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SNC-3693-3
ISOTOPES-INDUSTRIAL
TECHNOLOGY
TID 4500 ED.

THULIUM OXIDE FUEL CHARACTERIZATION STUDY
(THULIUM-170 FUELED CAPSULE PARAMETRIC DESIGN)

SNC--3693-3-11/69

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Division of Isotopes Development
U. S. Atomic Energy Commission
Contract Number: AT-(40-1)-3693

November 1969

By

SANDERS NUCLEAR CORPORATION
Nashua, New Hampshire

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ABSTRACT

An analytical parametric study was made of an infinitely long, cylindrical fuel capsule containing thulia ($\text{Tm}_2^{170}\text{O}_3$) encapsulated in two different physical forms and in two different liner configurations.

Diameters of wafers maintained at 0.060 inch thickness were varied between 0.6 and 3.0 inches. Radial temperature profiles were determined for thulia power densities ranging from 8 to 24 w/cc and fuel capsule surface temperatures ranging from 1000° to 2732°F . Hastelloy X, Haynes 25, T-222, tungsten, platinum and molybdenum are the liner materials investigated.

Methods of calculation, (including computer codes), assumptions used, error analyses and results are presented and discussed.

Recommendations are made with respect to additional studies.

SECTION 1

INTRODUCTION

The overall objective of this program is the determination of the feasibility for application of encapsulated thulium-170 as an isotopic fuel for operations at temperatures up to 2732°F (1500°C) for 180 days. The determination of feasibility is in part to result from analysis of a fuel capsule parametric design task, the elements of which are reported herein. Further, the results obtained will be used as a design guide in the preparation of test capsules for subsequent compatibility studies and to establish conditions and precision of measurements for property measurement tasks to be completed in subsequent program phases.

The study proceeded on two assumptions; one, that thulium-170 is encapsulated as thulium sesquioxide (the metal melts at 1545°C) and, two, that operations at temperatures up to 2732°F (1500°C) pertains not so much to the fuel capsule surface temperature as to the encapsulant/thulia interface, whenever occurring in a heat source subsystem.

A fuel capsule parametric design study is desirable because feasibility of application should be concluded on the basis that

satisfactory fuel capsule thermal profiles result when useful and practical capsule designs and capsule/fuel operating conditions are ascribed to the fuel capsule.

Specifically defined useful dimensions and operating conditions for an assumed infinitely long right circular cylinder fuel capsule were the parameters of the study; the parameters of capsule operation and design for which thermal profiles were determined were as follows:

- Three postulated fuel capsule wall temperatures - those used were: 1000°F (538°C), 1500°F (816°C), and 2000°F (1093°C). These are representative of useful fuel capsule surface temperatures in space thermoelectric systems. Operation in this capsule surface temperature range can generally be expected to permit assembly of multiple, reasonably dimensioned, fuel capsules into heat source subsystems without excessive radial thermal gradient being experienced.⁽¹⁾
- Two capsule fill gases - argon and helium.
- Two fuel thermal conductivities - 1.5 and 3.0 B/hr-ft- $^{\circ}\text{F}$ were used. In the absence of experimental data on thulia it was postulated on the basis of the thermal conductivity of other ceramics that these values should bracket the real case when this is determined.

(1) Compatibility test temperatures in Phase II will be 600°C , 1000°C , and 1600°C . These are not inconsistent with the analyzed capsule surface operating temperatures. Phase II test temperatures are obtained in isothermal soaks; these do not mock-up operating radial thermal gradients. Reference to Figures 5 to 14 show the test temperatures of Phase II are readily attained at thulium/liner interfaces when the capsule surface temperatures are as stated: This is even more true for multiple capsule heat source subsystems designed to meet intact impact safety design criteria after a re-entry thermal spike.

- ④ Three capsule diameters - those used accommodate fuel volume diameters of 0.6, 1.8, and 3.0 inches; the smallest of these is only slightly smaller than that of the SNAP-29 fuel rod, the largest of these approximates nominally the largest individual fuel capsule used to date in space, SNAP-19.
- ⑤ Three fuel power densities - 8, 16 and 24 w/cc were used. These correspond nominally to 1, 2 and 3 w/gm of thulia, attainable and eminently useful values. The lower value is only slightly less than SNAP-29 would use.
- ⑥ Two fuel form designs - microspheres and wafers.
- ⑦ Two liner configurations - multiple wafers stacked within a single liner; also, individual wafers within individual wafers liners.
- ⑧ Surface temperature 1500°C (2732°F) - on bulk encapsulated wafers of 0.6 inch diameter radial profiles were determined as a function of gas fill and fuel power density; this set of data was developed to provide a feel for the validity of extrapolations one might care to make on all other parametrically derived profiles.

The last two of the study parameters identified above, in effect, resulted in thermal profiles being generated for three basic fuel capsule configurations; these are shown schematically in Figure 1 and are described briefly below.

Configuration (a) consists of thulia wafers that are individually encapsulated within light-gauge, metallic liners prior to irradiation; subsequent to irradiation, a multiplicity of encapsulated wafers are assembled into a heavy-gauge containment capsule. In the test, this configuration is referred to as the individual wafer encapsulation design. By judicious selection of a compatible liner material of low neutron absorption cross-section and low energy, short half life activated species, that thulia-liner/containment capsule system is realized which is most readily assembled and quality control checked in the post activation period.

(a) Individual Wafer Encapsulation

(b) Bulk Wafer Encapsulation

(c) Microsphere Encapsulation

Figure 1. Fuel Form and Encapsulation Techniques

Configuration (b) consists of a multiplicity of individual bare thulia wafers which in the hot, radioactive state are assembled into a single light-gauge, metallic liner; subsequently this subassembly is assembled into a heavy-gauge containment capsule. It is referred to in the text as the bulk wafer encapsulation design. If the hot handling required for encapsulation of bulk thulia in the internal liner and the outer containment capsule does not consume more time than post activation quality check of configuration (a) then this encapsulation technique can provide the higher power density heat source.

Configuration (c) consists of a multiplicity of thulia microspheres assembled into a single light-gauge, metallic liner; subsequently this subassembly is assembled into a heavy-gauge, containment capsule. In the text, this configuration is referred to as the microsphere capsule design.

Section 2 summarizes results of the study.

Section 3 presents the calculation procedures followed in deriving thermal profiles for each of the three basic fuel capsule configurations; examples of the computer print-out resulting from execution of the calculation procedures are presented in Appendices A and B. Section 3 also presents the graphical results of the parametric study.

Study completion requires that parametric results be analyzed and evaluated to define limiting fuel capsule operating conditions based on the thermal properties of containment materials to be used and, to define the precision with which applicable experimental results will be obtained in testing performed in subsequent phases.

Section 4 discusses the results and presents an analysis of the data.

The appendices carry the computer data used in this work.

SECTION 2

SUMMARY

Equations were developed and calculations were performed to provide temperature distribution data for individual Tm_2O_3 wafer, Tm_2O_3 bulk wafer and Tm_2O_3 microsphere encapsulations. Analytical error in the procedures developed for the wafer cases is 1% or less.

Thermal profiles are presented for power densities ranging from 8-24 w/cc with fuel capsule surface temperatures ranging from 1000-2732°F. Hastelloy X, Haynes 25, T-222, tungsten, platinum and molybdenum liner materials are considered.

Results show that the individual wafer encapsulation approach offers the greatest flexibility in capsule design and that of microspheres the most restrictive. Further, the study indicates that the precision required in the investigation of the behavior of the $\text{Tm}_2\text{O}_3/\text{Yb}_2\text{O}_3$ system be sufficient to detect melting within 50-100°F and that solid state transitions, if they occur, are not expected to be a significant factor. Temperatures for compatibility tests should be well separated and accurate to $\pm 120^\circ\text{F}$.

The availability of several practical capsule designs for Tm_2O_3 demonstrates the feasibility of applying thulium sesquioxide as an isotopic heat source.

SECTION 3
FUEL CAPSULE PARAMETRIC DESIGN
CALCULATION PROCEDURES

3.1 GENERAL

The analytic technique to be used in determination of thermal profiles for configurations (a) and (b) of Figure 1 was derived initially on the individual wafer encapsulation design because it represented the more complex analysis problem. Figure 2 details the design analyzed. Sixty-mil thick wafers in 3-mil gage liners of the illustrated design have been fabricated and successfully irradiated by Sanders Nuclear, although not under this contract.

To arrive at the temperature distribution in the individual wafer encapsulation configuration, three different analytical techniques were investigated; each had a different degree of sophistication. The first technique investigated used the differential equations which describe the temperature profile in a two-dimensional representative section of an infinitely long capsule, as shown in Figure 3. Because of discontinuities at interfaces, this approach could not readily be solved by analytical methods and a numerical solution involving a nodal system would have had to be used. A second and less sophisticated approach to analysis of the two-dimensional representative section assumed no axial heat flow within either the liner or the fuel wafer; it did account for axial heat transfer between the fuel wafer and the liner. The resulting differential equations, however, again did not lend themselves to direct analytical solution.

Figure 2. Detail View of Individually Encapsulated Wafers

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Figure 3. Thulium Fuel Capsule Configuration Using Individual Wafer Encapsulation

The third approach investigated, and that used in this study, assumed no axial heat transfer anywhere in the representative thermal region. Before proceeding with this approach, however, an error analysis was made to determine the maximum error that would occur in the temperature computed to exist at any given radius as a result of assuming one-dimensional (radial) heat flow. The maximum error occurs in this one-dimensional analysis if, in a hypothetical case, all of the heat generated in the fuel wafer flowed axially out of the wafer and crossed axially to the outer boundary of the liner. This, of course, is not possible because there is no heat flow across the axial boundaries of the liners due to capsule system symmetry in the infinitely long capsule. This error analysis, however, does indicate the maximum temperature deviation from a two-dimensional analysis which could exist at the center plane of the wafer ($X = 0$) in this worst case. This deviation is shown in Paragraph 3.2 to be less than one percent, a tolerable error.

In the bulk wafer encapsulation design, the assumption of an infinitely long fuel capsule permitted the use of the one-dimensional radial heat transfer analysis without analytical error.

Once the equations defining the temperature distribution in the fuel capsule were established for the case of the individual wafer encapsulation design, the solution for the bulk wafer encapsulation design was also at hand. Similar computer codes were used for the two capsule configurations, the only difference being that a series of "DO" loops were necessary for the individual wafer encapsulation design because six different liner materials were to be investigated.

The thermal profiles within the microsphere-fueled capsule were determined using the standard one-dimensional heat transfer equation for heat flow in a cylinder with internal heat generation. The thermal conductivity for thulia microspheres was not available for these calculations. Experimental data available on plutonia and other metal oxide microspheres was used together with empirical

data available for these calculations. Experimental data available on porous packed beds to arrive at a representative thulia microsphere thermal conductivity.

The results of the analysis on microspheres led to a plot of the maximum fuel capsule diameter achievable without melting versus thulia power density. The plot defines the maximum fuel capsule diameter attainable without the centerline temperature exceeding 4172°F (2300°C). In this analysis, the temperature drop across the fuel capsule walls was not taken into consideration; it is available and identical for similar power densities in plots presented for the encapsulated wafer fuel forms.

3.2 CALCULATION PROCEDURE FOR INDIVIDUAL WAFER ENCAPSULATION DESIGN

Figure 3 represents a solid Tm_2O_3 wafer that is individually encapsulated. Gap B is the gas-filled gap separating wafer A from liner C. Gap D represents the loose fit of the encapsulated wafer in the containment capsule E.

The fuel capsule, as given, is assumed to be infinitely long in the X direction. As a result of this condition the heat transfer in the capsule is assumed to occur only in a radial direction. The thermal profile resulting from the assumption of one-dimensional heat transfer varies less than one percent from the profile given by the more rigorous two-dimensional analysis.

The total heat generated in the thulia wafer is given by:

$$Q = \pi R_1^2 L_A A_0 \quad (1)$$

where A_0 is the heat generated per unit volume. The outer fuel capsule housing temperature T_5 , is considered to be a known parameter. Knowing that the heat generated in the wafer must pass through the containment housing, temperature T_4 is obtained with the use of the equation for heat conduction through a cylinder with a concentrated heat source at the center.

$$Q = \frac{2\pi K_E L_C (T_4 - T_5)}{\ln [R_5 / (R_5 - t_E)]} \quad (2)$$

or upon rearranging

$$T_4 = \frac{\ln [R_5 / (R_5 - t_E)] Q}{2\pi K_E L_C} + T_5 \quad (3)$$

Substituting the value of Q from Equation (1) into Equation (3) yields:

$$T_4 = \frac{\{\ln [R_5 / (R_5 - t_E)]\} R_1^2 L_A A_O}{2K_E L_C} + T_5 \quad (4)$$

Once T_4 is obtained it is possible to calculate T_3 by considering the conduction through the gas gap in parallel with the radiation heat transfer across the gap.

$$\begin{aligned} Q &= Q_{\text{conduction}} + Q_{\text{radiation}} \\ Q &= \frac{K_D \pi [(R_3 + R_5 - t_E)/2] 2L_C (T_3 - T_4)}{R_5 - t_E - R_3} \\ &\quad + \frac{\sigma \pi [(R_3 + R_5 - t_E)/2] 2L_C (T_3^4 - T_4^4)}{1/\epsilon_E + 1/\epsilon_C - 1} \end{aligned} \quad (5)$$

Substitution of Equation (1) into Equation (5) and simplifying yields:

$$\frac{R_1^2 L_A A_O}{(R_3 + R_5 - t_E) L_C} = \frac{K_D (T_3 - T_4)}{R_5 - t_E - R_3} + \frac{\sigma}{1/\epsilon_E + 1/\epsilon_C - 1} (T_3^4 - T_4^4) \quad (6)$$

where:

K_D = thermal conductivity of the interstitial gas, B/hr-ft- $^{\circ}$ F

σ = Stefan - Boltzmann constant, 0.1715×10^{-8}
 $\text{B/hr-ft}^2 - ^\circ\text{R}^4$

ϵ_E = Emissivity of the inner surface of the fuel capsule housing

ϵ_C = Emissivity of the liner

Equation (6) yields an implicit relationship for T_3 and hence has to be solved by trial and error.

T_2 is determined by considering the temperature drop across the liner C, between R_3 and $R_3 - t_C$. This can be expressed as:

$$Q = \frac{2\pi K_C L_C (T_2 - T_3)}{\ln [R_3 / (R_3 - t_C)]} \quad (7)$$

or

$$T_2 = \frac{R_1^2 L_A A_O \ln [R_3 / (R_3 - t_C)]}{2K_C L_C} + T_3 \quad (8)$$

where K_C is the thermal conductivity of the liner material in $\text{B/hr-ft-}^\circ\text{F}$.

To obtain T_1 , it is necessary to consider three parallel heat transfer paths. These are:

- ① Conduction heat transfer through the gas B
- ② Radiation across the gap containing gas B
- ③ Conduction heat transfer through the liner material.

The region of concern for determining T_1 once T_2 is known is shown in Figure 4.

Figure 4. Heat Transfer Region for Determination of T_1

The heat transfer can be expressed as:

$$\begin{aligned}
 Q &= Q_{\text{radiation}} + Q_{\text{gas conduction}} + Q_{\text{solid conduction}} \\
 Q &= \frac{\sigma 2\pi [(R_1 + R_3 - t_C)/2] (L_C - 2t_C)}{1/\epsilon_A + 1/\epsilon_C - 1} (T_1^4 - T_2^4) \\
 &+ \frac{2\pi [(R_1 + R_3 - t_C)/2] (L_C - 2t_C) K_B (T_1 - T_2)}{R_3 - t_C - R_1} \\
 &+ \frac{K_C 2\pi [(R_1 + R_3 - t_C)/2] 2t_C (T_1 - T_2)}{R_3 - t_C - R_1} \quad (9)
 \end{aligned}$$

Substitution of equation (1) into equation (9) and reducing yields:

$$\begin{aligned}
 \frac{R_1^2 L_{A O}}{(R_1 + R_3 - t_C) (L_C - 2t_C)} &= \frac{\sigma}{1/\epsilon_A + 1/\epsilon_C - 1} (T_1^4 - T_2^4) + \frac{K_B (T_1 - T_2)}{R_3 - t_C - R_1} \\
 &+ \frac{2K_C t_C (T_1 - T_2)}{(L_C - 2t_C) (R_3 - t_C - R_1)} \quad (10)
 \end{aligned}$$

Again there is an implicit relationship for the unknown temperature T_1 and hence Equation (10) must be solved by trial and error.

The relationship for the temperature in a right circular cylinder with internal heat generation is:

$$T = \frac{A(R_1^2 - r^2)}{4K_1} + T_1 \quad (11)$$

where:

A = effective heat generation per unit volume,
B/hr-ft³

K_1 = effective conductivity of the cylinder, B/hr-ft-°F

r = radius of cylinder at which the temperature T
exists, ft

When considering the cylinder of radius R_1 it is necessary to determine the effective heat generation per unit volume, A , and the effective radial thermal conductivity, K_1 , of the cylinder with length L_C before applying Equation (11). The effective heat generation is given by the relation

$$A = A_0 \frac{\text{Volume of Thulia}}{\text{Volume of Thulia} + \text{Volume of Liner}} \quad (12)$$

or

$$A = A_0 \left(\frac{\pi R_1^2 L_A}{\pi R_1^2 L_A + \pi R_1^2 2t_C} \right) \quad (13)$$

And for the effective thermal conductivity

$$K_1 = \frac{K_A L_A + 2K_C t_C}{L_A + 2t_C} \quad (14)$$

Substituting Equations (13) and (14) into Equation (11) and solving for the centerline temperature T_0 yields:

$$T_O = \frac{A_O L_A R_J^2}{4(K_A L_A + 2K_C t_C)} + T_1 \quad (15)$$

In using the above technique for determination of the radial temperature profile, any error that results is due mainly to the assumption of no axial heat transfer between the wafer and the fuel liner. To determine the maximum attainable error in this analysis it is only necessary to assume that all of the heat which is generated in the thulia wafer is transferred axially from the wafer across gap B to the liner, i.e., no heat is transferred radially within the wafer. The temperature difference between the centerline of the wafer and the surface of the liner is then the maximum, i.e., the condition is described under which the calculated radial thermal profile can be expected to deviate to a maximum from the radial profile which would exist in an exact two-dimensional analysis.

Referring to Figure 3, the temperature profile within the thulia wafer in the axial direction between the center of the wafer and the surface of the wafer can be expressed as:

$$T_{A-X} = \frac{A_O [(L_A/2)^2 - X^2]}{2K_A} + T_{A-surface} \quad (16)$$

The axial temperature drop across the gas filled gap B is given by:

$$\begin{aligned} \frac{A_O L_A}{2} &= \frac{K_b (T_{A-surface} - T_C)}{L_C/2 - (t_c + L_A/2)} \\ &+ \frac{\sigma}{1/\epsilon_A + 1/\epsilon_C - 1} (T_{A-surface}^4 - T_C^4) \end{aligned} \quad (17)$$

Solving equation (16) for the temperature at $X = 0$ and then substituting the relationship for $T_{A-surface}$ into Equation (17) yields:

$$\frac{A_O L_A}{2} = \frac{K_B [(T_{A-O} - (A_O L_A^2)/8K_A - T_C)]}{L_C/2 - (t_C + L_A/2)} + \frac{\sigma}{1/\epsilon_A + 1/\epsilon_C - 1} \left[\left(T_{A-O} - \frac{A_O L_A^2}{8K_A} \right)^4 - T_C^4 \right] \quad (18)$$

Equation (18) enables the temperature drop between the center of the wafer, T_{A-O} , and the surface of the liner, T_C , to be obtained for any given value of T_{A-O} . This temperature difference is the maximum deviation from the two-dimensional radial temperature profile. For instance, if the temperature difference, $T_{A-O} - T_C$, were to be calculated by means of equation (18), to be 10°F and T_O from equation (15) was calculated to be 2500°F , then the maximum deviation of T_O would be $2500 \pm 5^{\circ}\text{F}$. For the parameters investigated to date the error involved has been less than one percent.

To obtain the temperature profile in the fuel capsule a computer was used to solve Equations (1) through (18). The results are shown graphically in Figures 5 through 10. Radial temperatures are given in the figures as a function of the radius of the fuel capsule. The gases present in the internal voids were taken to be argon or helium and are indicated as such on the curves. The thermal conductivity of the gases was determined as a function of the average temperature in the fuel capsule and was calculated by a sub-routine within the computer program.

Three thulium fuel wafer diameters and three power densities were examined. The diameters and power densities used in the calculations were chosen because they encompass practical constraints on thulia wafer design. The wafer thickness was held constant at 0.060 inch.

Two thulia thermal conductivities were used in the parametric analysis. These two conductivities, 1.5 and 3.0 B/hr-ft- $^{\circ}\text{F}$ (SRL DP-114)¹, are representative of thulia at the temperatures being considered in this analysis.

Parameters which were assumed constant during the analysis were:

- Gap thickness between the thulia wafer and the liner, 0.001 inch
- Gap distance between the liner and the housing, 0.008 inch
- Liner thickness, 0.003 inch.
- Containment capsule wall thickness, 0.100 inch
- Containment capsule wall thermal resistance, equivalent to that of 100 mils of Haynes-25. Analysis showed that for the metals under consideration the variation in temperature rise across the capsule wall was insignificant as compared to the rise across other thermal resistances determinant of the total thermal profile.

To achieve an absolute radial temperature profile within the fuel capsule it was necessary to postulate a capsule outer wall temperature. In the immediate future it is likely that most applications of thulia will be as heat sources for thermoelectric energy conversion. Operating on this assumption, the three temperatures chosen for the fuel capsule surface were 1000, 1500, and 2000°F to satisfy use with Pb-Te, the more imminent Ge-Si systems and the more advanced Ge-Si systems respectively.

As noted previously, six materials were considered for use as liners on the premise that their compatibility with Tm_2O_3 would later be demonstrated. These were: Hastelloy-X, Haynes-25, platinum, T-222, molybdenum and tungsten. Unlike the containment capsule wall, in the liner the variance in thermal resistance among the various metals significantly effects thermal profiles. Since Hastelloy-X and Haynes-25 were to be used as liner materials in the operating range up to 1830°F, nickel comes out at an accelerated rate in hard vacuum at this temperature, the outer capsule wall temperature was set at 1000°F for these two liner materials. The outer wall temperature was set at 1500°F for the fuel capsules having liner materials of platinum or T-222 on the basis that

a. 0.6 in. dia Thulia Wafer,
 $K = 3.0 \text{ B/hr-ft-}^{\circ}\text{F}$

b. 0.6 in. dia Thulia Wafer,
 $K = 1.5 \text{ B/hr-ft-}^{\circ}\text{F}$

c. 1.8 in. dia Thulia Wafer,
 $K = 3.0 \text{ B/hr-ft-}^{\circ}\text{F}$

Figure 5. Fuel Capsule Thermal Profiles for Hastelloy X Liners
 (Sheet 1 of 2)

d. 1.8 in. dia Thulia Wafer,
K = 1.5 B/hr-ft-°F

e. 3.0 in. dia Thulia Wafer,
K = 3.0 B/hr-ft-°F

f. 3.0 in. dia Thulia Wafer,
K = 1.5 B/hr-ft-°F

Figure 5 . Fuel Capsule Thermal Profiles for Hastelloy X Liners
(Sheet 2 of 2)

a. 0.6 in. dia Thulia Wafer,
 $K = 1.5 B/hr-ft-^{\circ}F$

b. 0.6 in. dia Thulia Wafer,
 $K = 3.0 B/hr-ft-^{\circ}F$

c. 1.8 in. dia Thulia Wafer,
 $K = 1.5 B/hr-ft-^{\circ}F$

Figure 6. Fuel Capsule Thermal Profiles for Haynes 25 Liners
(Sheet 1 of 2)

d. 1.8 in. dia Thulia Wafer,
 $K = 3.0 \text{ B/hr-ft-}^\circ\text{F}$

e. 3.0 in. dia Thulia Wafer,
 $K = 1.5 \text{ B/hr-ft-}^\circ\text{F}$

f. 3.0 in. dia Thulia Wafer,
 $K = 3.0 \text{ B/hr-ft-}^\circ\text{F}$

Figure 6. Fuel Capsule Thermal Profiles for Haynes 25 Liners
(Sheet 2 of 2)

a. 0.6 in. dia Thulia Wafer,
 $K = 1.5 \text{ B/hr-ft-}^{\circ}\text{F}$

b. 0.6 in. dia Thulia Wafer,
 $K = 3.0 \text{ B/hr-ft-}^{\circ}\text{F}$

c. 1.8 in. dia Thulia Wafer,
 $K = 1.5 \text{ B/hr-ft-}^{\circ}\text{F}$

Figure 7. Fuel Capsule Thermal Profiles for Platinum Liners
(Sheet 1 of 2)

a. 1.8 in. dia Thulia Wafer,
 $K = 3.0 \text{ B/hr-ft-}^{\circ}\text{F}$

e. 3.0 in. dia Thulia Wafer,
 $K = 1.5 \text{ B/hr-ft-}^{\circ}\text{F}$

f. 3.0 in. dia Thulia Wafer,
 $K = 3.0 \text{ B/hr-ft-}^{\circ}\text{F}$

Figure 7. Fuel Capsule Thermal Profiles for Platinum Liners
(Sheet 2 of 2)

a. 0.6 in. dia Thulia Wafer,
 $K = 1.5 \text{ B/hr-ft-}^{\circ}\text{F}$

b. 0.6 in. dia Thulia Wafer,
 $K = 3.0 \text{ B/hr-ft-}^{\circ}\text{F}$

c. 1.8 in. dia Thulia Wafer,
 $K = 1.5 \text{ B/hr-ft-}^{\circ}\text{F}$

Figure 8. Fuel Capsule Thermal Profiles for T-222 Liners
(Sheet 1 of 2)

d. 1.8 in. dia Thulia Wafer,
 $K = 3.0 \text{ B/hr-ft-}^{\circ}\text{F}$

e. 3.0 in. dia Thulia Wafer,
 $K = 1.5 \text{ B/hr-ft-}^{\circ}\text{F}$

f. 3.0 in. dia Thulia Wafer,
 $K = 3.0 \text{ B/hr-ft-}^{\circ}\text{F}$

Figure 8. Fuel Capsule Thermal Profiles for T-222 Liners
(Sheet 2 of 2)

a. 0.6 in. dia Thulia Wafer,
 $K = 1.5 \text{ B/hr-ft-}^{\circ}\text{F}$

b. 0.6 in. dia Thulia Wafer
 $K = 3.0 \text{ B/hr-ft-}^{\circ}\text{F}$

c. 1.8 in. dia Thulia Wafer,
 $K = 1.5 \text{ B/hr-ft-}^{\circ}\text{F}$

Figure 9. Fuel Capsule Thermal Profiles for Molybdenum Liners
(Sheet 1 of 2)

d. 1.8 in. dia Thulia Wafer,
 $K = 3.0 \text{ B/hr-ft-}^\circ\text{F}$

e. 3.0 in. dia Thulia Wafer,
 $K = 1.5 \text{ B/hr-ft-}^\circ\text{F}$

f. 3.0 in. dia Thulia Wafer,
 $K = 3.0 \text{ B/hr-ft-}^\circ\text{F}$

Figure 9. Fuel Capsule Thermal Profiles for Molybdenum Liners
(Sheet 2 of 2)

a. 0.6 in. dia Thulia Wafer,
 $K = 1.5 \text{ B/hr-ft-}^\circ\text{F}$

b. 0.6 in. dia Thulia Wafer,
 $K = 3.0 \text{ B/hr-ft-}^\circ\text{F}$

c. 1.8 in. dia Thulia Wafer,
 $K = 1.5 \text{ B/hr-ft-}^\circ\text{F}$

Figure 10. Fuel Capsule Thermal Profiles for Tungsten Liners
(Sheet 1 of 2)

d. 1.8 in. dia Thulia Wafer,
 $K = 3.0 B/hr-ft-^{\circ}F$

e. 3.0 in. dia Thulia Wafer,
 $K = 1.5 B/hr-ft-^{\circ}F$

f. 3.0 in. dia Thulia Wafer,
 $K = 3.0 B/hr-ft-^{\circ}F$

Figure 10. Fuel Capsule Thermal Profiles for Tungsten Liners
 (Sheet 2 of 2)

centerline temperatures would approach the melt temperature of platinum (3200°F) and on the basis that the hafnium constituent of T-222 potentially would react with thulia at high temperature. The outer wall temperature was set at 2000°F for the fuel capsules having liner materials of molybdenum or tungsten on the basis that this surface temperature would readily yield centerline temperatures in excess of the thulia melt temperature, 4172°F.

For the reasons of clarity, the abscissa for each of Figures 5 through 10 has superimposed on it a sectioned view of the thulia encapsulation. It should be noted that the abscissa is not to scale. Because of the large temperature changes across the interfaces, it was necessary to exaggerate the interface distances. The ordinate represents the centerline and is the point of maximum temperature within the fuel capsule.

3.3 CALCULATION PROCEDURE FOR BULK WAFER ENCAPSULATION DESIGN

Essentially the same set of equations were used to calculate the thermal profiles in the bulk wafer encapsulation design as were used in Paragraph 3.2. Referring to Figure 3, it can be seen that if the inner liner, C, is removed from above and below the wafer and subsequently the wafer thickness is allowed to assume the value L_c , then the figure is indicative of the bulk wafer encapsulation design as depicted in Figure 1b.

As a result of removing the individual liner, Equation 10, which defines the heat transfer between the wafer and the inner liner, assumes the form:

$$\frac{R_1^2 A_0}{R_1 + R_3 - t_c} = \frac{\sigma}{1/\epsilon_A + 1/\epsilon_C - 1} (T_1^4 - T_2^4) + \frac{K_B (T_1 - T_2)}{R_3 - t_c - R_1} \quad (19)$$

This equation allows T_1 to be solved by trial and error techniques.

In Equation (12) the volume of the liner has a value of zero and $A=A_0$. This allows the temperature distribution through the wafer to be determined using the relationship set forth in Equation 11, where K_1 is now the conductivity of the thulia wafer.

The analysis involving the bulk wafer encapsulation utilized the following parameters:

Fuel capsule wall thickness	- 0.1 inch
Thulia thermal conductivity	- 1.5 to 3.0 B/hr-ft-°F ⁽¹⁾
Liner thickness	- 0.020 inch
Gap between liner and capsule	- 0.004 inch
Gap between wafer and liner	- 0.002 inch
Wafer thickness	- 0.060 inch
Capsule emissivity	- 0.3
Liner emissivity	- 0.3
Wafer emissivity	- 0.3

(1) The values used for thermal conductivity in this parametric analysis were assumed to bracket the range which will be met in practice. At present only scattered data exist on the thermal conductivity of thulia. Extrapolation of available data led to a conductivity for solid thulia of 3.0 B/hr-ft-°F at 2000°F and 1.5 B/hr-ft-°F at 4000°F. Extrapolation was based on thulia conductivity behaving in the same manner as BeO, i, e., the conductivity drops off rapidly with increasing temperature until at approximately 2000°F (1093°C) it begins to level off and by 3000°F (1649°C) it becomes almost flat. In this investigation the thulia conductivity was assumed to be the fixed values noted. If thulia does in fact behave like BeO and approach a stable value of thermal conductivity at 2000 to 3000°F, then the thermal profiles established in this report are quite valid. On the other hand, if the thermal conductivity proves to be strongly dependent upon temperature in the temperature range of concern, results are not valid and the calculation procedure must be modified to include a temperature dependent thulia conductivity sub-routine.

For the numerous thermal profiles obtained for the bulk wafer encapsulation the capsule material was assumed to have the thermal resistance of Haynes-25 and the inner liner the thermal resistance of platinum. (In this instance neither the capsule nor the liner contribute significantly to the thermal profile.) The capsule surface temperature was assigned three separate values of 1000, 1500 and 2000°F. For these surface temperatures the thermal profiles were determined for power densities of 8, 16, and 24 w/cc, capsule diameters of 0.6, 1.8, and 3.0 inches, and argon or helium as the internal gas. The results of the investigation are given in Figures 11 through 13. (Identification of capsule and liner materials as Haynes-25 and platinum is of little consequence to results, i.e., had refractories or other materials been identified for capsule and/or liner material, the wafer diameter for centerline melting would be changed only by a few mils for any given fuel power density.)

Figure 14 shows the thermal profiles that exist when 2732°F (1500°C) is assumed to be the fuel capsule surface temperature; other parameters of analysis are precisely those of Figure 13a. Only the 0.6 inch diameter capsule was analyzed at this surface temperature because it was apparent from investigations conducted at 2000°F that at larger diameters center line temperatures can readily become excessive and center line temperatures are meaningful when the theoretical world of the infinitely long right circular cylinder capsule is exchanged for the real world of capsules of finite lengths.

3.4 CALCULATION PROCEDURE FOR MICROSPHERE FUEL FORM

In addition to employing thulia in the wafer form it is also possible to make use of thulia microspheres. The major design drawbacks to use of the microsphere heat source fuel form are the reduction in power density resulting from the void fraction and the extremely low thermal conductivity of microsphere beds. This latter constraint forces operation at either a low capsule surface temperature

a. 0.6 in. dia Thulia Wafer,
 $K = 1.5 \text{ B/hr-ft-}^\circ\text{F}$

b. 0.6 in. dia Thulia Wafer,
 $K = 3.0 \text{ B/hr-ft-}^\circ\text{F}$

c. 1.8 in. dia Thulia Wafer,
 $K = 1.5 \text{ B/hr-ft-}^\circ\text{F}$

Figure 11. Bulk Encapsulated Wafers, Surface Temperature 1000°F
(Sheet 1 of 2)

d. 1.8 in. dia Thulia Wafer,
K = 3.0 B/hr-ft-°F

e. 3.0 in. dia Thulia Wafer,
K = 1.5 B/hr-ft-°F

f. 3.0 in. dia Thulia Wafer,
K = 3.0 B/hr-ft-°F

Figure 11. Bulk Encapsulated Wafers, Surface Temperature 1000°F
(Sheet 2 of 2)

a. 0.6 in. dia Thulia Wafer
 $K = 1.5 \text{ B/hr-ft-}^{\circ}\text{F}$

b. 0.6 in. dia Thulia Wafer
 $K = 3.0 \text{ B/hr-ft-}^{\circ}\text{F}$

c. 1.8 in. dia Thulia Wafer
 $K = 1.5 \text{ B/hr-ft-}^{\circ}\text{F}$

Figure 12. Bulk Encapsulated Wafers, Surface Temperature 1500°F
(Sheet 1 of 2)

d. 1.8 in. dia Thulia Wafer
 $K = 3.0 \text{ B/hr-ft-}^{\circ}\text{F}$

e. 3.0 in. dia Thulia Wafer
 $K = 3.0 \text{ B/hr-ft-}^{\circ}\text{F}$

f. 3.0 in. dia Thulia Wafer
 $K = 1.5 \text{ B/hr-ft-}^{\circ}\text{F}$

Figure 12. Bulk Encapsulated Wafers, Surface Temperature 1500°F
 (Sheet 2 of 2)

a. 0.6 in. dia Thulia Wafer
K = 1.5 B/hr-ft-°F

b. 0.6 in. dia Thulia Wafer
K = 3.0 B/hr-ft-°F

c. 1.8 in. dia Thulia Wafer
K = 1.5 B/hr-ft-°F

Figure 13. Bulk Encapsulation Wafers, Surface Temperature 2000°F
(Sheet 1 of 2)

d. 1.8 in. dia Thulia Wafer
K = 3.0 B/hr-ft-°F

e. 3.0 in. dia Thulia Wafer
K = 1.5 B/hr-ft-°F

f. 3.0 in. dia Thulia Wafer
K = 3.0 B/hr-ft-°F

Figure 13. Bulk Encapsulation Wafers, Surface Temperature 2000°F
(Sheet 2 of 2)

Figure 14. Bulk Encapsulated Wafers, Surface
 Temperature 2732°F (1500°C)

or use of a small radius fuel capsule, or operation at near center-line melt conditions.

Experimental thermal conductivity data on thulia microspheres is not presently available. Empirical relationships for the determination of porous media thermal conductivity such as those given by Luikov, Slaskov, Vasilieu, and Fraimar² require detailed material data which are not presently available. Consequently, it was necessary to investigate the thermal conductivity data which are available on other oxide microspheres and arrive at a representative thermal conductivity value for thulia microspheres. Table 1 gives a list of thermal conductivities for five types of oxide microsphere beds.

TABLE 1
CHARACTERISTIC PROPERTIES OF OXIDE MICROSPHERES

Material	Temperature		Particle Diameter (μ)	Void Fraction Percent	Interstitial Gas	Effective Conductivity B/hr-ft- $^{\circ}$ F
	$^{\circ}$ F	$^{\circ}$ C				
MgO ⁽²⁾	1700	(927)	50-250	35	Air	0.75
ZrO ₂ ⁽²⁾	1700	(927)	50-250	30	Air	0.43
Al ₂ O ₃ ⁽²⁾	1700	(927)	50-250	42	Air	0.46
Pu O ₂ *	1004	(540)	50-250	30	He	0.73
Pu O ₂ *	1004	(540)	50-250	30	Ar	0.29

* Data supplied by Mound Laboratories

(2) Referenced in bibliography

The scattered experimental conductivity data as listed in Table 1, used in conjunction with available empirical relationships led to an estimated thulia microsphere bed conductivity of 1.1 B/hr-ft-[°]F with helium as the interstitial gas, at a mean temperature of 3086[°]F (1697[°]C) $(T_{\text{melt}} + T_{\text{surface}})/2$. For the same mean temperature but using argon as the interstitial gas, values of 0.4 B/hr-ft-[°]F was determined as a representative value.

Again assuming that the fuel capsule is an infinitely long circular cylinder, the radial thermal profile is given by:

$$T_r = \frac{A_o (r_o^2 - r^2)}{4 K_{\text{eff}}} + T_s \quad (20)$$

where:

K_{eff} - effective thermal conductivity

A_o - effective fuel power density

r_o - the outer radius of the porous system

T_s - surface temperature of the porous system

T_r - temperature at radius r

Thulia melts at 4172[°]F. Assuming an outside wall temperature of 2000[°]F and an average temperature in the fuel capsule of 3086[°]F $(T_{\text{melt}} + T_s)/2$, Equation (20) was used to produce the curves given in Figure 15. These curves indicate the maximum fuel capsule diameter attainable without centerline melting for a microsphere porosity of 30 percent.

This analysis was made assuming that no temperature drop occurred across the fuel capsule wall, i.e., liner-gap-containment capsule. In point of fact, a drop approximately equal to that in the similar region of the bulk wafer encapsulated design operating at 2000[°]F, is experienced.

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Figure 15. Characteristics of Thulia Microspheres Filled Capsule

SECTION 4

ANALYZED AND EVALUATED STUDY RESULTS

4.1 GENERAL

Conclusions are drawn with respect to the following on the basis of work performed:

- ① Limiting operating conditions of capsules based on the thermal properties of materials for appropriate Tm_2O_3 container systems to be evaluated under Phase II of the contract; these are defined by the contract statement of work at the time of this Phase I study as: Hastelloy-X, Haynes-25, platinum, T-222, molybdenum and tungsten.
- ② Precision with which applicable experimental results need be obtained in testing performed under Phase II; subject testing is phase diagram determination and compatibility.
- ③ Observations respecting 2732°F (1500°C) operation.
Significant observations, both on a component and system basis, pertaining to basic capsule design options.
- ④ Recommendations.

The foregoing presumes that refractory metals when used are protected from oxidizing atmospheres and that all materials are compatible with thulia at all operating temperatures specified as good. Melt temperatures are considered the basic criterion. The reader will note that specific comments are only nominally correct. Rigorous crossplots on all other data were beyond the scope of this program.

4.2 CAPSULE OPERATING CONDITIONS AS DICTATED BY CONTAINMENT MATERIAL

Hastelloy-X - In the individual wafer encapsulation design at a capsule diameter to slightly in excess of 0.6 inch, a capsule surface temperature in the range of 1000 to 1500°F can be tolerated when using a fill gas of as low a thermal conductivity as argon, a thulia conductivity as low as 1.5 B/hr-ft-°F and thulia power densities as high as 24 w/cc. Hastelloy -X can be used in a capsule of 1.8 inch diameter if helium is used as the fill gas and capsule surface temperature is maintained below about 1200°F; if thulia power density does not exceed about 8 watts/cc, it is possible to use argon as the fill gas at this diameter. When capsule diameter reaches 3.0 inches, Hastelloy-X can be used as containment only if capsule surface temperature is less than 1000°F and favorable conditions of fill gas, power density and thermal conductivity are enjoyed; see Figures 5e and f, and Table 2.

In the bulk encapsulated wafer capsule design, Hastelloy-X is excellent containment at surface temperatures to 1500°F so long as the diameter is of the order of 0.6 inch. When diameter reaches 1.8 inches, Hastelloy-X may be used only when thulia power density is low, thermal conductivity is high and helium fill gas is used at capsule surface temperatures not exceeding 1000°F. Hastelloy-X cannot be used when capsule diameter reaches 3.0 inches except in rare instances; see Figures 11e and f, and Table 3.

Haynes-25 - Limiting conditions not unlike those for Hastelloy-X apply as well for Haynes-25; the slightly increased melt temperature of Haynes over Hastelloy-X, approximately 100°F, is of little consequence.

Platinum - At a capsule surface temperature of 1500°F, platinum can be used without restriction in the individual wafer encapsulation design to a diameter of 1.8 inches; when diameter does not exceed 0.6 inch, capsule surface temperature can be raised to at least 2500°F. When capsule diameter reaches 3.0 inches, capsule surface

TABLE 2

Tm₂O₃ Wafers Individually Encapsulated, Hastelloy X or Haynes 25 *Capsule Surface Temperature: 1000°F

Thermal Conductivity K = 1.5 B/Hr-Ft-°F	Fill Gas: Argon			Fill Gas: Helium		
	Fuel Diameter, in.			Fuel Diameter, in.		
Power Densities, w/cc	0.6	1.8	3.0	0.6	1.8	3.0
8	yes	yes	no	yes	yes	no
16	yes	no	no	yes	yes	no
24	yes	no	no	yes	no	no
Thermal Conductivity K = 3.0 B/Hr-Ft-°F	Fuel Diameter, in.			Fuel Diameter, in.		
	0.6	1.8	3.0	0.6	1.8	3.0
8	yes	yes	no	yes	yes	yes
16	yes	no	no	yes	yes	no
24	yes	no	no	yes	yes	no

*(See Figure 1a, page 1-4)

TABLE 3
 Tm_2O_3 Bulk Encapsulated in Hastelloy-X or Haynes-25*

Capsule Surface Temperature: 1000°F

Thermal Conductivity K = 1.5 B/Hr-Ft-°F	Fill Gas: Argon			Fill Gas: Helium		
	Fuel Diameter, in.			Fuel Diameter, in.		
Power Density, w/cc	0.6	1.8	3.0	0.6	1.8	3.0
8	yes	no	no	yes	yes	no
16	yes	no	no	yes	no	no
24	yes	no	no	yes	no	no
Thermal Conductivity K = 3.0 B/Hr-Ft-°F	Fuel Diameter, in.			Fuel Diameter, in.		
	0.6	1.8	3.0	0.6	1.8	3.0
8	yes	yes	no	yes	yes	yes
16	yes	no	no	yes	yes	no
24	yes	no	no	yes	no	no

*(see Figure 1b, page 1-4)

TABLE 4

Tm₂O₃ Wafers Individually Encapsulated, Platinum or T-222*Capsule Surface Temperature: 1500°F

Thermal Conductivity K = 1.5 B/Hr-Ft-°F	Fill Gas: Argon			Fill Gas: Helium		
	Fuel Diameter, in.			Fuel Diameter, in.		
Power Density, w/cc	0.6	1.8	3.0	0.6	1.8	3.0
8	yes	yes	yes	yes	yes	yes
16	yes	yes	Pt only	yes	yes	yes
24	yes	yes	no	yes	yes	Pt only
Thermal Conductivity K = 3.0 B/Hr-Ft-°F	Fuel Diameter, in.			Fuel Diameter, in.		
	0.6	1.8	3.0	0.6	1.8	3.0
8	yes	yes	yes	yes	yes	yes
16	yes	yes	Pt only	yes	yes	yes
24	yes	yes	no	yes	yes	yes

*(see Figure 1a, page 1-4)

TABLE 5

 Tm_2O_3 Bulk Encapsulated in Platinum*Capsule Surface Temperature: 1500°F

Thermal Conductivity K = 1.5 B/Hr-Ft-°F	Fill Gas: Argon			Fill Gas: Helium		
	Fuel Diameter, in.			Fuel Diameter, in.		
Power Density, w/cc	0.6	1.8	3.0	0.6	1.8	3.0
8	yes	yes	no	yes	yes	no
16	yes	no	no	yes	no	no
24	yes	no	no	yes	no	no
Thermal Conductivity K = 3.0 B/Hr-Ft-°F	Fuel Diameter, in.			Fuel Diameter, in.		
	0.6	1.8	3.0	0.6	1.8	3.0
8	yes	yes	no	yes	yes	yes
16	yes	no	no	yes	yes	no
24	yes	no	no	yes	yes	no

*(see Figure 1b, page 1-4)

TABLE 6

Tm_2O_3 Wafers Individually Encapsulated, Molybdenum or Tungsten*

Capsule Surface Temperature: 2000°F

Thermal Conductivity K = 1.5 B/Hr-Ft-°F	Fill Gas: Argon			Fill Gas: Helium		
	Fuel Diameter, in.			Fuel Diameter, in.		
Power Density, w/cc	0.6	1.8	3.0	0.6	1.8	3.0
8	yes	yes	yes	yes	yes	yes
16	yes	yes	yes	yes	yes	yes
24	yes	yes	no	yes	yes	yes
Thermal Conductivity K = 3.0 B/Hr-Ft-°F	Fuel Diameter, in.			Fuel Diameter, in.		
	0.6	1.8	3.0	0.6	1.8	3.0
8	yes	yes	yes	yes	yes	yes
16	yes	yes	yes	yes	yes	yes
24	yes	yes	no	yes	yes	yes

*(see Figure 1a, page 1-4)

TABLE 7

Tm_2O_3 Bulk Encapsulated in Molybdenum, T-222, or Tungsten*

Capsule Surface Temperature: 2000°F

Thermal Conductivity K = 1.5 B/Hr-Ft-°F	Fill Gas: Argon			Fill Gas: Helium		
	Fuel Diameter, in.			Fuel Diameter, in.		
Power Density, w/cc	0.6	1.8	3.0	0.6	1.8	3.0
8	yes	yes	no	yes	yes	no
16	yes	no	no	yes	yes	no
24	yes	no	no	no	no	no
Thermal Conductivity K = 3.0 B/Hr-Ft-°F	Fuel Diameter, in.			Fuel Diameter, in.		
	0.6	1.8	3.0	0.6	1.8	3.0
8	yes	yes	yes	yes	yes	yes
16	yes	yes	no	yes	yes	no
24	yes	no	no	yes	yes	no

*(see Figure 1b, page 1-4)

temperature is limited to about 1500°F and thulia power density should not exceed 16 w/cc; see Figure 7 and Table 4.

When bulk encapsulated thulia is used at a capsule diameter of 0.6 inch, fuel capsule surface temperature can go to 2500°F without concern for power density, fill gas, thermal conductivity, etc. At 1.8-inch diameter, capsule surface temperature is limited to about 1500°F and power densities not exceeding 16 w/cc; at 3.0 inch diameter, thulia can only be bulk encapsulated if capsule surface temperature is less than 1500°F or thulia power density is less than 8 w/cc; neither is a very acceptable alternative; see Table 5.

T-222 - Comments similar to those for molybdenum apply.

Molybdenum - When the individual wafer encapsulation design is used, molybdenum can be used to a diameter of 1.8 inches at a capsule surface temperature of 2500°F regardless of power density, thermal conductivity, and fill gas; at a diameter of 0.6 inch, the same is true to at least 3000°F surface temperature. When diameter reaches 3.0 inches, surface temperature should not exceed 2500°F and argon fill gas should be avoided, see Table 6.

When the bulk encapsulated thulia is used with molybdenum, a capsule diameter as great as 3.0 inches can be used at a surface temperature of 2000°F if thulia power density is less than 8.0 w/cc; at 1.8 inch diameter, this surface temperature is legitimate if high power density (24 w/cc) is not combined with low thermal conductivity (1.5 B/hr-ft-°F). When capsule diameter is 0.6 inch, surface temperature can be as much as 3200°F without concern for capsule integrity; see Table 7.

Tungsten - Comments similar to those made respecting molybdenum are in order.

4.3 PRECISION REQUIRED IN EXPERIMENTAL TESTING, PHASE II

Phase Diagram - On the premise that compatibility is demonstrated with the various containment materials, i.e., that no low melting alloys are formed, then the precision with which the thulia-ytterbia

system phase diagram need be obtained is not great. Solid-state dimensional changes if occurring due to shift from the cubic structure should be detected for purposes of understanding the system but are not expected to be of significance in a fuel capsule design where the radial clearance permitted between fuel and containment is measured in mils. The melt temperature of the thulia-ytterbia systems should be determined within 50 to 100°F so that maximum advantage can be taken of the fuel form as a thermionic fuel; also, so that multiple capsule heat source subsystems can be designed wherein some capsules are operated of necessity closer to the melt temperature than others but without serious concern for this; also, so that design margin is provided in heat source subsystem design for the consequences of the intact impact safety criterion, etc.

Compatibility - Temperatures of test should be sufficiently above anticipated steady-state, long-term system operating temperatures that need for accuracy in temperature measurement is not essential; similarly, tests should be made at several well separated temperatures and over varied time periods so that consequences of errors in time and temperature are mitigated; e.g., temperatures plus or minus 50°C are sufficiently accurate when tests are run at several temperatures separated by 500°C; time plus or minus a few days is sufficiently accurate when test times run to 4000 or more hours.

Greater precision will be required if all test materials show some lack of compatibility with thulia and it is essential to pick the best from among these - it will then become important to accurately measure diffusion rates, mass loss rates, etc. Where high compatibility is demonstrated, it is conversely going to require far less precision in measuring these rates. Specifying precision required any more accurately than in this qualified manner prior to the test is not warranted.

4.4 OBSERVATIONS RESPECTING 1500°C OPERATIONS

Reference to Figure 14 reveals that for bulk encapsulated 0.6 inch diameter wafers operated at a capsule surface temperature of

2732°F (1500°C) the temperature rise from surface to centerline will be in the range of 100 to 500°F for 1.5 B/hr-ft-°F thulia; the lowest Δt results when helium fill gas is used with thulia of 8 w/cc power density, the highest Δt when argon fill gas is used with thulia of 24 w/cc. These data are most meaningful when compared with that of Figure 13a where similar parameters are examined at 2000°F (1093°C) surface temperature and a Δt in the range 100 - 600°F is realized.

Some conclusions may be drawn from these observations:

- A lesser Δt from surface to centerline will exist as surface temperature is increased. This results from the T^4 relationship for radiation heat transfer from wafer to liner to containment and is evidenced by the max 500°F Δt at 2732°F surface temperature and the max 600°F Δt at 2000°F surface temperature.
- Platinum, T-222, molybdenum and tungsten can be used in a 1500°C surface temperature thulia fuel capsule of 0.6 inch wafer diameter if helium is the fill gas; if argon fill gas and a high power density thulia are used (24 w/cc) then platinum cannot be used because its melt temperature would be exceeded.
- On the basis that T-222, molybdenum and tungsten each have melt temperatures in excess of thulia, and on the basis that Δt surface to centerline reduces with increasing surface temperature; it can be postulated that even with low thermal conductivity thulia (1.5 B/hr-ft-°F) of high power density (24 w/cc) an argon filled 0.6 inch diameter thulia bulk encapsulated fuel capsule is feasible to 3632°F (2000°C) surface temperature.
- In terms of system use, it is feasible to forecast that a nominal SNAP-29 fuel capsule could contain thulia, be fabricated of T-222, molybdenum or tungsten, and be operated to at least 1500°C surface temperature. This would provide an immediate option to the system designer of obtaining greater system efficiencies or lower degrada-

tion rates via resort to advanced Ge-Si thermoelectrics, or of obtaining greater system efficiencies via use of cascaded or segmented technology.

4.5 SIGNIFICANT OBSERVATIONS PERTAINING TO BASIC FUEL CAPSULE DESIGN OPTIONS

- ⊗ Reference to Figure 15 quickly shows that a straight micro-sphere fuel capsule probably is of little merit; it does not provide much in the way of design flexibility to the heat source subsystem designer. In all likelihood the micro-sphere technology would need to be combined with a metal matrix before heat source subsystem design options would be of sufficiently wide range.
- ⊗ In comparing the data of the individual and bulk wafer encapsulations, it is noted that the centerline temperature is lower for the individual encapsulated wafer when fuel capsules with similar parameters are compared. This is primarily a consequence of the additional radial conduction path offered by the liner's within the individual wafer encapsulation. As can be seen by comparing Figures 5d and 11c, the temperature difference between the centerline and the wafer outer diameter is greater for the bulk wafer encapsulation. This is typical. It should also be noted that the temperature difference across the radial gap between the wafer and the liner is much less for the individual wafer encapsulation. This is also a consequence of the additional radial heat transfer offered by the individual liner material.
- ⊗ The higher centerline temperatures existing in the bulk wafer encapsulation, in contrast to the individual encapsulation, should not necessarily be taken as a negative factor for bulk encapsulations. Since thulia is the only material existing within the interior of the bulk wafer encapsulation design, the operating temperature is limited by the thulia and not by the liner material as is the case with some of the individually encapsulated wafers.

- As an example. Figure 6d shows that for a 1.8 inch diameter wafer having a thulia conductivity of 3.0 B/hr-ft-°F and a power density of 16 w/cc, the Haynes-25 liner will melt prior to the thulia melting when an argon atmosphere is present within the individually encapsulated wafer design. On the other hand, Figure 1ld indicates that using the bulk encapsulation design, the centerline temperature is higher for the same 1000°F surface temperature but this higher temperature has not compromised the integrity of the fuel capsule materials.
- Thermal profiles indicate that the liner material has a considerable influence on the temperature within the wafer in the individual encapsulated wafer design. For instance, the values of thermal conductivity used for molybdenum and tungsten were 42 and 60.- B/hr-ft-°F respectively; as a result of this difference in thermal conductivity the centerline temperature was 4000°F and 3750°F for the molybdenum and tungsten lined wafers respectively, as can be witnessed by viewing Figure 9e and 10e where power density is 16 w/cc and argon is the fill gas.
- Caution should be exercised in assuming bulk encapsulated thulia fuel capsules are as good as the thermal profiles would lead one to believe. It must be recalled that infinitely long right circular cylinder fuel capsules have been assumed. They will, in fact, have ends on them and if these are not cold-sinked then the metal end will have a similar thermal profile to the thulia - it may not tolerate the indicated centerline temperature. Finite length is not as serious a problem with the individually encapsulated wafer design.
- The high operating temperature of thulia allows the use of relatively large diameter fuel capsules without compromising the integrity of the fuel capsule. In the case of the individually encapsulated wafers, the capsule

is temperature limited by the liner material when using Haynes-25, Hastelloy-X, and platinum and by the thulia fuel when using T-222, molybdenum, and tungsten. This assumes that fuel capsule design should be such that the temperature within the capsule at no point exceeds the softening temperature of the liner material. If the liner material melts during operation it is conceivable that the thulia can come into contact with the fuel capsule wall and result in reduced fuel capsule life and decreased biological safety margins.

- ④ With the bulk wafer encapsulation design, one is limited only by the melt temperature of the thulia given compatibility of materials and operation at surface temperatures appropriate to the containment. The consequences of use of a capsule having a molten center core must, however, be examined in more detail before use is made of this untried concept. It is noted again, however, that as a generalization larger capsules are feasible with the individually encapsulated wafers than are feasible with bulk encapsulated fuel.
- ④ Because of the relatively large temperature drops occurring across the materials interfaces it would behoove the designer to concentrate on achieving high emissivities on the containment capsule and liner interfaces to aid in radiation heat transfer. In addition, care should be taken in selecting the fits between the wafers, liner, and containment capsule so that a minimum void gap will exist after assembly.
- ④ For fixed fuel capsule diameter and thulia conductivity, and individually encapsulated wafer configuration having helium as the interstitial gas gives the lowest centerline temperature. In addition, the higher the thermal conductivity of the liner, the lower the centerline temperature. Hence, a helium filled capsule having a

tungsten liner yields the lowest centerline temperature for a given surface temperature; it also gives the largest capsule diameter without melting of any fuel capsule constituent.

- Individually encapsulated wafers potentially suffer a single drawback, effective capsule power density is reduced due to the increased volume of liner material. The drawback is classified as potential until it is proven that the processing time for bulk encapsulated fuel is not so long as to result in that capsule design having a lesser power density than the individually encapsulated design at the time of system fueling.

4.6 RECOMMENDATION

On the basis that study results are incomplete until they reflect the compatibility assessments of Phase II it is recommended that upon completion of compatibility assessments in Phase II and upon acquisition of actual thulia thermal conductivity data, that the results presented herein be made specific for compatible containment materials and true conductivity data.