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M-3679 (38th Edition)
NUCLEAR TECHNOLOGY--
AEROSPACE SAFETY

UNCLASSIFIED

SC-RR-65-78

RE-ENTRY ABLATION OF A STRONTIUM FUEL FORM
(Title Unclassified)

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Exempt from CCRP Re-review Requirements
(per 7/22/82 Duff/Caudle memorandum)

Classification cancelled (or changed to) _____

by authority of 77D-1389-52

April 1965

by EB DTIE, date 3-4-75

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ABSTRACT (U)

The purpose of this paper is to evaluate the re-entry ablation of a proposed strontium fuel form for an isotopic generator. The effects of capsule diameter, length-to-diameter ratio, and container emissivity are studied. A droplet-vaporization analysis includes the effect of varying droplet sizes formed from the fusing capsules. Final particle sizes are estimated and compared to current safety criteria.

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List of Symbols

$$\dot{q}_{hw} = \text{area-averaged hot-wall heat rate} = \dot{q}_{cw} \left(1 - \frac{h_w}{h_s} \right)$$

$$\dot{q}_{cw} = \text{area-averaged cold-wall heat rate} = \frac{C_1 St_2 V^3}{2Jg}$$

C_1 = a constant to convert area-averaged heat rate on a hemisphere to area-averaged heat rate on a cylinder. For an end-over-end tumbling and spinning cylinder in hypersonic-continuum flow,

$$C_1 = \frac{0.167 + 0.121 \frac{D}{L}}{0.275}$$

D = diameter

ℓ = heat of vaporization

L = length

$$h_w = \text{wall enthalpy} = \int_0^{T_w} C_p dT$$

$$h_s = \text{stagnation enthalpy} \approx \frac{V^2}{2}$$

$$K_{hw} = \frac{0.3 \dot{q}_{cw}}{h_s} = \text{hot-wall conductivity}$$

T = temperature

w = wall

θ = time

m = mass

ϵ = hemispherical total emittance

r = radius

σ = surface tension

St = Stanton number

Q = dynamic pressure

V = free-stream velocity

W = weight

ρ = density

A = cross-sectional area

C_d = aerodynamic drag coefficient

$$\dot{q}_{rad} = \text{area-averaged radiation loss} = \sigma \epsilon A (T_w^4 - T_{space}^4)$$

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List of Symbols (cont)

$$\dot{q}_{\text{stored}} = mC_p \frac{\Delta T}{\Delta \theta} = \text{heat stored}$$

$$\dot{q}_{\text{cond}} = \text{amount of heat conducted to adjacent nodes}$$

$$\dot{q}_{\text{hw correction}} = \text{amount of correction needed to change the cold-wall heat rate to a hot-wall heat rate}$$

$$\dot{q}_{\text{int}} = \text{internal heat generated within the fuel capsule per node}$$

$$J = \text{Joule's mechanical equivalent of heat} = 778 \frac{\text{ft-lb}}{\text{BTU}}$$

$$g = \text{gravitational constant} \left(\frac{\text{ft-lb}_f}{\text{lb}_m \cdot \text{sec}^2} \right)$$

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RE-ENTRY ABLATION OF A STRONTIUM FUEL FORM

Introduction

This study has been performed in partial response to questions posed by the Atomic Energy Commission concerning the ablation and dispersal of strontium fluoride during re-entry heating.

Current safety philosophies for most aerospace isotope systems seem to require that, upon random re-entry into the earth's atmosphere, the fuel be dispersed as particles 1 micron or less in diameter at altitudes above 100,000 feet. The above criteria will be assumed to be adequate for strontium fluoride. An analysis of a strontium-fluoride-fueled* system was performed in a way which would tend to satisfy these requirements within all reasonable limits. The generator system was assumed to re-enter from an operational orbit with the fuel capsules released at an optimum altitude for burnup.

Thermal Analysis

General Approach

To calculate the time-temperature response of a material during re-entry, one must describe all the possible heat sources and heat sinks available to the body. These are then combined with a thermal model of the body, and the resulting transient heat rate problem is solved through the use of high-speed digital computers and finite difference methods.

The initial temperature of the fuel capsules upon release from the generator was taken as 1600°F, the operating SNAP-17 fuel capsule temperature.¹

Upon random release from a burning reactor, fuel capsules with small length-to-diameter (L/D) ratios, will tumble and spin in some fashion during re-entry. Since the SrF₂ fuel capsules have a small L/D ratio, heating rates and drag coefficients were calculated for an end-over-end tumbling and spinning mode of re-entry.² Heat inputs may be assumed to be uniform around the circumference of the capsules for this mode of re-entry. Calculations could have been made assuming random

*This report is classified CRD because strontium fluoride and Haynes 25 are mentioned in conjunction with their use in isotopic generators.

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tumbling and spinning of the capsules, but the total amount of ablation would be no different, since net integrated heating is the same for both modes of re-entry.

Heat Sources

Heat sources for the strontium fluoride fuel capsules consist of aerodynamic heating and the internal heat generated within the capsules themselves. Since strontium fluoride is assumed to be the most stable compound of strontium in the presence of oxygen and nitrogen, no other chemical reactions that tend to provide heat sources will take place during re-entry.

Area-averaged cold-wall-convective heating rates were calculated using the curve shown in Figure 1, which is taken from Reference 3. This curve enables calculation of heating rates in continuum, transition, and free-molecular flow regimes.

There are several proposed fuel capsule configurations for the SNAP-17. Two representative configurations are analyzed in this report. Internal heat generated in the large capsule configuration shown in Figure 2 was taken as 0.464 BTU/sec, and in the small capsule configuration shown in Figure 3 as 0.103 BTU/sec.¹

Hot-Wall Correction

Aerodynamic heating to a body whose temperature rises as a function of the heat input may be called a hot-wall heat rate and described in terms of the cold-wall heat rate by the following equation:

$$\dot{q}_{hw} = \dot{q}_{cw} \left(1 - \frac{h_w}{h_s} \right). \quad (1)$$

Hot-wall corrections become important only at relatively high wall temperatures, where one may assume, for all practical purposes, that the specific heat of air is a constant equal to 0.3. With this assumption one obtains

$$h_w = 0.3 T_w \quad (2)$$

Substituting Eq. (2) in Eq. (1) obtains

$$\dot{q}_{hw} = \dot{q}_{cw} - \frac{0.3 \dot{q}_{cw} T_w}{h_s}. \quad (3)$$

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* For a cylinder tumbling end-over-end and spinning

Figure 1. Area averaged Stanton number behind the shock for a hemisphere at high velocity in air versus Knudsen number in front of the shock

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Figure 2. Thermal model for the large capsule configuration

Figure 3. Thermal model for the small capsule configuration

The coefficient of the wall temperature term is used in the computer programs to make the hot-wall correction. This coefficient is referred to as the hot-wall conductivity, i.e.,

$$K_{hw} = \frac{0.3 \dot{q}_{cw}}{h_s} \quad (4)$$

This term can be readily handled in the iterative computer process when it is used as a value of heat conduction from the capsule surface to a "false node" at zero temperature (°F) in the thermal program. Although the hot-wall correction term usually amounts to less than 10 percent of the cold-wall convective heat rate until

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after peak heating, this is not the governing criterion for the importance of a hot-wall correction. Hot-wall correction values must be compared to the heat-stored term which inherently reflects the time-temperature history of the re-entering material. An example from calculations performed in the present study can be used to illustrate this point.

The heat balance for the small capsule at a time near peak heating during re-entry after the Haynes container has ablated is written below, along with the values of the various terms in BTU/sec,

$$0.026 + 8.094 = 6.61 + 0.324 + 0.657 + 0.528$$

$$\dot{q}_{\text{int}} + \dot{q}_{\text{cw}} - \dot{q}_{\text{rad}} + \dot{q}_{\text{stored}} + \dot{q}_{\text{cond}} + \dot{q}_{\text{hw correction}} \quad (5)$$

If the hot-wall correction were omitted, this amount of heat would be added to the heat-stored term, meaning that $\dot{q}_{\text{stored}}$ would be large by a factor of

$$\frac{0.528 + 0.324}{0.324},$$

or 2.63. In other words, the calculated temperature rise rate of the capsule surface with respect to time would be 2.63 times too great near peak heating if the hot-wall correction were ignored.

Reradiation

In the framework of this analysis, as shown in Eq. (5), heat sinks consist of the hot-wall correction, conduction to adjacent nodes, heat used in causing a material temperature rise, and reradiation to space. The reradiation term is, of course, dependent upon the value of emissivity used for the capsule surface. An emissivity of 0.25 or 0.80 was used for Haynes, and 0.9 for strontium fluoride. Haynes emissivity was obtained from Reference 4. An emissivity of 0.25 holds for Haynes in its polished condition while that of 0.80 corresponds to Haynes in an oxidized condition. The emissivity of 0.25 was used (to be extremely optimistic) and compared to an emissivity of 0.80. In reality, the Haynes will probably be oxidized during launch preparations for the generator, where the Haynes experiences a temperature of 1600°F at ambient pressure. Even if the Haynes were in a polished condition at the start of re-entry, it would be oxidized to some extent during re-entry, making the 0.8 value of Haynes the most realistic value.

The value of emissivity used for strontium fluoride is typical of emissivities in the beryllium, magnesium, calcium, strontium, etc., family and coincides with that used in Reference 1. An emissivity of 0.9 for strontium fluoride is believed to be realistic and is used for lack of better data. Molten strontium fluoride was also considered to have an emissivity of 0.9.

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Thermal Models

Two thermal configurations are needed to study the re-entry burnup of fuel capsules. One configuration approximates the fuel capsule itself, and the other approximates spherical particles that form from the fusing capsule.

Figures 2 and 3 show the thermal model approximations used for the fuel capsules. The nodal configurations show that the problem solved by the computer to determine the capsule's time-temperature history is a transient, one-dimensional, heat-transfer problem. The use of a one-dimensional, heat-transfer model is permitted by the fact that heat transfer can be assumed to be uniform around the capsule surface. The outer node accounts for the Haynes-25 container, while the four equal-volume nodes numbered 2 through 5 represent the strontium fluoride. The Haynes endcaps are ignored in the thermal models.

The second thermal configuration, that of a sphere, comes into play when the output of the computer thermal program predicts fusion of nodes 2 through 5 in the capsule thermal models. When node 2 becomes fused (i.e., 25 percent of the SrF_2), this material is assumed to break into spherical particles and continue re-entry. This is also the case with the other three nodes. A generalized thermal model for a sphere consisting of five equal volume nodes and an arbitrary radius is shown in Figure 4. Heating is assumed to be uniform about the surface of the sphere.

Figure 4. Thermal model for a sphere of arbitrary radius

Determination of Molten Particle Sizes

The Weber number criterion^{5, 6} results in an equation that can be used to determine the maximum stable droplet sizes for spheres formed from the fusing capsules. This equation is:

$$D_p = \frac{6\sigma_p(1b_f/ft)}{Q(1b_f/ft^2)} \quad (6)$$

where

- D_p = the maximum stable droplet diameter in feet,
- σ_p = the surface tension of the molten material, and
- Q = dynamic pressure experienced by the particle on its specific trajectory.

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Reference 7 proves that Eq. (6) applies when used to predict maximum stable sizes of molten zirconium subjected to hypersonic conditions in a shock tube. It was surprising that the Weber number criterion would predict maximum droplet sizes for zirconium since various chemical reactions (such as oxidation and nitridation) which occur are not accounted for in the Weber number analysis. Since strontium fluoride will be nonreactive during ablation, the Weber number criterion should certainly apply to this material, if a realistic value of surface tension of molten SrF_2 is used.

No satisfactory theory or experimental evidence exists that permits any postulations about the distribution of particle sizes below the maximum stable size. However, for an inert material such as SrF_2 , the authors feel that many particles will be present near the maximum stable size, since there are no chemical reactions to further decrease this size. Aerodynamic forces alone will break up the molten material, and the maximum energy available for this type of breakup is used in the Weber number criteria. This process of droplet breakup should not be confused with results of bomb fallout tests where tremendous amounts of energy produce a large amount of very small particles that statistically fit a log-normal size distribution.

Reference 7 also shows that if a droplet much larger than the maximum stable size is suddenly exposed to the free-stream conditions, the breakup no longer follows the Weber number criterion. This large, completely molten, and very unstable droplet is not simply broken into stable-sized droplets as would be predicted by the Weber number criteria, but is sheared into a fine spray-type formation by the aerodynamic forces. As yet, there is no information about particle sizes produced in the spray-type formation. In addition, no presentation exists which can realistically postulate the release of droplets larger than the maximum stable-sized droplet from a fusing capsule during re-entry. This is especially true of strontium fluoride, which is a reasonable insulator in that surface melting occurs while the inner portion of the material is still solid. Large amounts of completely molten strontium fluoride will not exist at any given time during re-entry.

Consideration must be given to the methods of droplet removal from the fusing capsule. If the capsule is in free molecular flow at the time of surface fusion, free-stream forces will be present at the body surface for droplet removal, and formation of large droplets cannot be postulated. In this case, the Weber number criteria should hold. If capsule surface fusion takes place while the capsule is in transition flow (i.e., the region between continuum and free-molecular flow), there will be no distinct boundary layer, but a shock-wave/boundary-layer interaction at or very near the capsule surface will produce rather severe aerodynamic forces on the capsule surface. In the present case, all strontium fluoride fusion that occurs takes place at altitudes above 165,000 feet, where both capsule configurations are in transition flow. The occurrence of severe aerodynamic forces at the capsule surface combined with the large temperature gradient throughout the capsule in a radial direction, certainly must reduce the probability that a large

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droplet can be formed on the capsule surface. Therefore, postulations of spray-type formation of droplets would not seem logical in this analysis.

A realistic and logical approach to a material ablation study of this type, consequently, would be to assume that the molten capsule material forms maximum stable-sized droplets which continue to re-enter. The molten droplets which leave these capsules experience a further temperature increase because the droplets are so small that they are in free-molecular flow with a Stanton number of 0.25 although the capsules are in transition flow with Stanton numbers of 0.02 to 0.05. Since a tumbling, spinning cylinder is approximately three times more efficient in converting available energy to heat than a sphere for a given flow regime, the change in shape would decrease the heat transfer to the small spheres by a factor of 3 if the flow regime for the cylinder and the spheres were the same. The change in flow regime, however, increases the Stanton number for the small spheres by at least a factor of 50. The net heat transfer to the small droplets per pound of droplet material will, therefore, be increased by a factor of at least 16 over the net heat input to the capsule per pound of capsule material.

Thermophysical Properties

The properties of Haynes alloy and strontium fluoride used in this analysis are listed below:

HAYNES 25

Emissivity	= 0.25 or 0.80	Reference 4
Density	= 570 lb/ft ³	}
Specific heat	= 0.092 at 32°F	
	= 0.168* at 2495°F	
Fusion temperature	= 2505°F	
Thermal conductivity	= 1.575 x 10 ⁻³ BTU/ft-sec °F at 68°F	}
	= 4.26 x 10 ⁻³ BTU/ft-sec °F at 1652°F	
	= 4.5 x 10 ^{-3*} BTU/ft-sec °F at 2600°F	
Heat of fusion	= 100 BTU/lb (estimated from values for components)	Reference 8

STRONTIUM FLUORIDE

Emissivity	= 0.9 (estimated)	
Density	= 267 lb/ft ³	Reference 9
Specific heat	= 0.140 BTU/lb °F at 32°F	}
	= 0.218 BTU/lb °F at 2552°F	
Fusion temperature	= 2552°F	Reference 10

* Extrapolated

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Vaporization temperature	= 4312°F	Reference 11
Heat of fusion	= 114 BTU/lb (average of values in References 12 and 13)	
Heat of vaporization	= 1015 BTU/lb	Reference 12
Surface tension at 2552°F	= 0.0104 lb f/ft	Reference 14
Thermal conductivity	= 1.34 x 10 ⁻⁴ BTU/ft-sec °F at 32°F = 3.69 x 10 ⁻⁴ BTU/ft-sec °F at 572°F = 2.01 x 10 ⁻⁴ BTU/ft-sec °F at 1337°F = 2.8 x 10 ⁻⁴ BTU/ft-sec °F at 2552°F	Reference 15

The specific heat of the molten strontium fluoride was assumed to be 0.218 and constant with respect to temperature increases above the fusion temperature. This assumption will tend to predict greater temperature rises than would actually be experienced because specific heat values generally increase with temperature above the fusion point.

Vaporization of Strontium Fluoride Droplets

Droplets of molten strontium fluoride were assumed to continue re-entry from their point of formation. Heating rates to the droplets were again calculated using Figure 1. These heating rates will be the maximum possible rates since no "blocking effects" were considered and the droplet was assumed to encounter free-stream conditions upon formation. "Blocking effects" occur when a re-entering body experiences vapor effusion from its surface. This vapor tends to build up a gas cap around the body which inhibits heat transfer from the airstream to the body.

Vapor pressure and evaporation rate data for strontium fluoride are of extreme importance in this part of the analysis. The vapor pressures were determined from a graph of log P versus 1/T. The data of Ruff and Boucher¹¹ were graphed, and the best straight line through these points and the published boiling point were determined. The temperatures and corresponding vapor pressures as determined from the graph were used to calculate the rate of evaporation at a given temperature.

The evaporation rate was calculated using the Langmuir equation:

$$\dot{Z}_{\max} = \frac{P_v}{(2\pi MRT)^{\frac{1}{2}}} \quad (7)$$

where

$\dot{Z}_{\max}$ mass loss in a vacuum (moles/cm²-sec),

P_v vapor pressure (dynes/cm²),

M = molecular wt,

R = universal gas constant, and

T temperature (°K).

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Equation (7) is derived from kinetic theory and gives the maximum possible rate of evaporation or the rate of evaporation in a vacuum. The following assumptions are inherent in the work:

1. The equation $\text{SrF}_2 \text{ (liquid)} \rightleftharpoons \text{SrF}_2 \text{ (gas)}$ holds over the entire temperature range rather than a dissociation or disproportionate $2\text{SrF}_2 \text{ (gas)} \rightleftharpoons 2\text{SrF} + \text{F}_2$.
2. The ambient pressures are less than 10 mm of Hg (altitude > 150,000 ft).
3. Immediately adjacent to the surface of the molten material, there is a layer of vaporized material less than one mean free path thick.

The method outlined above, along with the proper changes in units, resulted in the curve of evaporation rate versus temperature shown in Figure 14, page 28.

When the ambient pressure over a portion of the body is greater than 10 mm of Hg, a correction must be applied to extrapolate the evaporation rate to the higher pressure region. In order to handle the evaporation from the higher pressure area near the stagnation point, the assumption is made that the local evaporation rate is linearly proportional to the ratio of the maximum pressure that will permit the maximum evaporation rate and the local pressure:

$$\dot{z}_a(T) = \frac{P_{cr}}{P_a} \dot{z}_{max}(T) \quad (8)$$

$$\dot{z}_a(T) = \frac{P_{cr}}{P_s \cos^2 a} \dot{z}_{max}(T) = \frac{P_{cr}}{2Q \cos^2 a} \dot{z}_{max}(T) \quad (9)$$

where

- $\dot{z}_a$ = local evaporation rate,
- P_{cr} = maximum pressure that will permit the use of available published data on evaporation rates of SrF_2 at reduced ambient pressure,
- P_a = local pressure distribution in free molecular flow:
 $P_a = P_s \cos^2 a$,
- P_s = stagnation pressure,
- Q = free-stream dynamic pressure,
- $\dot{z}_{max}(T)$ = maximum evaporation rate (valid for $P_a \leq 10$ mm of Hg),
- a = angle from the stagnation point to a local point on the sphere, and
- a_{cr} = angle corresponding to that point on the sphere where
 $P_a = P_{cr}$.

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To determine the evaporative mass losses, it is necessary to compute simultaneously the trajectory, heat transfer history of the surface, and mass changes as they affect these values. A fairly simple computer program can handle these variations since the small particles remain at an essentially constant altitude, and the temperature throughout the particle is nearly constant. That is, a single-node heat-transfer code incorporating evaporative cooling and surface evaporation is used in conjunction with a point mass trajectory program.

The equation governing the trajectory of the droplets is:

$$-D + W \sin \gamma = ma \quad (10)$$

where

$$D = C_D A \rho V^2 / 2g,$$

W = droplet weight,

γ = angle of flight path below the horizontal,

m = droplet mass,

a = acceleration of droplet = $dV/d\theta$, and

A = cross-sectional area of droplet.

Since $\sin \gamma$ is extremely small and may be neglected, Eq. (10) may be rearranged to give:

$$\Delta V = \frac{\frac{1}{2} \rho V^2}{W/C_D A} \Delta \theta. \quad (11)$$

Since mass loss due to evaporation in a time interval $d\theta$ is:

$$m_{1v} = \int_{\theta} \int_A \dot{Z}_a(T) d\theta dA \quad (12)$$

and

$$dA = r^2 \sin \alpha d\alpha d\phi \text{ (see Figure 15, page 28),} \quad (13)$$

then by combining Eqs. (9), (12), and (13):

$$m_{1v} = \int_0^{a_{cr}} \int_0^{2\pi} \int_{\theta_1}^{\theta_2} \frac{P_{cr}}{2Q \cos^2 \alpha} \dot{Z}_{max}(T) r^2 \sin \alpha d\alpha d\phi d\theta, \quad (14)$$

for $\alpha \leq a_{cr}$.

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For $a \geq a_{cr}$,

$$m_{lv} = \int_{\theta_1}^{\theta_2} \dot{z}_{max}(T) \left[4\pi r^2 - \int_0^{a_{cr}} \int_0^{2\pi} r^2 \sin a \, da \, d\phi \right] d\theta. \quad (15)$$

Combining Eqs. (14) and (15) yields:

$$m_{lv} = \int_{\theta_1}^{\theta_2} \left\{ \dot{z}_{max}(T) \left[4\pi r^2 - \int_0^{a_{cr}} \int_0^{2\pi} r^2 \sin a \, da \, d\phi \right] + \int_0^{a_{cr}} \int_0^{2\pi} \frac{P_{cr}}{2Q \cos^2 a} r^2 \sin a \, da \, d\phi \right\} d\theta \quad (16)$$

With proper substitutions, Eq. (16) becomes:

$$m_{lv} = \int_{\theta_1}^{\theta_2} \dot{z}_{max}(T) \left[4\pi r^2 + 2\pi r^2 (\cos a_{cr} - 1) + 2\pi r^2 \frac{P_{cr}}{2Q} \left(\frac{1}{\cos a_{cr}} - 1 \right) \right] d\theta, \quad (17)$$

which is the evaporative mass loss over the entire surface in a time interval $d\theta$.

The heat loss rate due to evaporation from the surface may be described by the product of mass loss rate and the heat of vaporization. This term can then be accounted for in the heat balance for the droplet as:

$$\dot{q}_{int} + \dot{q}_{cw} = \dot{q}_{rad} + \dot{q}_{stored} + \dot{q}_{hw \text{ correction}} + \dot{q}_{cond} + \dot{q}_{evaporation \text{ loss}} \quad (18)$$

Equation (18) is the same as Eq. (5) except that there is now an evaporation heat loss included.

Since a one-node system is used, the $\dot{q}_{cond}$ term is equal to zero, and Eq. (18) may be written for a vaporizing sphere as:

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$$\begin{aligned} \dot{q}_{\text{int}} + \dot{q}_{\text{cw}} = \sigma \epsilon 4\pi r^2 (T^4 - T_{\text{space}}^4) + mc_p \frac{dT}{d\theta} \\ + \frac{C_p T}{V^2/2Jg} \dot{q}_{\text{cw}} + \frac{m_{1v} \cdot \ell}{d\theta} \end{aligned} \quad (19)$$

where

ℓ = the heat of vaporization and

m_{1v} = mass loss due to evaporation in time interval $d\theta$ --see Eq. (17).

Heating to the sphere, as shown in Figure 1, is described by:

$$\dot{q}_{\text{cw}} \frac{\text{BTU}}{(\text{sec})} = St_2 \times 1/2 \frac{\rho V^3}{Jg} \times 2\pi r^2 \quad (20)$$

Now, Eqs. (11), (17), (19), and (20) describe the trajectory, mass loss, temperature rise and aerodynamic heating, respectively, of an evaporating droplet. Iterative computer solutions of these equations for several of these droplets formed during ablation will yield a total evaporative mass loss.

Trajectory Selection

Re-entry Vehicle Ballistic Parameter

To determine the effect of the ballistic parameter of the parent vehicle on fuel capsule ablation, theoretical orbital-decay trajectories¹⁶ for two different re-entry vehicles were acquired. A maximum ballistic parameter ($W/C_D A$) of 300 lb/ft² was chosen to be compared with a more realistic value of 50 lb/ft². Fuel capsules were assumed to be released from the parent vehicle at an altitude of 256,000 feet. A comparison of Figures 5 and 6 shows the differences in the heating rates and temperature histories of the smaller fuel capsule. These differences may be attributed to the difference in $W/C_D A$ of the parent vehicles. It can be seen from these figures that even at a low fuel capsule release altitude (256,000 feet), where the re-entry vehicle has been subjected to considerable drag, the ballistic parameter of the parent vehicle has little effect upon the amount of capsule fusion. At higher fuel capsule release altitudes, the effect is decreased even further. Since the effect is small, the remainder of this analysis will be based upon the more realistic ballistic parameter of 50 lb/ft² for the re-entry vehicle.

This imaginary re-entry vehicle was assumed to have a nose radius of 6 inches so that the drag coefficient and the trajectory could be computed in the free molecular, transition, and continuum flow regimes.¹⁷ (See Appendix A.)

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Figure 5. Node temperatures and area-averaged cold-wall heat rate versus altitude for the 1.4-inch-diameter capsule released at 256,000 feet--re-entry vehicle $W/C_D A = 50$, Haynes emissivity = 0.25

Figure 6. Node temperatures and area-averaged cold-wall heat rate versus altitude for the 1.4-inch-diameter capsule released at 256,000 feet--re-entry vehicle $W/C_D A = 300$, Haynes emissivity = 0.25

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Capsule Release Altitude

Fuel capsule release altitudes of 325,000 and 256,000 feet were considered for ablation analyses since they represent the altitude of maximum net integrated heat and the minimum release altitude for which complete burnup might be achieved, respectively. Net heating refers to that energy which is stored in the fuel capsule. If the capsules are released above 325,000 feet, they will experience a short period of decrease in temperature in all cases until the aerodynamic heating becomes sufficient to balance radiation losses. Therefore, release altitudes above 325,000 feet do not result in additional capsule ablation. Figure 5 shows that a release altitude of 256,000 feet will permit 95 percent of the small capsule to fuse. This release altitude then appears to be subminimal.

A comparison of Figures 5 and 9 shows the effect of release height upon the fusion altitude for the small capsule configuration. A similar effect would occur for the large capsule configuration. These figures show that a release altitude of 325,000 feet produces maximum capsule fusion. This release height will be used to obtain final results.

Trajectory Analysis

Since the ablation process is an eroding or tearing away of the surface of the fuel capsule, the weight, surface area, and principal body dimension are decreased.

If inertial forces are neglected, the ballistic parameter ($W/C_D A$) determines the trajectory of a re-entering body. The drag coefficient of an end-over-end tumbling and spinning cylinder in hypersonic-continuum flow is given by:²

$$C_D = (0.518 + 1.11 r/L). \quad (21)$$

Therefore, the ballistic parameter for a tumbling cylinder in hypersonic-continuum flow may be written as

$$W/C_D A = \frac{\rho \pi r^2 L}{(0.518 + 1.11 r/L) 2rL} = \frac{\rho \pi r}{2(0.518 + 1.11 r/L)}. \quad (22)$$

Assuming, for ballistic parameter calculations, that r/L is constant during ablation implies a high rate of ablation from the ends of the cylinder and still shows that:

$$W/C_D A = f[\text{constant } (r - \Delta r)]. \quad (23)$$

In other words, the ballistic parameter for a cylinder varies linearly with a change in r even when one assumes a high rate of ablation from the ends of the cylinder. The above reasoning shows that a nonconstant W/A must be used in the trajectory analysis of bodies that experience considerable ablation over a period of time.

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This change in the geometry causes a decrease in the ballistic parameter of the capsule and a slight increase in the efficiency of heat transfer to the capsule. These changes, in turn, affect the trajectory and the net convective heating rate. A comparison of Figures 7 and 8 shows the effect of the variation in geometry.

Figure 7. Node temperatures and area-averaged cold-wall heat rate versus altitude for the 3-inch-diameter capsule released at 256,000 feet--re-entry vehicle $W/C_D A = 50$, Haynes emissivity = 0.25

Figure 8. Node temperatures and area-averaged cold-wall heat rate versus altitude for the 3-inch-diameter capsule released at 256,000 feet--re-entry vehicle $W/C_D A = 50$, Haynes emissivity = 0.25

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Since there was no computer program available which would incorporate transient multinode heat transfer computations with the theoretical trajectory history, it was necessary to utilize these computer programs separately. Specifically, the chain of events necessary to conduct this type of analysis is:

1. Calculate the convective heating rate from the trajectory which would occur if the geometry of the fuel rod were constant.
2. Using this heating rate, determine the fusion altitudes for finite volumes of the cylinder.
3. On the basis of this variation in geometry due to fusion as a function of altitude, recalculate the more realistic trajectory and the convective heating rate associated with it.
4. Using this modified heating rate, determine more realistic fusion altitudes and then predict the maximum stable droplet size.
5. Finally, conduct the trajectory and corresponding heat transfer analyses for the droplets formed by fusion in order to investigate vaporization of these droplets.

Trajectory Used in the Ablation Analysis

A final trajectory which, although realistic, would provide for the maximum possible ablation of the SNAP-17 fuel capsules was selected for use in the ablation analysis. A SNAP-17 generator with a ballistic parameter of 50 was assumed to re-enter from an operational circular orbit carrying the fuel capsules to an altitude of 325,000 feet. The capsules were assumed to be released from the generator at this altitude and exposed to aerodynamic heating. The ballistic parameters for the 3-inch-diameter capsule and the 1.4-inch-diameter capsule with their initial geometries in hypersonic-continuum flow are 91.0 and 50.0 lb/ft², respectively. The variation of ballistic parameter with flow regime is described in Appendix A. The initial conditions describing the trajectory of the capsules are as follows:

Capsule release altitude	= 325,342 feet
Initial capsule velocity	= 25,596 ft/sec
Re-entry angle with respect to the horizontal	= -0.397°
Latitude	= 83.58°
Longitude	= 141.70°
Angle of flight path with respect to the equator	= -57.7°

These conditions were used to compute the trajectory and heating rates of the capsules. The change in ballistic parameter of the capsules as they ablated was approximated by the method described above.

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Results of the Ablation Analysis

The results of the ablation analysis are presented in Figures 9 through 13.

Haynes Fusion Altitude

Although two emissivities were assumed for Haynes 25, an emissivity of 0.80 was thought to be the more realistic value. As may be seen from Figures 9 and 10, the Haynes container on the 1.4-inch-diameter capsule will fuse at 254,000 feet with an emissivity of 0.25, or at 229,000 feet with an emissivity of 0.80. Figures 11 and 12 show Haynes fusion on the 3.0-inch-diameter capsule at 241,000 feet with an emissivity of 0.25, or at 213,000 feet with an emissivity of 0.80.

Strontium Fluoride Fusion Altitude

Figures 9 through 12 show that complete fusion of the strontium fluoride in the two capsules can occur only in the small capsule configuration if the Haynes container is in a polished condition during re-entry (emissivity 0.25). Several things should be pointed out about these results. When the small capsule becomes completely fused at 191,000 feet, it just barely does so. The temperature reaches the fusion temperature and immediately begins to decrease in the capsule configuration. The heat balance at the time of the fusion of last node in the small capsule configuration (Figure 9) is:

$$\dot{q}_{\text{int}} + \dot{q}_{\text{cw}} = \dot{q}_{\text{rad}} + \dot{q}_{\text{stored}} + \dot{q}_{\text{cond}} + \dot{q}_{\text{hw correction}}$$

$$0.025 + 4.56 = 3.70 + 2.06 \, dT/d\theta + 0_{\text{last node}} + 0.86$$

or
$$dT/d\theta = 0.025$$

This shows that with the heating rate decreasing as the capsule ablates, most of the heat is being reradiated, and the temperature rise of the capsule material with respect to time is approaching zero. In other words, even with unrealistically optimistic conditions for ablation assumed, complete fusion of the strontium fluoride can be shown, but with no margin of safety.

Figures 10, 11, and 12 show that complete fusion of the strontium fluoride will not be attained for any condition other than the one described above. The more realistic results from Figures 10 and 12 show that 1.61 pounds of strontium fluoride will re-enter intact from a generator fueled with one large capsule and that 2.80 pounds will re-enter intact from a generator fueled with five small capsules.

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Figure 9.

Node temperatures and area-averaged cold-wall heat rate versus altitude for the 1.4-inch-dia capsule released at 325,342 feet, re-entry vehicle $W/CpA = 50$, Haynes emissivity = 0.25

Figure 10.

Node temperatures and area-averaged cold-wall heat rate versus altitude for the 1.4-inch-dia capsule released at 325,342 feet, re-entry vehicle $W/CpA = 50$, Haynes emissivity = 0.80

Figure 11.

Node temperatures and area-averaged cold-wall heat rate versus altitude for the 3-inch-diameter capsule released at 325,342 feet, re-entry vehicle $W/CpA = 50$, Haynes emissivity = 0.25

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Figure 12. Node temperatures and area-averaged cold-wall heat rate versus altitude for the 3-inch-dia capsule released at 325,342 feet--re-entry vehicle $W/C_D A = 50$, Haynes emissivity = 0.80

Figures 9 through 12 show that the small capsule is much more sensitive to changes in Haynes emissivity than the large capsule. This is caused by the difference in heating rate levels on the two capsules. At the strontium fluoride fusion temperature, the capsules are losing heat at the rate of approximately $50 \text{ BTU/ft}^2 \text{ sec}$ because of hot-wall and reradiation losses. The heating rate for the small capsule exceeds this value in only a limited altitude range, while the heating rate for the large capsule is above $50 \text{ BTU/ft}^2 \text{ sec}$ over a wide range of altitude. This means that later removal of the Haynes container causes a marked decrease in the amount of fusion attained in the small capsule, but the large capsule is affected to a lesser degree.

Initial Strontium Fluoride Droplet Sizes

Even though complete capsule fusion does not occur in a realistic case, it seemed advisable to take the less realistic case with Haynes emissivity of 0.25 and continue the study of the ablation of droplets from these capsules. Figure 13 shows the maximum stable-sized droplets that can exist versus altitude for the fusion of these two capsules. No droplets larger than those shown in Figure 13 will be formed from fused strontium fluoride. Maximum stable-droplet diameters range from 655 to 250 microns for the small capsule, and from 490 to 71 microns for the large capsule with an unfused portion amounting to a mass equivalent to that of cylinder 1.0 inch in diameter by 2.5 inches long in the case of the large capsule.

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Figure 13. Maximum stable particle size from Weber number criteria fusion considerations only from capsules shown in Figures 9 and 11, Haynes emissivity = 0.25

Strontium Fluoride Droplet-Vaporization Predictions

Figures 14 through 20 show the results of the strontium fluoride droplet-vaporization analysis. The values shown in these figures represent the maximum possible reductions in size due to evaporation since over half the droplet surface area was assumed to be producing metal vapor at a rate which would occur in a perfect vacuum.

Figures 16 through 18 show the histories of three maximum stable-sized droplets formed from the re-entry fusion of the 3-inch-diameter capsule. These droplets are assumed to have maximum diameters and velocities at the given altitudes. Inspection of the figures shows that the maximum mass loss due to evaporation of any droplet formed during re-entry is 50 percent of the original droplet mass.

Figure 19 compares the final droplet diameters after vaporization to the droplet diameters initially formed from the 3-inch-diameter capsule. As shown in this figure, evaporation does very little to alter the size of the molten droplets, and solid droplets ranging in size from 440 to 70 microns in diameter must be expected from ablation of the 3-inch-diameter capsule. Larger droplets should be expected from ablation of the 1.5-inch-diameter capsule.

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Figure 14. Strontium fluoride evaporation rate (as defined in Eq. (7)) versus temperature

Figure 15. Surface area increment on a sphere

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Figure 16. Heat sources and sinks, droplet temperature and diameter versus time during re-entry-- initial droplet size = 490μ , from beginning fusion of No. 2 node of 3-inch-diameter capsule with Haynes emissivity = 0.25 (Fig. 11)

Figure 17. Heat sources and sinks, droplet temperature and diameter versus time during re-entry-- initial droplet size 270μ from No. 2 node fusion of the 3-inch-diameter capsule with Haynes emissivity = 0.25 (Fig. 11)

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Figure 18. Heat sources and sinks, droplet temperatures and diameter versus time during re-entry--initial droplet size = 71μ , from terminal fusion of 3-inch-diameter capsule with Haynes emissivity = 0.25 (Figure 11)

Figure 19. Maximum stable droplet size and final size after vaporization--initial size determined from fusion of 3-inch-diameter capsule

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To this point, only maximum stable sized droplets have been considered. For completeness, the droplets formed from a capsule at a given point in space were assumed to vary in size from the maximum stable size down to 10 microns. Then a vaporization study was performed to determine the fate of the 10-micron particle. Figure 20 shows that a 10-micron-diameter particle with a high velocity (23,400 ft/sec) formed at an altitude of 218,000 feet has a final diameter of 8 microns after evaporation and resolidification. A similar calculation, not shown in the figures, was performed for a 10-micron droplet released at 236,000 feet with a velocity of 23,300 ft/sec. Its size was reduced to 8.5 microns. These studies show that total droplet vaporization expressed as a percentage of the original droplet mass is generally a function of initial velocity and altitude of formation rather than of droplet size. For example, a 270- and a 10-micron droplet formed with an initial velocity of 23,400 ft/sec at an altitude of 218,000 feet both experience 50-percent evaporation of their original mass. All other droplets of SrF_2 formed along this realistic trajectory experience less than 50-percent mass loss due to evaporation.

Figure 20. Heat sources and sinks, droplet temperature and diameter versus time during re-entry--initial droplet size assumed to be 10μ , from No. 2 node fusion of the 3-inch-diameter capsule with Haynes emissivity ~ 0.25 (Figure 11)

In other words, all molten droplets formed with a size greater than 1.25 microns in diameter will solidify and fall to earth as particles larger than 1 micron. As stated earlier in this report, most of the strontium fluoride should form droplets near the size predicted by the Weber number criteria; and as shown in Figure 19, the final range of sizes will be only slightly decreased by vaporization.

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A comparison of Figures 11 and 19 reveals a total evaporative mass loss along the trajectory of approximately 30 percent of the original SrF_2 mass. Since the authors feel that a very small percentage of the original mass will result in molten droplets of a size less than 10 microns in diameter, nearly 70 percent of the original mass of the SrF_2 would reach the earth as particles 10 microns or larger in diameter.

Summary

Prediction of re-entry burnup cannot be considered a precise art for several reasons, the most outstanding of which, for this analysis at least, is the lack of data concerning the size distribution of molten droplets formed from capsule fusion. However, confidence may be placed in the negative results of an analysis which is based on optimistic assumptions. This analysis was conducted, within realistic limits, in a manner intended to provide maximum fusion and subsequent vaporization of strontium fluoride. From a safety viewpoint, the results of this analysis are negative. Under optimum conditions for burnup, using an emissivity of 0.8 for the Haynes container, incomplete fusion of the strontium fluoride was shown for both capsule configurations. These results will hold true for any strontium fluoride capsule with an L/D ratio greater than 2.5. Continued analysis merely assumed complete strontium fluoride fusion along the trajectory of the 3-inch-diameter capsule from 400,000 to 100,000 feet and studied the vaporization of molten droplets. The vaporization studies show that the average amount of fused mass which is subsequently vaporized on this trajectory (suited to optimum vaporization) will be under 30 percent. The remaining 70 percent of the strontium fluoride will fall to earth as large solid particles. In other words, if the strontium fluoride is assumed to be molten even at the start of re-entry, the safety criteria cannot be satisfied. These results will hold true for capsules of any L/D ratio.

The distribution of particles formed at a point in space will have little effect on the results of the analysis since it was shown that a 10-micron-diameter particle will be reduced in size by vaporization only to 8 microns. The only possible way to imply that strontium fluoride will meet safety criteria during re-entry burnup (i.e., 1 micron or less final particle size) is to assume that all molten particles of strontium fluoride formed from the fusing capsules are less than 1.25 microns in diameter. This would be a grossly unrealistic assumption since the only experimentally verified criteria for particle-size determination, the Weber number criteria, show that particles can exist as large as 650 to 70 microns in diameter. The authors feel that much of the mass will exist as particles in this size range.

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Conclusions

1. Any re-entry of strontium fluoride in the two configurations studied will result in a high probability of incomplete fusion of the strontium fluoride.
2. Of the fused strontium fluoride, less than 30 percent of the mass will be vaporized, with the remainder falling to earth as large particles.
3. For these reasons, strontium fluoride does not appear to satisfy the current safety philosophy requiring submicron particles dispersed at altitudes above 100,000 feet.

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APPENDIX A

Variation of Ballistic Parameter
with Flow Regime

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APPENDIX A

Variation of Ballistic Parameter with Flow Regime

Drag coefficients, and therefore ballistic parameters, must vary with flow regime. This variation is taken into account in the following manner.

Average drag coefficients for cylinders tumbling end-over-end and spinning can be calculated for continuum and free-molecular flow. These calculated coefficients--see Eq. (21)--vary with cylinder L/D ratio.²

Re-entering bodies usually experience three flow regimes during re-entry: continuum, free molecular, and transition flow (where transition flow is defined as the regime between continuum and free molecular). It is desirable to provide a curve in the trajectory computation program which will reflect the proper variation of drag coefficient with hypersonic-flow regime for any given shape.

Reference 17 provides a curve (Figure 21) which shows the variation of drag coefficient of a sphere versus Knudsen number for the three hypersonic-flow regimes. This curve has been inserted into the trajectory computer program, and therefore drag coefficients for spheres are automatically computed as a function of flow regime.

Figure 21. Drag coefficient versus Knudsen number for a sphere in hypersonic flow (from Reference 17, p. 325)

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It can be shown that the total variation in drag coefficient from continuum to free molecular flow is the same for spheres and end-over-end or random-tumbling cylinders in hypersonic flow. As shown in Figure 21, the ratio of the free-molecular drag coefficient to the continuum drag coefficient is 2.18. It is assumed that the trend of drag coefficient variation in the transition regime is also the same for end-over-end or random-tumbling cylinders and spheres. Therefore, to obtain the proper variation of drag coefficient for cylinders, one merely adjusts the ordinate of Figure 21. The input to the trajectory computation program is a ballistic parameter ($W/C_D A$). Since the computer always used the curve of Figure 21 for C_D computations, the weight term in the ballistic parameter must be adjusted in the case of a cylinder to effectively change the ordinate of Figure 21. If $W_R/C_D A$ is the real ballistic parameter of the cylinder in hypersonic-continuum flow, a new weight must be calculated for computer use such that

$$\frac{W_R}{C_D A} = \frac{W_{\text{new}}}{0.92 A} \quad (24)$$

where 0.92 is the sphere drag coefficient in hypersonic-continuum flow. Then, the term $W_{\text{new}}/0.92 A$ is given to the computer to use as the ballistic parameter. Thus the computer uses the correct value of ballistic parameter and varies it with flow regime as shown in Figure 21.

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APPENDIX B

Theoretical Trajectory Results

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APPENDIX B

Theoretical Trajectory Results

The heating rates presented in this report were plotted versus altitude to obtain a better comparison between the two different capsules. Appendix B is included to present trajectory results versus time, thus enabling the reader to check the results of the main text.

Figure 22 shows the velocity, altitude, and range results for the orbital decay of the re-entry vehicle. Figures 23 and 24 show the theoretical trajectory results for the two fuel capsule configurations. Velocity and heating rates do not plot smooth curves as a function of time because cylindrical elements of the fuel capsules were removed as the capsules fused, and thus the trajectories of the capsules were affected. The changes in capsule geometry as a function of time are listed below. (Refer to Figures 2 and 3 for identification of node configurations.)

<u>Capsule Configuration</u> <u>(in. dia)</u>	<u>Node Removed</u> <u>(No.)</u>	<u>Time</u> <u>(sec)</u>
3	1	300
1.4	1	270
3	2	367
1.4	2	310
3	3	391
1.4	3	321
3	4	410
1.4	4	332

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Figure 22. Theoretical orbital decay trajectory for re-entry vehicle of $W/C_{DA} = 50.0$, Re-entry angle at 400,000 ft = -0.05 degree

Figure 23. Theoretical trajectory results for the 3-inch-diameter capsule

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Figure 24. Theoretical trajectory results for the 1.4-inch-diameter capsule

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