under this condition, then it can be deduced that the actual re-entry situation will present even less of a toxic hazard.

Atmospheric Dispersal, Fallout, and Toxic Hazard

The beryllium residue dispersed over the re-entry trajectory at altitudes from 250,000 to 150,000 ft will eventually settle to earth after a certain residence time in the atmosphere, the duration of which will be a function of particle size, particle density, altitude, and meteorological conditions. Several analytical treatments were used to predict fallout patterns, since any one treatment would contain limitations that might restrict the generalized concept it was desired to investigate. No atmospheric fallout theory has been completely verified under any possible set of conditions in the actual case. However, by selecting suitable boundary conditions and evaluating several theories, it is possible to arrive at a conclusion which will indicate whether a toxic hazard could exist.

To present the most conservative estimate, the entire mass of the SNAP-10A reflector (58 lb of beryllium) was assumed to have been released as an instantaneous point source at the lowest possible altitude at which ablation could occur. This served three purposes: the mathematical treatment of fallout was simplified; the worst possible toxic hazard was created; and the analysis of potential ground hazard was treated independently of the re-entry behavior of any assumed shape. In this way the analysis of fallout and toxic hazard generation became an independent study. It did not depend on the accuracy of body re-entry calculations, which were made under somewhat arbitrary assumptions. Since a point release was considered here, the actual re-entry probably will produce orders of magnitude lower ground concentrations than calculated, due to the long flight path.

Four different analytical procedures were used. Westinghouse concluded from a Stokes-Cunningham sedimentation analysis and a Sutton turbulent diffusion analysis that ground concentrations of beryllium would be at least 10^3 below the maximum permissible concentration of 0.01 $\mu g/m^3$ specified

Table 3 SNAP-10A reflector re-entry ablation (axial position)[a]

Release alt, kft	W/C_DA = 25 psf[b]				W/C_DA = 250 psf[b]			
	V, fps	θ, deg	Alt ablation ceases, kft	Mass loss, %	V, fps	θ, deg	Alt ablation ceases, kft	Mass loss, %
300	25,400	0.56	180	96	25,700	0.41	191	98
250	24,400	1.27	158	88	25,500	0.59	176	92
200	18,900	3.01	127	78	24,200	1.19	146	76
150	9,600	7.10	110	80	20,300	2.52	120	56

[a] Initial re-entry conditions: y_0 = 400 kft, V_0 = 25,600 fps, θ_0 = 0.1°.
[b] Ballistic parameter of carrier vehicle.

by the AEC for continuous exposure. This assumed average wind and atmospheric conditions. In the Stokes-Cunningham analysis the fall velocity of various size particles was calculated from the Stokes equation modified for free molecule flow effects:

$$V_{SC} = 2r_s^2(\rho_s - \rho)g\alpha/9\eta$$

For the Sutton analysis several equations were used to predict the distance of maximum toxic particle concentration, the maximum concentration itself, the total integrated dose (TID), and the distance to the maximum total integrated dose. These equations took the following forms:

$$d_{\psi_{\max}} = \left(\frac{2h^2}{3c^2}\right)^{1/(2-n)}$$

$$\psi_{\max} = \frac{Q}{(2/3e\pi)^{3/2}h^3}$$

$$\mathrm{TID}_{\max} = \frac{Q}{\pi e\bar{U}h^2}$$

$$d_{\mathrm{TID}_{\max}} = \left(\frac{h^2}{c^2}\right)^{1/(2-n)}$$

Sowle,[5] using a mathematical analysis of a line source under similar atmospheric conditions combined with Sutton's theory for long range diffusion, predicted concentrations 10^3–10^4 below permissible levels. Harr[6] used a different approach to determine an average predicted dispersion and to relate it to the necessary dispersion for a safe contamination level. He concluded that a safety factor of at least 10^3 existed. The close agreement among the independent predictions is an encouraging argument for the validity of the approaches used. If the possibility of multiple launching of SNAP-10A reactors over a time period of several years is considered, some slight reduction in the safety factor of 10^3 may be anticipated. However, even if 100 such re-entries occurred over a limited area of the earth's surface in a short time period, a very unlikely occurrence, a safety factor of 10 below minimum continuous exposure concentrations would be realized. This is because the concentration or integrated dose is a linear function of the source strength.

The assignment of a critical toxic size range for airborne beryllium particles was based on information developed by the AEC and the Kettering Institute.[7] A ten-year study concluded that the primary toxic hazard is a respiratory one, although nonfatal forms of dermatitis or ulcers can be produced by skin contact. Particles greater than 5 μ in diameter will not be inhaled into the respiratory tract and, therefore, cannot contribute to a respiratory hazard. No lower limit on toxic particle diameter has been set. For the purposes of the burnup study, the lower limit was set at 0.1 μ to permit mathematical calculations. This lower limit was considered reasonable since particles of this size, released at altitudes above 100,000 ft, would require many years to return to earth because of extremely low settling rates.

SNAP-10A Reflector Re-Entry

The SNAP-10A reflector consists of two half-section semicylindrical shells, joined together by spring clamps to form a hollow cylindrical shell. This shell encloses the reactor-can containing the fuel rods. Total weight of beryllium parts is 58 lb. The reflector will be ejected clear of the SNAP unit during re-entry by a spring-loaded mechanism that is released upon burnthrough of a retaining band by aerodynamic heating. Upon ejection, the two half-sections will separate and travel individual re-entry trajectories. Therefore, it is necessary to treat only the case of one section of the reflector. The release point could be made to occur at various altitudes by proper design of the retaining band structure or by alternate ejection mechanisms. It was decided to employ release altitudes of 300,000, 250,000, 200,000, and 150,000 ft to cover the regime of significant aerodynamic heating.

The primary objective of this analysis was to predict the amount of heating and ablation that would occur under two extreme conditions of assumed reflector re-entry attitude, the normal (cross-axial) and axial (end-on) positions. Ballistic coefficients (W/C_DA) of 25 and 250 are considered for each case. The results of a computer program incorporating these parameters for one set of initial re-entry conditions are listed in Table 3. The choice of a 1.0° or 0.1° initial re-entry angle resulted in no significant variation in the velocity and flight path angle at any given altitude. However, varying the ballistic parameter has a great influence on the velocity and flight path angle at any given altitude.

It was assumed that the reflector sections, upon ejection, will initially be traveling at the same flight velocity and flight path angle as the carrier vehicle. From that instant the reflector will follow a different trajectory dependent upon its particular aerodynamic characteristics. The possible effects of tumbling, oscillation, or spinning were not considered, although such dynamic behavior would tend to reduce the total heat input.

The results for the normal entry are shown in Fig. 5, which plots reflector surface temperature vs altitude. It is noted that the reflector surface does not reach the melting temperature under any condition of release altitude or vehicle ballistic parameter. The maximum temperature reached from re-entry into a stationary atmosphere is 2250°R. Even with an E → W equational orbit re-entry, the surface temperature reaches only 2360°R. The melting point of beryllium is 2800°R. From the plot it can be seen that the peak surface temperatures diminish with decreasing release altitudes. To obtain maximum heating conditions, the reflector should be released at the highest possible altitude, once positive re-entry has begun. The maximum drag consideration for re-entry, therefore, predicts no ablation of the SNAP-10A reflector under the selected re-entry conditions.

For the axial re-entry the effective thickness of the body is large; hence thermal equilibrium cannot be assumed throughout the reflector mass. Therefore, the temperature gradient from leading edge to trailing edge must be determined in order to calculate effective radiation heat loss. A steady-state one-dimensional heat transfer analysis was used. The results are

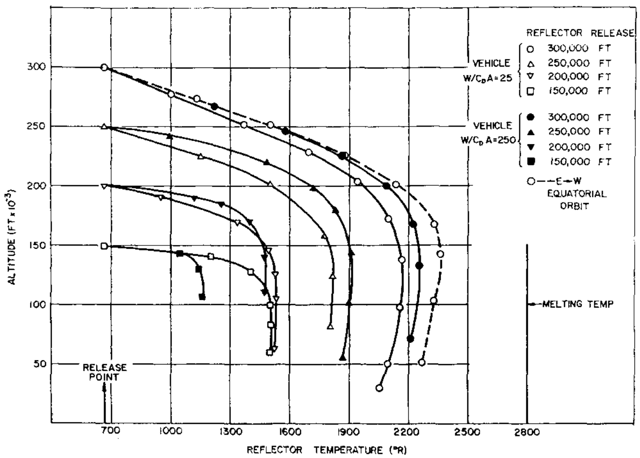

Fig. 5 SNAP-10A reflector re-entry, surface temperature vs altitude, re-entry with axis normal to airstream.

tabulated in Table 3, which indicates the percent ablation to be expected as a function of release altitude and the altitude at which ablation ceases. It is interesting to note that under the conditions assumed, it is possible to obtain between 56 and 98% ablation. Initial vehicle re-entry angle (0.10° or 1°) had little effect on V and θ at the release altitude, but W/C_DA did. It is fairly certain that the minimum drag, highest heating rate situation will be modified by actual flight characteristics of the body to a degree whereby the ablation will be less severe than predicted by this study. The only purpose of the study was to determine the theoretical maximum ablation in a standard vehicle re-entry trajectory with reflector release at various altitudes.

Conclusions

The parametric studies indicated that beryllium bodies are difficult to ablate during re-entry because of high specific heat, high thermal conductivity, and low density. Oxidation of the surface will have insignificant effects for the re-entry paths determined, because the oxide film generated before base metal melting occurs is very thin. The means of mass loss would most likely be removal of liquid layers of metal from the surface by means of aerodynamic shear forces. Consideration of re-entry into a moving atmosphere will result in a heating rate approximately 25% greater than for a stationary atmosphere (E → W equatorial orbit re-entry). In a W → E re-entry, the heating rate would be nearly 20% less than for a stationary atmosphere. The ablated beryllium droplets entering the airstream in continuum or free molecule flow regimes will be completely reduced to toxic size range (5-μ diam) for initial droplet sizes less than150 μ in diameter. Larger droplets will be reduced in size depending on release altitude and initial droplet size but will not terminate in the toxic particle size range.

Studies of postulated SNAP-10A reflector shape re-entry show that either no ablation, or almost complete ablation, can be obtained depending on the re-entry attitude and release altitude. The actual ablation can be calculated only from a complete knowledge of the reflector dynamics during its entire residence in the aerodynamic heating regime. Such a study was beyond the scope of this program. Logically, it would appear that partial ablation between these extremes would occur due to oscillation, spin, or tumble during re-entry.

Several theories of atmospheric dispersion were used to predict the maximum toxic hazard situation that could exist at ground level, assuming the entire mass of the reflector to be released as a point source of toxic size particles at the lowest possible ablation altitude. The results of the several analyses showed that no toxic hazard would exist for any reasonable normal conditions of the atmosphere. Furthermore, the ground level concentrations would be 3 or 4 orders of magnitude lower than the maximum permissible by AEC specifications. In an actual re-entry, the dispersion of ablated residue along hundreds of miles of the trajectory would assure ground concentrations considerably lower than those derived in the study. This condition would render any possible hazard even more remote.

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