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TECHNICAL DATA RECORD		PAGE 1 OF 144			
AUTHOR <i>Edward M. Mouradian</i> E. M. Mouradian		DEPT. & GROUP NO. 731-141		DATE 2-16-66 GO NO. 7611	
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STATEMENT OF PROBLEM Conduct a thermal analysis of the SNAP 10A reactor core to determine at what time and altitude the fuel elements of the core are released as a result of disintegration of the grid plates.					
ABSTRACT: A thermal analysis is carried out to determine the temperature distribution throughout a SNAP 10A reactor core,* particularly in the vicinity of the grid plates, during atmospheric reentry. The transient temperature distribution of the grid plate indicates when sufficient melting occurs so that fuel elements are free to be released and continue their descent individually. In Chapter III, the flight trajectories and heating functions are discussed. Among the topics considered are the aerodynamic drag coefficients for different flight orientations, aerodynamic heating functions, and reentry flight trajectory parameters. The local effect of the fuel element pins on the temperature distribution in the grid plate is discussed in Chapter IV. In Chapter V, the temperature distributions in the reactor core grid plates during reentry are given. The applicability of the results to different flight trajectories is also considered. The thermal models developed to investigate the above problems are used with the TAP-3 (Thermal Analyzer Program) computer code. Flight trajectory calculations are carried out by means of the RESTORE (Reentering SNAP Trajectory on an Oblate Rotating Earth) computer code.					
*"Reactor core" in this report refers to the fuel element bundle and internal beryllium reflectors held together by the grid plates and with the containment vessel stripped away due to prior reentry heating.					

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I. INTRODUCTION

The behavior of the entire SNAP 10A system during atmospheric reentry is currently under analysis, particularly with respect to aerodynamic heating and the resulting melting and ablation of the various components. A complex series of events occurs during the reentry, the general sequence being the ejection of the external reflectors, release of NaK, separation of the reactor from the shielding and energy conversion unit, melting open of the reactor containment vessel and release of the core, breakup of the reactor core and separation of the individual fuel elements, ablation and breakup of the fuel elements, burnup of fuel fragments, and dispersal of the remaining fine particles into the upper atmosphere.

This report presents the results of an investigation of one of the above series of events, the breakup, or disintegration of the reactor core. This action separates the fuel elements and allows them to undergo ablation individually. In this report, the term "reactor core" is taken to signify the bundle consisting of the thirty-seven fuel elements, the six beryllium internal reflectors, and the two stainless steel grid plates, and to exclude the reactor containment vessel which is assumed to have been stripped away by prior reentry heating.

The simplest, and most desirable mode of reactor core breakup would be for the grid plates to simply fall off the fuel element and reflector pins. This could very well occur since the initial placement of the grid plates on the pins is a rather loose fit. If this were to happen, it would be advantageous since it would mean an almost immediate core breakup and fuel element separation. Unfortunately, however, such a mode of breakup, while possible, cannot be considered to be sufficiently probable so that it could be depended upon. It can well be that during the long life of the system, the grid plates may have become warped or the fuel elements may have swollen or bent in such a way as to make the fuel element pins bind in the grid plate holes, causing the entire assembly to hold firmly together. If this were to happen, it would be necessary to melt

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away the grid plates holding the fuel elements together in order to bring about their separation. This is the process that is investigated in this report. Aerodynamic heating inputs and transient temperature distributions in the reactor grid plates are investigated for various reentry trajectory conditions. The approximate time and corresponding altitude drop required for the removal of the grid plates by melting are determined. This condition, of course, represents a somewhat pessimistic view, since it disallows several possibilities. The grid plates could just fall off because of their loose fit (either at the start or at a later time when some fuel elements which may have been causing the binding have either been loosened or released). The heating up of the grid plates might bring about their weakening which may cause a warping, tearing, or fracture, thus releasing the elements before actual grid plate meltdown. These, and other like possibilities are not considered quantitatively because of the uncertainty of these events occurring, and the difficulty of predicting their occurrence analytically at this time. At any rate, the model and calculations represent, for the most part, a generally conservative estimate of the required reactor disintegration time.

A satellite in orbit near the upper boundary of the earth's atmosphere has a total energy of about 13,700 Btu/lbm, (this value is based on a satellite with a 400,000 foot altitude and a 25,694 ft/sec velocity), with most of it in the kinetic form (kinetic energy $\approx 13,200$ Btu/lbm, potential energy ≈ 500 Btu/lbm). Essentially all of this energy is converted to heat as the body comes to the ground and impacts at a relatively low velocity. Obviously, this quantity of heat is several times what is necessary to vaporize any reentering body. However, a very small fraction (on the order of 2 or 3% for blunt shaped bodies) of the total heat generated actually is delivered to the object. Most of it is carried off by the air flow stream, particularly in the case of blunt shaped bodies which induce a strong frontal shock wave. (This, incidentally, is why manned reentry spacecraft have a blunt frontal shape.) In addition, as the body heats up, a portion of the heat absorbed is radiated away.

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The results is that, initially, it is not at all apparent whether, as a body reenters, it receives and retains sufficient heat to melt it, and further, that even if it does, whether the meltdown occurs rapidly enough to achieve reactor disintegration at a sufficiently high altitude. This thermal behavior for a reentering SNAP 10A reactor core is investigated in this report.

II. CORE CONFIGURATION

The geometric configuration and dimensions of the SNAP 10A reactor core are specified in the design drawings (Reference 1a-1e). In describing the geometry of the core for trajectory and thermal calculations, design parameters were followed, except in a few minor cases in which slightly different geometry or properties were assumed for simplicity. The core configuration and dimensions used in the calculations of this report are indicated in this section.

Figure 1 shows the overall dimensions of the reactor core. Figure 2a and 2b are views of the design details of the upper grid plate. It is made of 1/8 inch thick stainless steel, with holes as shown. The lower grid plate is constructed somewhat differently. It is formed of two parallel plates, each 1/16 inch thick, with studs for structural support. Furthermore, the NaK flow holes are of various sizes (the holes getting smaller as one moves out radially on the grid plate) in order to control the NaK flow distribution during reactor operation. For the thermal calculations subsequently shown, it has been assumed that both grid plates have the geometry and thermal characteristics of the upper plate.

The assumed geometry of the fuel elements is shown in Figure 3. It can be seen that the geometry of the fuel element has been idealized somewhat, as squaring off the fuel material, assuming a uniform hydrogen gap thickness, etc.

As the reactor core reenters, the outer edges of the grid plate heat

FOR DETAIL
OF UPPER GRID
PLATE, SEE
FIGURES 2a & 2b.

WEIGHTS

37 FUEL ELEMENTS	125.50
6 Be REFLECTORS	8.69
GRID PLATES	5.22
TOTAL	139.41 lb _m

FIGURE 1

OVERALL GEOMETRY
OF SNAP-10A
REACTOR CORE

FIGURE 2a

CUT AWAY VIEW OF UPPER
GRID PLATE GEOMETRY

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FIGURE 2b
 UPPER GRID PLATE GEOMETRY

Sketches Not
to Scale

FIGURE 3

ASSUMED FUEL ELEMENT
GEOMETRY

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FIGURE 4
PARTIAL VIEW
CORE CROSS-SECTION

SHOWS CORE SIZES AS RINGS
OF FUEL ELEMENTS SUCCESSIVELY
FALL AWAY.

(SEE TABLE I)

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up and melt first, so that the beryllium reflectors and the outer ring of fuel elements are released first. The remainder of the core, now with a different ballistic coefficient (hence a modified trajectory and aerodynamic heating) continues on until the grid plate melts away sufficiently to allow the next ring of fuel elements to fall away, and so on. Each time a cluster of fuel elements comes off the main core body, the properties (weight, reference area, and drag coefficient) of the remaining parcel changes, with a resultant change in the ballistic coefficient. Figure 4 shows a portion of the cross-section of the core. The effective radii are shown for the cases where the reflectors and each successive ring of fuel elements are lost.

Table I summarizes the significant geometric parameters of the reactor core used in this report. Other values are shown in Figures 1, 2, and 3. Table II lists the values of the thermal properties of the reactor core materials used in the calculations.

TABLE I
Reactor Core Geometric Parameters

	Length L inch	Effective Diameter D inch	Reference Area A_{Ref} ft^2	$\frac{L}{D}$	Mass W lbm
Full Core	13.08	8.830	0.4253	1.481	139.41
Core with Reflectors Gone	13.08	8.022	0.3510	1.630	129.81
Core with One Ring Elements Gone	13.08	5.714	0.1780	2.282	66.63
Core with Two Rings Elements Gone	13.08	3.426	0.0640	3.817	24.53
One Element	13.08	1.250	0.00852	10.464	3.49

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TABLE II

THERMOPHYSICAL PROPERTIES

(Values Assumed for Calculations)

Material	Thermal Conductivity k Btu/sec in. °F	Heat Capacity $\bar{c}_p$ Btu/in. ³ °F	Specific Heat c_p Btu/lbm °F	Melting Temperature T_m °F
SS 316	3.4×10^{-4}	0.038	0.138	2600
Be	1.18×10^{-3}	0.0416	-	-
Fuel	3.08×10^{-4}	0.035	-	-
Barrier	1.85×10^{-5}	-	-	-

Radiative Emissivity, ϵ

ϵ (Surface to Ambient) = 0.333

ϵ (Grid Plate to Fuel Cap) = 0.447

ϵ (Between Fuel Elements) = 0.333

Radiation Factor, $\mathcal{F}$

$\mathcal{F}$ = 0.333

$\mathcal{F}$ = 0.288

$\mathcal{F}$ = 0.200

Convection Coefficient

1 mil hydrogen gap,
(Assumed Gap Thickness)

$h = 5 \times 10^{-3} \frac{\text{Btu}}{\text{sec in.}^2 \text{ °F}}$

Air:

$k = 7.8 \times 10^{-7} \frac{\text{Btu}}{\text{sec in.} \text{ °F}}$

$c_p = 0.25 \frac{\text{Btu}}{\text{lbm °F}}$

The approximation was made that these properties did not vary with temperature.

III. FLIGHT TRAJECTORIES AND HEATING FUNCTIONS

A. Aerodynamic Drag Coefficients

1. Derivation of Drag Coefficients on a Cylinder

The aerodynamic drag on a plane surface (assuming a continuum flow regime) oriented normally to the flow stream can be determined easily (see Figure 5a). The momentum balance on a column of incoming air is

$$F = \left(\frac{dm}{dt} \right) \frac{\Delta V}{g_c} \quad \dots(\text{III-1})$$

from which

$$F = \left(\frac{\rho A V}{g_c} \right) (V - 0) = \frac{\rho A V^2}{g_c} \quad \dots(\text{III-2})$$

The drag coefficient is defined by the expression

$$F = C_D \frac{\rho V^2}{2g_c} A \quad \text{or} \quad C_D = \frac{F}{\frac{\rho V^2}{2g_c} A} \quad \dots(\text{III-3})$$

Thus, one finds that for a surface normal to the flow stream (stagnation point), the drag coefficient is:

$$C_D \frac{\rho V^2}{2g_c} A = \frac{\rho A V^2}{g_c} \quad \dots(\text{III-4a})$$

so,

$$C_D = C_{P_s} = 2 \quad \dots(\text{III-4b})$$

FIG. 5a
FLOW STREAM NORMAL
TO PLANE SURFACE, A.

FIG. 5b
FLOW STREAM INCLINED
TO PLANE SURFACE, A.

FIG. 5c
DRAG FORCES ACTING ON
RIGHT CIRCULAR CYLINDER

FIGURE 5

AIR FLOW VECTOR DIAGRAMS

FIG. 5d

FIG. 5e

FIG. 5f

FIGURE 5 (CON'T)

AIR FLOW VECTOR DIAGRAMS

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If the plane surface is not normal to the flow stream (see Figure 5b), the momentum balance yields

$$F = \frac{dm}{dt} \Delta V = \frac{\rho A V \sin \beta}{g_c} (V \sin \beta) = \frac{\rho A V^2 \sin^2 \beta}{g_c}, \dots (\text{III-5})$$

so that

$$C_D = C_P = 2 \sin^2 \beta = C_{P_s} \sin^2 \beta = C_{P_s} \cos^2 \gamma \quad \dots (\text{III-6})$$

In deriving an expression for the aerodynamic drag (and drag coefficient) on a right circular cylinder, two forces are determined, and then their components in the direction of the velocity are found and combined. The two forces are the drag acting on the end of the cylinder, normal to that surface, F_A (the axial force), and the force acting on the cylindrical surface normal to the axis, F_N (see Figure 5c).

The force F_A (Figure 5c) is acting normal to the plane surface on the end of the cylinder. In the manner indicated by Figure 5b and Equations (III-5) and (III-6), F_A is found to be

$$F_A = \left(\frac{\rho V^2}{g_c} \right) A \cos^2 \alpha = 2 \left(\frac{\rho V^2}{2g_c} \right) A \cos^2 \alpha \quad \dots (\text{III-7})$$

To determine the force acting on the cylindrical surface, refer to Figures 5d and 5e. The component of the flow velocity, V , acting normal to the axis at any point is $V \sin \alpha$, and the component of that which is also acting normal to the surface at any point is $V \sin \alpha \cos \eta$. The force acting at any small increment of surface area, dA , (see Figure 5f) can be written

$$F_N = \int C_r \left(\frac{\rho V^2}{2g_c} \right) dA = \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} C_{P_s} \frac{\rho}{2g_c} V^2 \sin^2 \alpha \cos^2 \eta dA \quad \dots (\text{III-8})$$

with

$$dA = RL \cos n \, dn, \quad \dots(\text{III-9})$$

(see Figure III-5f), from which it follows that

$$F_N = C_{P_s} \left(\frac{\rho V^2}{2g_c} \right) RL \sin^2 \alpha \int_{-\frac{\pi}{2}}^{+\frac{\pi}{2}} \cos^3 \eta \, d\eta, \quad \dots(\text{III-10})$$

and finally

$$F_N = \frac{4}{3} C_{P_s} \left(\frac{\rho V^2}{2g_c} \right) RL \sin^2 \alpha = \frac{8}{3} \left(\frac{\rho V^2}{2g_c} \right) RL \sin^2 \alpha. \quad \dots(\text{III-11})$$

Since we are interested in the total drag force, F_D , in the direction of the flow velocity, we determine the proper components of the axial and normal forces, F_A and F_N , and combine them for F_D as shown in Figure 5c,

$$F_D = F_N \sin \alpha + F_A \cos \alpha. \quad \dots(\text{III-12})$$

Applying Equations (III-7) and (III-11), Equation (III-12) becomes

$$F_D = \frac{8}{3} \left(\frac{\rho V^2}{2g_c} \right) RL \sin^3 \alpha + 2 \left(\frac{\rho V^2}{2g_c} \right) \frac{\pi D^2}{4} \cos^3 \alpha. \quad \dots(\text{III-13})$$

Recalling the definition of the drag coefficient, C_D ,

$$C_D = \frac{F}{\left(\frac{\rho V^2}{2g_c} \right) A}, \quad \dots(\text{III-3})$$

and arbitrarily defining the reference area as that of the cross-section of the cylinder,

$$A_{Ref} = \frac{\pi D^2}{4} , \quad \dots(III-14)$$

the drag coefficient of the cylinder, with the angle of attack as defined by Figure 5c, is found to be

$$C_D = \frac{16}{3\pi} \frac{L}{D} \sin^3 \alpha + 2 \cos^3 \alpha . \quad \dots(III-15)$$

2. Drag Coefficients for Various Flight Orientations

Equation (III-15) gives the drag coefficient for a right circular cylinder based on the cross-section as the reference area. The coefficient is given as a function of the angle of attack, α . The value of C_D for various flight orientations is to be determined.

a) End-On

With the cylinder oriented end-on in the flow stream, $\alpha = 0$. From Equation (III-15), it follows that

$$C_{D, \text{End-On}} = 2.0 \quad \dots(III-16)$$

b) Side-On (Cross-flow)

If the cylinder is oriented side-on (flow stream normal to the axis), $\alpha = 90^\circ$, and Equation (III-15) indicates

$$C_{D, \text{Side-On}} = \frac{16}{3\pi} \frac{L}{D} = 1.698 \frac{L}{D} . \quad \dots(III-17)$$

Side-On

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The value of C_D varies with the angle of attack, α . It is of interest to determine where its minimum and maximum values lie. Differentiating Equation (III-15), one obtains

$$\frac{dC_D}{d\alpha} = \frac{16L}{\pi D} \sin^2 \alpha \cos \alpha - 6 \cos^2 \alpha \sin \alpha. \quad \dots(\text{III-18})$$

Setting $\frac{dC_D}{d\alpha} = 0$, and checking the sign of the second derivative, one finds that local maxima for C_D occur at $\alpha = 0$ and $\alpha = 90^\circ$, and the minimum occurs at $\alpha = \tan^{-1}\left(\frac{3\pi}{8} \frac{D}{L}\right)$.

$$C_D \text{ is } \begin{cases} \text{max. at } \begin{cases} \alpha = 0 \\ \alpha = 90^\circ \end{cases} \\ \text{min. at } \alpha = \tan^{-1}\left(\frac{3\pi}{8} \frac{D}{L}\right) \end{cases} \quad \dots(\text{III-19})$$

d) End-Over-End Tumbling

The mean value of the drag coefficient for end-over-end tumbling can be written

$$\bar{C}_D = \frac{\int_0^{\frac{\pi}{2}} C_D d\alpha}{\int_0^{\frac{\pi}{2}} d\alpha}, \quad \dots(\text{III-20})$$

since each angular position is equally probable. Thus, Equation (III-20) becomes

$$\bar{C}_D = \frac{2}{\pi} \int_0^{\frac{\pi}{2}} \left[\frac{16}{3\pi} \frac{L}{D} \sin^3 \alpha + 2 \cos^3 \alpha \right] d\alpha = \left[\frac{64}{9\pi^2} \frac{L}{D} + \frac{8}{3\pi} \right]. \quad \dots(\text{III-21})$$

$$\begin{aligned} r &= l \sin \alpha \\ ds &= l d\alpha \\ dA &= 2\pi r ds \\ dA &= 2\pi l^2 \sin \alpha d\alpha \end{aligned}$$

FIGURE 6

SURFACE AREA INCREMENT
FOR SPHERICAL GEOMETRY

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TABLE III

DRAG COEFFICIENT EXPRESSIONS
FOR RIGHT CIRCULAR CYLINDERS

GENERAL: $C_D = \frac{16}{3\pi} \frac{L}{D} \sin^3 \alpha + 2 \cos^3 \alpha$

END-ON: $C_D = 2.0$

SIDE-ON: $C_D = \frac{16}{3\pi} \frac{L}{D}$

END-OVER-END: $C_D = \frac{64}{9\pi^2} \frac{L}{D} + \frac{8}{3\pi}$

RANDOM TUMBLING: $C_D = \frac{L}{D} + \frac{1}{2}$

Reference Area is Cylinder Cross-section:

$$A_{\text{ref}} = \frac{\pi D^2}{4}$$

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e) Random Tumbling

When random tumbling occurs, the end point of the cylinder describes a spherical surface. At any particular instant, that end point has an equal probability to be at any point on the sphere. (Note that this means that the probability of $\alpha = 90^\circ$ is a maximum, and $\alpha = 0^\circ$ is a minimum, whereas for end-over-end tumbling, all values are equally probable.) Therefore, the mean value of C_D for random tumbling is defined by

$$\bar{C}_D = \frac{\int_A C_D dA}{\int_A dA} \quad \dots(\text{III-21a})$$

Referring to Figure 6, the area increment is given as

$$dA = 2\pi l^2 \sin \alpha d\alpha \quad \dots(\text{III-22})$$

so that Equation (III-21) becomes

$$\bar{C}_D = \frac{2\pi l^2 \int_0^{\frac{\pi}{2}} \left[\frac{16L}{3\pi D} \sin^3 \alpha d\alpha + 2 \cos^3 \alpha d\alpha \right] \sin \alpha}{2\pi l^2 \int_0^{\frac{\pi}{2}} \sin \alpha d\alpha} \quad \dots(\text{III-23})$$

and

$$\bar{C}_D = \left[\frac{16L}{3\pi D} \int_0^{\frac{\pi}{2}} \sin^4 \alpha d\alpha + 2 \int_0^{\frac{\pi}{2}} \cos^3 \alpha \sin \alpha d\alpha \right], \quad \dots(\text{III-24})$$

and finally

$$C_D = \left(\frac{L}{D} + \frac{1}{2} \right) \quad \dots \text{(III-25)}$$

Random
Tumbling

Table III summarizes the expressions for the drag coefficient, C_D .

3. Numerical Evaluation of Drag Coefficients and Ballistic Coefficients

Drag coefficients and ballistic coefficients are evaluated for the reactor core reentering in different orientations, and for the partially disintegrated core under random tumbling conditions. The results are summarized in Table IV. It is interesting to note that for the particular dimensions of the reactor core, the drag coefficients for end-on and random tumbling are nearly the same.

Figure 7 shows the variation of C_D with α for the full core.

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TABLE IV
Ballistic Coefficient

$$\frac{W}{C_D A_{Ref}}$$

Full Core:	$\frac{L}{D} = 1.481$	$A_{Ref} = 0.425 \text{ ft}^2$
	C_D	$\frac{W}{C_D A}$
End-On	2.0	163.9
Side-On	2.514	130.4
End-Over-End	1.916	171.1
Random Tumbling	1.981	165.5

Random Tumbling $(C_D = \frac{L}{D} + \frac{1}{2})$

	$\frac{L}{D}$	$\frac{W}{C_D A}$
Full-Core	1.481	165.5
One Ring Gone	2.282	134.5
Two Rings Gone	3.817	88.76
Three Rings Gone	10.464	37.36

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FIGURE 7

REACTOR CORE DRAG COEFFICIENT, C_D
VS. ANGLE OF ATTACK, α .

$$C_D = 2.514 \sin^3 \alpha + 2.0 \cos^3 \alpha \quad \left(\frac{L}{D} = 1.481 \right)$$

(See Tables III & IV)

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B. Aerodynamic Heating Correlations

The basic aerodynamic heating relationship used in making the calculations reported herein is the Detra-Hidalgo correlation,

$$q_{SS} \left(\frac{\text{BTU}}{\text{sec ft}^2} \right) = 865 \sqrt{\frac{R_0}{R}} \sqrt{\frac{\rho}{\rho_{SL}}} \left(\frac{V}{V_0} \right)^{3.15} \left(\frac{H_{\text{STAG}} - H_{\text{WALL}}}{H_{\text{STAG}} - H_{T=540^\circ R}} \right) \quad \dots(\text{III-26})$$

Sphere
Stagnation
Point

which is presented in Reference 2. Equation (III-26) is for the stagnation point heating on a sphere of radius, R , and velocity, V , in flight through air of density, ρ . The terms R_0 , ρ_{SL} , and V_0 are reference parameters. The reference radius, R_0 , is one foot, the reference velocity, V_0 , is 10,000 ft/sec, and the reference air density, ρ_{SL} , is that of standard air at sea level, 0.07647 lbm/ft³.

Detra and Hidalgo claim that their correlation is accurate to 10% in the velocity range of 26,000 to 6,000 ft/sec, and the range of air density, $8 \times 10^{-5} \leq \rho/\rho_{SL} \leq 1.0$. The velocity range restriction causes no difficulty. The initial velocities for the trajectories considered are somewhat under 26,000 ft/sec, and by the time the body has been slowed down to a velocity of 6,000 ft/sec, the stagnation point heating rate is decreasing rapidly and is approximately 10% of its peak value, while about 99% of the total heat to be deposited in the body has already been delivered, (Q_{INT}). On the other hand, some of the aerodynamic heating calculations that follow do not fall completely within the air density range stipulated. The range of $8 \times 10^{-5} \leq \rho/\rho_{SL} \leq 1.0$ dictates an altitude range of 230,000 feet to sea level. A good deal of the region of concern in this report is above 230,000 feet. However, Elliott (see Reference 3) indicates that there is considerable evidence to justify using the Detra-Hidalgo relation, Equation (III-26) to substantially higher altitudes.

The final term of the Detra-Hidalgo expression is called the

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"hot wall correction factor," and accounts for the fact that the higher the temperature of a surface, the less heat will flow to it from the heat source (which is presumably at the stagnation temperature of the air). The hot wall correction factor is:

$$\left[\begin{array}{c} \text{HOT WALL} \\ \text{CORRECTION} \\ \text{FACTOR} \end{array} \right] = \left(\frac{H_{\text{STAG}} - H_{\text{WALL}}}{H_{\text{STAG}} - H_{T=540^{\circ}\text{R}}} \right) \quad \dots(\text{III-27a})$$

or, assuming a constant specific heat, c_p ,

$$(\text{H.W.C.F.}) \cong \left(\frac{T_s - T_w}{T_s - 540^{\circ}\text{R}} \right) \quad \dots(\text{III-27b})$$

The term, $\sqrt{\frac{R_o}{R}}$, is called the "size correction factor," with R_o a nominal one foot radius, and R the radius of the projectile under consideration,

$$\left[\begin{array}{c} \text{SIZE} \\ \text{CORRECTION} \\ \text{FACTOR} \end{array} \right] = \sqrt{\frac{R_o}{R}} \quad \dots(\text{III-28})$$

Equation (III-29) defines the reference aerodynamic heating,

$$q_{\text{Ref}} \left(\frac{\text{BTU}}{\text{sec ft}^2} \right) = 865 \sqrt{\frac{\rho}{\rho_{SL}}} \left(\frac{V}{V_o} \right)^{3.15} \quad \dots(\text{III-29})$$

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It can be noted that the reference heating relation is the same as Equation (III-26) except that the hot wall correction factor (which is dependent on the body temperature) and the size correction factor have been excluded. The result is that the reference heating is a function only of the velocity and altitude of the body. It is essentially the stagnation point heating for a cold ($T = 540^{\circ}\text{R}$) spherical body with a one foot radius.

While the stagnation point heating on a sphere is a reference quantity, in the problem of the reentering reactor core we are concerned with the aerodynamic heating all over the surface of a cylinder (particularly the ends). As a result, the use of various geometric correlation factors is necessary in order to obtain the desired result. These corrections are discussed in detail by Klett in Reference 4, and also by Kemp, Rose, and Detra in Reference 5. Those which are used in this study are presented below.

The term, F_a , is the ratio of the stagnation point heating at the center of the disk end of a cylinder with end-on flow, to the stagnation point heating for a sphere with the same radius. According to Klett (Reference 4, Page 21), this ratio is equal to $\frac{1}{2}$.

$$F_a = \frac{q_{sp}}{q_{ss}} = \frac{1}{2} = \frac{\text{Stag Pt. Heating, End of Cylinder, End-On Flow}}{\text{Stag Pt. Heating, Sphere of Same Radius}} \dots(\text{III-30})$$

The term, F_b , describes the local heat distribution on the disk end of a cylinder in end-on flow. F_b is the ratio of local heating to stagnation point heating, and is given by Klett, Page 23, to be:

$$F_b = \frac{q_L}{q_{sp}} = 1.0 + 0.6 \left(\frac{x}{R}\right)^{3.3} = \frac{\text{Local Heating on Disk, End-On Flow}}{\text{Stag Pt. Heating, End of Cylinder, End-On Flow}} \dots(\text{III-31})$$

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Integration of F_b over the area of the disk end of the cylinder yields the term, F_c , which is the ratio of average heating on the end disk of the cylinder to the stagnation point heating, with end-on flow.

$$F_c = \frac{\bar{q}_L(\alpha=0)}{q_{sp}} =$$

$$= \frac{\text{Avg. Local Heating, End of Cylinder, End-On Flow}}{\text{Stag. Pt. Heating, End of Cylinder, End-on Flow}} \quad \dots(\text{III-32a})$$

$$F_c = \frac{\int_A \left(\frac{q_L}{q_{sp}} \right) dA}{\int_A dA} = \frac{\int_0^R \left[1.0 + 0.6 \left(\frac{x}{R} \right)^{3.3} \right] 2\pi x dx}{\int_0^R 2\pi x dx} = 1.2264 \quad \dots(\text{III-32b})$$

Klett, on Page 23, shows the plot of average heat transfer to a disk at varying angles of attack as compared to the same disk normal to the flow (end-on flow). That is,

$$\frac{\bar{q}_L(\alpha)}{\bar{q}_L(\alpha=0^\circ)} = f(\alpha) \quad \dots(\text{III-33})$$

This plot is shown in Figure 8, and it can be seen that at $\alpha = 90^\circ$,

$$\frac{\bar{q}_L(90)}{\bar{q}_L(0)} = 0.24:$$

$$F_d = \frac{\bar{q}_L(\alpha=90^\circ)}{\bar{q}_L(\alpha=0^\circ)} = 0.24 =$$

$$= \frac{\text{Avg. Local Heating, End of Cylinder, Cross Flow (} \alpha=90^\circ \text{)}}{\text{Avg. Local Heating, End of Cylinder, End-On Flow (} \alpha=0^\circ \text{)}} \quad \dots(\text{III-34})$$

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On Page 19, Klett points out that the ratio of aerodynamic heating at the stagnation line of a cylinder in cross flow to the heating of a sphere of the same radius (other conditions assumed to identical) is 0.747:

$$F_e = \frac{q_{sl}(\alpha=90^\circ)}{q_{ss}} = 0.747 = \dots(\text{III-35})$$

$$= \frac{\text{Stag. Line Heating, Cylinder Side, Cross Flow}}{\text{Stag. Pt. Heating, Sphere of Same Radius}}$$

Klett, on Page 20, gives a plot of the ratio of the heating on the side of a cylinder in cross-flow to the stagnation line heating. This curve is reproduced in Figure 9:

$$\frac{q_L(\text{side})}{q_{sl}} = f(\theta) = \frac{\text{Local Heating, Side of Cylinder}}{\text{Stag. Line Heating, Side of Cylinder}} \dots(\text{III-36})$$

Integrating the curve of Figure 9, one determines the average value of the local heating on the side surface of a cylinder in cross flow ($\alpha=90^\circ$) as compared to the stagnation line heating and it is found to be 0.385:

$$F_f = \frac{\bar{q}_L(\alpha=90^\circ)}{q_{sl}(\alpha=90^\circ)} = 0.385 = \dots(\text{III-37})$$

$$= \frac{\text{Avg. Heating on Cylinder Side Surface, } \alpha=90^\circ}{\text{Stag. Line Heating, Cylinder in Cross-Flow, } \alpha=90^\circ}$$

The average heating ratio on the end of a cylinder while in random tumbling flight can be determined by properly integrating the curve of Figure 8, (in the same manner as Equation III-21 and Figure 6).

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FIGURE 8 RATIO OF HEATING ON DISK AT ANGLE α TO HEATING ON DISK AT $\alpha = 0^\circ$ (F_d)

FIGURE 9 RATIO OF LOCAL TO STAG-LINE HEATING ON CYLINDER IN CROSS-FLOW. (STAG-LINE, $\theta = 0^\circ$)

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$$\frac{\bar{q}_L}{\bar{q}_{L_{\alpha=0}}} = \frac{\int_0^\pi \frac{q_L(\theta)}{q_{L(\theta=0)}} \sin \theta d\theta}{\int_0^\pi \sin \theta d\theta} = \frac{\sum \frac{\bar{q}_L(\theta)}{\bar{q}_{L(\theta=0)}} \sin \theta (\Delta \theta)}{\sum \sin \theta (\Delta \theta)}, \dots \text{(III-38a)}$$

$$F_g = \frac{\bar{q}_{L_{RT}}}{\bar{q}_{L_{\alpha=0}}} = 0.5226 = \dots \text{(III-38b)}$$

$$= \frac{\text{Avg. Heating on End of Cylinder, Random Tumbling}}{\text{Avg. Heating on End of Cylinder, End on Flow, } \alpha = 0^\circ}$$

Klett, on Page 22, gives a plot of the average heating to the side of an end-on cylinder ($\alpha = 0^\circ$) to stagnation point heating to a sphere of the same radius. This curve is shown in Figure 10. On the basis of this plot, F_h is defined:

$$F_h = \frac{\bar{q}_{side_{\alpha=0}}}{q_{ss}} = \frac{q_{sr}}{q_{ss}} \int \frac{q_L(\alpha=0)}{q_{sr}} d\left(\frac{x}{R}\right) = f\left(\frac{L}{D}\right) \dots \text{(III-39a)}$$

$$F_h = \frac{\text{Avg. Heating on Side of Cylinder, End-On Flow } (\alpha = 0^\circ)}{\text{Stag. Pt. Heating on Sphere}} \dots \text{(III-39b)}$$

There is relatively little data available on heat transfer to yawed cylinders. However, Klett, on Page 24, suggests the use of the expression

$$\frac{\bar{q}_L(\alpha)}{q_{ss}} = \frac{\text{Avg. Heating on Side of Cylinder, Angle of Attack}}{\text{Stag. Point Heating, Sphere}} =$$

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FIGURE 10

RATIO OF AVERAGE HEATING TO THE SIDE
OF AN END-ON CYLINDER ($\alpha = 0^\circ$) TO STAG.
POINT HEATING TO SPHERE OF SAME RADIUS.

 (F_h)

see Eq. (III-39) & Table V.

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$$= \left\{ \left(\begin{array}{l} \text{Avg. Heat Ratio} \\ \text{on Cylinder Side} \\ \text{at } \alpha = 0^\circ \\ \text{(end-on)} \end{array} \right) \cos^2 \alpha + \left(\begin{array}{l} \text{Avg. Heat Ratio} \\ \text{on Cylinder Side} \\ \text{at } \alpha = 90^\circ \\ \text{(cross-flow)} \end{array} \right) \sin^2 \alpha \right\} = \dots(\text{III-40})$$

$$= \left[M \cos^2 \alpha + N \sin^2 \alpha \right]$$

Equation (III-40) describes the average heating on the side of cylinder which is at a particular angle of attack, α . In order to determine the average heating under conditions of random tumbling, an integration similar to that done in Equations (III-21, 22, and 23) and Figure 6 must be carried out.

$$\left(\frac{\bar{q}_L}{q_{ss}} \right)_{RT} = \frac{\int \frac{\bar{q}_L(\alpha)}{q_{ss}} dA}{\int dA} = \frac{2\pi \int_0^{\frac{\pi}{2}} [M \cos^2 \alpha \sin \alpha + N \sin^3 \alpha] d\alpha}{2\pi \int_0^{\frac{\pi}{2}} \sin \alpha d\alpha} \dots(\text{III-41a})$$

This leads to:

$$\left(\frac{\bar{q}_L}{q_{ss}} \right) = \frac{1}{3} M + \frac{2}{3} N = C_1 M + C_2 N \dots(\text{III-41b})$$

where $C_1 = \frac{1}{3}$ and $C_2 = \frac{2}{3}$.

Equation (III-41b) can be rewritten in the form:

$$F_i = \frac{\text{Avg. Heat, Cylinder Side, Random Tumb}}{\text{Stag. Pt., Sphere}} =$$

$$= \left(\frac{\bar{q}_L}{q_{ss}} \right)_{RT} = \left\{ (C_1) \underbrace{(F_h)}_M + (C_2) \underbrace{(F_e)(F_h)}_N \right\}, \quad \dots(\text{III-42a})$$

which is seen to be

$$\left(\frac{\bar{q}_L}{q_{ss}} \right) = \left\{ C_1 \left(\frac{\bar{q}_L^{\text{side}}}{q_{ss}} \right)_{\alpha=0} + C_2 \left(\frac{q_{SL}^{\text{side}}}{q_{ss}} \right) \left(\frac{\bar{q}_L^{\text{side}}}{q_{SL}^{\text{side}}} \right)_{\alpha=90} \right\}, \quad \dots(\text{III-42b})$$

and for $\frac{L}{D} = 1.481$, $F_h = 0.114$, and Equation (III-42b) yields,

$$F_i = \left(\frac{\bar{q}_L}{q_{ss}} \right)_{RT} = \left\{ \frac{1}{3} (0.114) + \frac{2}{3} (0.747)(0.385) \right\} = 0.230. \quad \dots(\text{III-42c})$$

For end over end tumbling, expressions analogous to Equations (III-38) and (III-41) can be obtained, if desired, by carrying out the appropriate integration, as in Equation (III-20).

The average heating ratio on the end of a cylinder in end over end tumbling flight is determined by integrating the curve of Figure 8.

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$$\frac{\bar{q}_L \epsilon/\epsilon}{\bar{q}_L \alpha=0} = \frac{\int_0^\pi \frac{q_L(\theta)}{q_L(\theta=0)} d\theta}{\int_0^\pi d\theta} = \frac{\sum_{\theta=0}^{\theta=180} \frac{q_L(\theta)}{q_L(\theta=0)} (\Delta\theta)}{\sum (\Delta\theta)}, \quad \dots(\text{III-43a})$$

$$F_j = \frac{\bar{q}_L \epsilon/\epsilon}{\bar{q}_L \alpha=0} = 0.542 = \frac{\text{Avg. Heat on End of Cylinder, End Over End Tumb}}{\text{Avg. Heat on End of Cylinder, End on Flow, } \alpha=0} \quad \dots(\text{III-43b})$$

To determine the average heating on the side of a cylinder in end over end tumbling, Equation (III-40) must be integrated,

$$\left(\frac{\bar{q}_L}{q_{ss}} \right)_{\epsilon/\epsilon} = \frac{\int_0^{\pi/2} (M \cos^2 \alpha + N \sin^2 \alpha) d\alpha}{\int_0^{\pi/2} d\alpha} = \frac{\frac{\pi}{4} M + \frac{\pi}{4} N}{\frac{\pi}{2}} = \frac{1}{2} M + \frac{1}{2} N. \quad \dots(\text{III-44a})$$

$$\left(\frac{\bar{q}_L}{q_{ss}} \right)_{\epsilon/\epsilon} = C_3 (M + N), \quad \text{where } C_3 = \frac{1}{2}. \quad \dots(\text{III-44b})$$

Equation (III-44) can be rewritten:

$$\frac{\text{Avg. Heat, Cylinder Side, End/End}}{\text{Stag. Pt., Sphere}} = \left(\frac{\bar{q}_L}{q_{ss}} \right)_{\epsilon/\epsilon} = \left\{ \underbrace{C_3 (F_h)}_M + \underbrace{C_3 (F_e) (F_F)}_N \right\},$$

which, as in the case of Equation (III-42), can be seen to be

$$\left(\frac{\bar{q}_L}{q_{ss}} \right) = \left\{ C_3 \left(\frac{\bar{q}_L^{side}}{q_{ss}} \right) + C_3 \left(\frac{q_{ss}^{side}}{q_{ss}} \right) \left(\frac{\bar{q}_L^{side}}{q_{ss}^{side}} \right) \right\} \dots (III-45a)$$

which yields, for $\frac{L}{D} = 1.481$,

$$F_k = \left(\frac{\bar{q}_L}{q_{ss}} \right)_{E/E} = \left\{ \frac{1}{2} (0.114) + \frac{1}{2} (0.747)(0.385) \right\} = 0.201 \dots (III-45b)$$

The correlation factors presented in the preceding section are summarized in Table V. These factors were used in establishing the aerodynamic heating distribution inputs in the thermal model presented later in this report.

It should be pointed out that the correlation factors of Table V do not take into account the fact that the heat input may vary along the side of the cylinder as a function of the distance from the end. Only average heating values are used. On the other hand, heat input variation with position on the end of the cylinder is taken into account by F_b . As a result, the heat input on the ends of the cylinder are probably represented somewhat better by this correlation. In the thermal problem investigated later in this report, it is the heating at the ends of the cylinder which is of primary significance, since the meltdown of the grid plates is being studied.

The RESTORE (Re-entering SNAP Trajectory on an Oblate Rotating Earth) computer program (see References 6 and 7) was used to calculate the trajectory of the reentering reactor core, depending on its ballistic coefficient, $(W/C_D A)$, and its initial velocity and position conditions. Among the trajectory parameters determined are the altitude, velocity,

TABLE V

AERODYNAMIC HEATING

CORRELATION FACTORS

Detra-Hidalgo Correlation $q_{ss} = 865 \sqrt{\frac{R_o}{R}} \sqrt{\frac{p}{p_{sl}}} \left(\frac{V}{V_o} \right)^{3.15} \left(\frac{H_s - H_w}{H_s - H_{s40}} \right)$ III-26

Reference Heating $q_{Ref} = 865 \sqrt{\frac{p}{p_{sl}}} \left(\frac{V}{V_o} \right)^{3.15}$ III-29

Hot Wall Correction Factor $(HWCF) = \left(\frac{H_s - H_w}{H_s - H_{s40}} \right) \approx \left(\frac{T_s - T_w}{T_s - T_{s40}} \right)$ III-27

Size Correction Factor $(SCF) = \sqrt{\frac{R_o}{R}}$ III-28

$F_a = \frac{\text{Stag. Pt. Heat, Cyl. end, } \alpha=0}{\text{Stag. Pt. Heat, sphere}} = \frac{q_{sp}}{q_{ss}} = \frac{1}{2}$ III-30

$F_b = \frac{\text{Local heat, Cyl. end, } \alpha=0}{\text{Stag. Pt. Heat, Cyl. end, } \alpha=0} = \frac{q_{L \alpha=0}^{end}}{q_{sp}} = \left[1.0 + 0.6 \left(\frac{x}{R} \right)^{3.3} \right]$ III-31

$F_c = \frac{\text{Avg. Local Heat, Cyl. end, } \alpha=0}{\text{Stag. Pt. Heat, Cyl. end, } \alpha=0} = \frac{\bar{q}_{L \alpha=0}^{end}}{q_{sp}} = 1.2264$ III-32

$F_d = \frac{\text{Avg. Local Heat, Cyl. end, } \alpha=90}{\text{Avg. Local Heat, Cyl. end, } \alpha=0} = \frac{\bar{q}_{L \alpha=90}^{end}}{\bar{q}_{L \alpha=0}^{end}} = 0.24$ III-34
Fig. 8

$F_e = \frac{\text{Stag Line Heat, Cyl. side, } \alpha=90}{\text{Stag Pt. Heat, sphere}} = \frac{q_{sl \alpha=90}^{side}}{q_{ss}} = 0.747$ III-35

$F_f = \frac{\text{Avg. Heat, Cyl. side, } \alpha=90}{\text{Stag Line Heat, Cyl. side, } \alpha=90} = \frac{\bar{q}_{L \alpha=90}^{side}}{q_{sl \alpha=90}^{side}} = 0.385$ III-37

$F_g = \frac{\text{Avg. Heat, Cyl. end, random Tumb.}}{\text{Avg. Heat, Cyl. end, } \alpha=0} = \frac{\bar{q}_{L RT}^{end}}{\bar{q}_{L \alpha=0}^{end}} = 0.5226$ III-38

TABLE V (CON'T)

$$F_h = \frac{\text{Avg. Heat, Cyl. side, } \alpha=0}{\text{Stag. Pt., sphere}} = \frac{\bar{q}_L^{\text{side}}}{q_{ss}} = f\left(\frac{L}{D}\right) \quad \text{III-39}$$

Fig. 10

$$\text{For } \frac{L}{D} = 1.481; F_h = 0.114$$

$$\frac{\text{Avg. Heat, Cyl. side, } \alpha}{\text{Stag Pt., sphere}} = \frac{\bar{q}_L(\alpha)}{q_{ss}} = \left\{ \left(\frac{\bar{q}_L^{\alpha=0}}{q_{ss}} \right) \cos^2 \alpha + \left(\frac{\bar{q}_L^{\alpha=90}}{q_{ss}} \right) \sin^2 \alpha \right\} \quad \text{III-40}$$

$$F_i = \frac{\text{Avg Heat, Cyl. side, Random Tumb.}}{\text{Stag. Pt., sphere}} = \left(\frac{\bar{q}_L}{q_{ss}} \right)_{RT} = 0.230 \quad \text{III-42}$$

$$F_j = \frac{\text{Avg. Heat, Cyl. end, end/end}}{\text{Avg Heat, Cyl. end, } \alpha=0} = \frac{\bar{q}_L^{\text{E/E}}}{\bar{q}_L^{\text{end}}}_{\alpha=0} = 0.542 \quad \text{III-43}$$

$$F_k = \frac{\text{Avg. Heat, Cyl. side, end/end}}{\text{Stag Pt., sphere}} = \left(\frac{\bar{q}_L}{q_{ss}} \right)_{E/E} = 0.201 \quad \text{III-45}$$

flight angle, longitude, latitude, azimuth, and range as a function of time. It is not the purpose of the code to determine aerodynamic heating, but as a side calculation, it determines and tabulates the reference heating, q_{Ref} , and the stagnation enthalpy, H_s . These quantities are functions solely of the projectile velocity and air properties, (which are functions of altitude), and are used, along with the aerodynamic heating distribution factors of Table V, in determining the heat input functions for the thermal model of the reentering core presented in a later section.

The aerodynamic heat input to each surface node is determined by the equation,

$$Q_N \left(\frac{\text{BTU}}{\text{sec}} \right) = q_{Ref} \sqrt{\frac{R_o}{R}} A_N \mathfrak{F} \left(\frac{T_s - T_w}{T_s - 540^\circ \text{R}} \right),$$

or

...(III-46a)

$$Q_N = Y(T_s - T_w) = \left\{ \left(\frac{q_{Ref}}{T_s - 540^\circ \text{R}} \right) \left(\sqrt{\frac{R_o}{R}} A_N \mathfrak{F} \right) \right\} (T_s - T_w)$$

with

$$Y = \left\{ \left(\frac{q_{Ref}}{T_s - 540^\circ \text{R}} \right) \sqrt{\frac{R_o}{R}} A_N \mathfrak{F} \right\} \quad \dots(\text{III-46b})$$

and

$$\mathfrak{F}_m = \prod_i (F_i) \quad \dots(\text{III-46c})$$

where A_n is the nodal surface area, and $\mathfrak{F}$ is the product of the appropriate F factors of Table V, and q_{Ref} and T_s are determined by the RESTORE code for any particular trajectory. Table VI indicates the proper F factors

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TABLE VI

AERODYNAMIC HEATING

FACTORS, $\mathfrak{F}$

Heat Input
to Node N

$$Q_N = q_{Ref} \sqrt{\frac{R_o}{R}} (HWCF) A_N \mathfrak{F}$$

III-46

END-ON FLOW

$$\alpha = 0^\circ$$

$$\text{Cylinder End} \quad \mathfrak{F} = (F_a)(F_b) = \frac{1}{2} \left[1 + 0.6 \left(\frac{x}{R} \right)^{3.3} \right]$$

$$\text{Cyl. Side} \quad \mathfrak{F} = F_h = f\left(\frac{L}{D}\right)$$

$$\text{For } \frac{L}{D} = 1.481, F_h = 0.114, \mathfrak{F} = 0.114$$

SIDE-ON FLOW

$$\alpha = 90^\circ$$

$$\text{Cyl. End} \quad \mathfrak{F} = (F_a)(F_b)(F_d) = 0.12 \left[1 + 0.6 \left(\frac{x}{R} \right)^{3.3} \right]$$

$$\text{Cyl. Side} \quad \mathfrak{F} = (F_e)(F_f) = 0.288$$

RANDOM TUMBLING

$$\text{Cyl. End} \quad \mathfrak{F} = (F_a)(F_b)(F_g) = 0.261 \left[1 + 0.6 \left(\frac{x}{R} \right)^{3.3} \right]$$

$$\text{Cyl. Side} \quad \mathfrak{F} = F_i = 0.230$$

END OVER END

$$\text{Cyl. End} \quad \mathfrak{F} = (F_a)(F_b)(F_j) = 0.271 \left[1 + 0.6 \left(\frac{x}{R} \right)^{3.3} \right]$$

$$\text{Cyl. Side} \quad \mathfrak{F} = F_k = 0.201$$

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which combine to form the $\int$ aerodynamic heat distribution terms for various flight orientations.

C. Trajectories

The aerodynamic heating of a reentering body is, of course, dependent on the particular trajectory that the projectile follows. There are an infinite number of possible paths, depending on the initial conditions (velocity, altitude, flight angle, etc.) and properties of the body (mass, projected area, drag coefficient). In order to study the problem of a reentering SNAP 10A reactor core, a set of reference trajectories were chosen, and the thermal analysis was based on the these.

It was initially assumed that a reentering body containing the reactor core had $W/C_D A = 100$, descending from a polar orbit, with the initial position of the projectile immediately over the north pole at an altitude of 400,000 feet, a velocity of 25,693.94 feet per second, and a flight angle of 0 degrees. As this orbit decays, the altitude decreases, until the point is reached where it is considered that the containment vessel has broken open, and that the reactor core is released. From this point, a new trajectory calculation is initiated, based on the ballistic coefficient of the released body (the reactor core), and with the same orbital parameters that the original trajectory had at the particular release point.

As indicated in Table IV, the ballistic coefficient of the reentering reactor core under conditions of random tumbling is equal to 165.5. Trajectories for $W/C_D A = 165.5$ were determined for starting altitudes of 230,000, 240,000, 250,000, 275,000, and 300,000 feet, with initial velocity, position, and orientation parameters as indicated by the base trajectory ($alt_0 = 400,000$ ft, $W/C_D A = 100$). Data on projectile velocity, altitude, etc. versus time were obtained in both printout and CRT form. This information is available from the author, but it was not included here because it is not the information of principal interest in this study. The concern here is with the aerodynamic heating. In Figure 11, the

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FIGURE 11
 REFERENCE HEATING
 VS. ALTITUDE
 for Various Trajectories

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reference heating, q_{ref} , is plotted versus altitude for the six trajectories mentioned above. The five trajectories representing the reactor core indicate very nearly the same reference heating as a function of altitude (which is essentially equivalent to saying that the velocity versus altitude is the same). The reference heating curve for the $W/C_D A = 100$ trajectory lies below those for $W/C_D A = 165.5$, which is qualitatively what one would expect. The more massive (it can be considered that $C_D A$ are the same for the two projectiles, and the difference in $W/C_D A$ are the same for the two projectiles, and the difference in $W/C_D A$ can be attributed to W) projectile is decelerated less rapidly and therefore maintains a high velocity (high $\left(\frac{V}{V_0}\right)^{3.15}$ term) longer, yielding a higher reference heating. An alternative way of looking at it is to recall that for given velocity and altitude conditions, a projectile has a given total (kinetic and potential) energy per unit mass. Thus, the total energy to be released by aerodynamic heating should be in proportion to the ballistic coefficient. (In fact, it is found that the peak heating and the integrated heat delivered to the projectile vary approximately as the square root of the ballistic coefficient. Only about 2% to 3% of the total energy released by the reentry is deposited in the projectile.) It is interesting to note from Figure 11, that in the altitude range between 300,000 and 200,000 feet, the reference heating varies almost linearly with altitude.

Figure 12a and 12b show curves of integrated heating, Q_{INT} , versus time and altitude for the reentering reactor core for initial altitudes of 250,000, 275,000 and 300,000 feet. Integrated heat is defined as

$$Q_{INT} \left(\frac{BTU}{ft^2} \right) = \int_{alt_0}^{alt} q_{Ref} dt \quad \dots(III-47)$$

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FIGURE 12a
 INTEGRATED HEATING
 VS. TIME
 REENTERING CORE

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It can be observed from Figures 12a and 12b that over quite a wide range, the integrated heat (total heat per unit area delivered to the stagnation point of a cold sphere) is directly proportional to the drop in altitude, even though different lengths of time are involved. This fact will prove useful later on. For instance, if one finds that if a body is released at 250,000 feet, melting of a certain portion occurs at 225,000 feet, one can say, with reasonable accuracy, that if the body were to be released at 270,000 feet instead, it again would take approximately a 25,000 foot drop to deliver the same integrated heat, though it may take somewhat more time.

For example, consider the reactor core released at an altitude of 250,000 feet. (Figure 13 shows the altitude versus time for this descent trajectory.) In 70 seconds it has descended to an altitude of 224,919 feet, a drop of about 25,000 feet, and the indicated integrated heating is 7543 Btu/ft². Now, studying Figures 12 and 13, one can observe how long a time and how great an altitude drop it takes to obtain the same Q for different release altitudes. These values are shown in Table VII and Figure 14. (This particular numerical example was chosen because, as will be discussed in a later section, thermal calculations indicate that for a release altitude of 250,000 feet, it takes about 70 seconds to melt the reactor grid plates sufficiently to allow the release of the outer ring of fuel elements from the core.)

As the reactor core begins to disintegrate by having the outer fuel elements fall away, the ballistic coefficient of the remaining core changes, which in turn affects the trajectory and aerodynamic heating. To study this effect, the following idealized picture of the disintegration of the reactor core was assumed. When sufficient melting of the grid plates has occurred, the beryllium reflectors and all the fuel elements in the outer ring fall away simultaneously. Then, at a later time, the next ring of fuel elements fall away, then the next, until just the central fuel element remains. For the purposes of this study, the separation of the fuel elements, such that each one is independent of the others, constitutes reactor disintegration. (See Figure 4 and Tables I and IV. Ballistic

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TABLE VII

TIME AND ALTITUDE DROP FOR $Q_{INT} = 7543 \frac{BTU}{ft^2}$
 $(\frac{W}{C_0 A} = 165.5 \frac{lb_m}{ft^2})$

Release Altitude (feet)	Altitude for $Q = 7543$ (feet)	Altitude Drop (feet)	Drop Time (Seconds)
300,000	278,070	21,930	238.5
275,000	250,500	24,500	118.9
250,000	224,920	25,080	70.0
240,000	214,640	25,360	59.0
230,000	204,210	25,790	50.8

$$Q_{INT} = \int_{t_0}^t q_{ref} dt = 7543 \frac{BTU}{ft^2}$$

FIGURE 14

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coefficients of 165.5, 134.5, 88.76, and 37.36 are indicated.)

In order to understand the effect of varying ballistic coefficient, trajectories were calculated for four reentering bodies with the $W/C_D A$ values listed above (and in the lower portion of Table IV) and the same release altitude and velocity conditions. In Figure 15, curves of reference heating versus time are shown for an initial altitude of 250,000 feet. The smaller bodies (lower $W/C_D A$) indicate a lower reference heating. However, this does not take into account the "size correction factor" discussed earlier. (See Equations (III-26, 28, and 29). It has been pointed out that the aerodynamic heating varies inversely as the square root of the projectile radius.

$$q_{ss} = q_{ref} [HWCF] \sqrt{\frac{R_o}{R}} \quad \dots(\text{III-26, 27, 28, 29})$$

Accordingly, the reference heating curves shown in Figure 15 are corrected by the factor, $\sqrt{\frac{R_o}{R}}$. The result is the sphere stagnation point heating for a body of radius, R , neglecting the "Hot Wall Correction Factor." These curves are shown in Figure 16, where it can be seen that the smaller (lower $W/C_D A$) body actually receives the more intense heating for a time, at least until after the peak heating point has been passed. This indicates that when fuel elements fall off the reactor core, the intensity of heating on the remaining body actually increases. The significance of this is as follows. A thermal model is set up later in this report to determine the transient temperature distribution in the reentering reactor core. Aerodynamic heat inputs are based on the ballistic coefficient of the entire core, with the result that the aerodynamic heating functions are appropriate until the reactor starts to disintegrate. From then on, the heating functions used in the calculations are lower than should actually be used for that phase of the trajectory, with the result that the time for complete reactor disintegration may be somewhat overestimated, and a slight amount of conservatism is introduced into the results. At any rate,

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FIGURE 16

$$\frac{q_{ss}}{(HWCF)} = q_{ref} \sqrt{\frac{R_o}{R}}$$

VS. TIME

For Trajectories
 of Figure 15

$q_{ref} \sqrt{\frac{R_o}{R}}$ BTU / ft² sec

— TIME — (Seconds) —>

the discrepancy is slight, since at the time the outer edge of the grid plate is sufficiently molten to allow the release of the outer ring of fuel elements, the remainder of the grid plate is approaching the melting temperature.

It is of interest to compare some aerodynamic heating parameters of the curves of Figures 15 and 16. These are tabulated in Table VIII. Note that while the peak heating and total integrated heat vary greatly among the trajectories, when modified by the $\sqrt{\frac{R_o}{R}}$ term, they are in quite close agreement. The agreement also occurs when q_{peak} and Q_{INT} are corrected by $(W/C_D A)^{-\frac{1}{2}}$, which apparently indicates that the heating varies inversely as the square root of the ballistic coefficient. However, this may merely be a peculiarity of the constant length cylindrical geometry. Since we are dealing essentially with a constant length, constant density cylinder, W varies as R^2 , A varies as R^2 , and C_D varies as $1/R$, ($C_D = \frac{1}{2} + \frac{L}{D}$).

Thus;

$$\left(\frac{W}{C_D A} \right)^{-\frac{1}{2}} \rightarrow \left(\frac{C_D A}{W} \right)^{\frac{1}{2}} \rightarrow \left(\frac{\frac{1}{R} R^2}{R^2} \right)^{\frac{1}{2}} \rightarrow \left(\frac{1}{R} \right)^{\frac{1}{2}}, \dots \text{(III-48)}$$

which is the same variation as $\sqrt{\frac{R_o}{R}}$,

which means that:

$$\left(\frac{W}{C_D A} \right)^{-\frac{1}{2}} \sqrt{\frac{R_o}{R}} \cong \text{Constant}, \dots \text{(III-49)}$$

which is indicated by Table VIII.

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TABLE VIII

TRAJECTORY PARAMETERS

(Release Altitude = 250,000 ft)

	Full Reactor Core	One Ring Fuel Gone	Two Rings Fuel Gone	One Fuel Element
$\frac{W}{C_D A} \frac{\text{lbm}}{\text{ft}^2}$	165.5	134.5	88.76	37.36
R Inches	4.415	2.857	1.713	0.625
Time to Hit the Ground, seconds	370.7	376.7	394.1	459.4
$Q_{\text{INT}} \frac{\text{Btu}}{\text{ft}^2}$ (Total to Ground)	41,443	37,041	29,404	17,685
$Q_{\text{INT}} \sqrt{\frac{R_0}{R}}$	68,100	75,900	77,900	77,500
$Q_{\text{INT}} \left(\frac{W}{C_D A} \right)^{-\frac{1}{2}}$	3220	3198	3122	2890
$(q_{\text{Ref}})_{\text{Peak}} \frac{\text{Btu}}{\text{sec ft}^2}$	275.9	244.7	193.8	122.3
$(q_{\text{Ref}})_{\text{Peak}} \sqrt{\frac{R_0}{R}}$	455	506	513	541
$(q_{\text{Ref}})_{\text{Peak}} \left(\frac{W}{C_D A} \right)^{-\frac{1}{2}}$	21.60	21.26	20.59	20.20
$\frac{Q_{\text{INT}} (\text{Total})}{(q_{\text{Ref}})_{\text{Peak}}}$	150.1	151.1	152.0	144.2
$\left(\frac{W}{C_D A} \right)^{\frac{1}{2}} \sqrt{\frac{R_0}{R}}$	21.2	23.8	24.9	26.8

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In the foregoing, trajectories were studied which had different ballistic coefficients, but the same starting conditions. In reality, what will happen is that as the body reenters, the ballistic coefficient will change along the way, and successive trajectories must be considered, rather than the concurrent ones depicted in Figures 15 and 16.

Accordingly, the following trajectory calculation was carried out. Starting at an altitude of 250,000 feet, follow a trajectory based on $W/C_D A = 165.5$ for 70 seconds, at which time the $W/C_D A$ is changed to 134.5, and kept at this value for the remainder of the flight. Figure 17 shows the reference heating curve for this combined trajectory. As expected, a lower reference heating curve occurs for the $W/C_D A = 134.5$ portion of the trajectory. However, when a size correction is made, it is seen that when the ballistic coefficient is reduced, the intensity of heating actually increases. The size correction used here is the square root of the ratio of projectile radii before and after the change in $W/C_D A$.

$$\left[\begin{array}{c} \text{SIZE} \\ \text{CORRECTION} \\ \text{(Figure 17)} \end{array} \right] = \sqrt{\frac{R_{\frac{W}{CA} = 165.5}}{R_{\frac{W}{CA} = 134.5}}} = \sqrt{\frac{4.415}{2.875}} = 1.239. \dots(\text{III-50})$$

A further indication of the fact that the heating intensity increases as the radius of the body decreases is shown in Figure 18. Two factors are combined to indicate the increased intensity, the "size correction factor,"

$$[S.C.F.] = \sqrt{\frac{R_o}{R}} \dots(\text{III-28})$$

and the F_b factor describing the distribution of heating over the end surface of the cylinder,

FIGURE 18

Φ VS. $\frac{r}{R_0}$

AERODYNAMIC HEATING
GEOMETRIC PARAMETER
VS. GRID PLATE
RADIUS

$$\Phi = \left\{ 1 + 0.6 \left(\frac{r}{\bar{R}} \right)^{3.3} \right\} \left(\sqrt{\frac{R_0}{\bar{R}}} \right)$$

$\frac{r}{\bar{R}}$ = POSITION ON END OF CYLINDER

$$F_b = \left[1.0 + 0.6 \left(\frac{x}{R} \right)^{3.3} \right] \quad \dots(\text{III-31})$$

Figure 18 shows how the heating at any point on the end of the cylinder (the grid plate) varies with R. The term, ϕ ,

$$\phi = \left[1.0 + 0.6 \left(\frac{x}{R} \right)^{3.3} \right] \sqrt{\frac{R_o}{R}} \quad \dots(\text{III-51})$$

is to be multiplied by the reference heating and other F factors to determined aerodynamic heat input. (See Tables V and VI, and Equations (III-26) to (III-45).)

In the thermal calculations carried out later in this report, a reference trajectory was assumed, based on $W/C_D A = 165.5$ and a release altitude of 250,000 feet.

In Table IX, the various trajectories calculated are listed.

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TABLE IX
TRAJECTORY COMPUTER RUNS

Computer Run No.	Initial Altitude	Ballistic Coefficient
	Alt _o (kft)	$\frac{W}{C_D A}$ $\frac{lbm}{ft^2}$
7604-47	400	100
7248-72	250	165.5
7323-01	a) 230 b) 240 c) 250	165.5
7323-31	a) 275 b) 300	165.5
7323-28	250	a) 165.5 b) 134.5 c) 88.8 d) 37.4
7323-30	224.919	134.5

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IV. THERMAL EFFECT OF FUEL ELEMENT PIN

("Single-Cell" Problem)

As discussed previously, the disintegration of the reactor core, and the separation of the fuel elements, are considered to be dependent on the melting of the reactor core grid plates, and so the transient temperature distribution in the grid plates are of primary interest. Of special concern is the heat sink effect of the fuel element pin and the fuel element behind it.

If the end surface of the fuel element is separated from the inside surface of the grid plate, there is relatively poor thermal linkage between the grid plate and fuel elements, except in the region where the fuel element pin is inserted into the grid plate. This can lead to lateral temperature gradients in the grid plate, with hot spots occurring in the regions farthest removed from the pin.

Of course, in the event that the grid plate and fuel element caps are in good thermal contact, this lateral temperature gradient would not be expected, and the overall grid plate temperature would be lower. This results because the heat sink represented by the fuel elements is more uniformly and readily accessible to heat deposited in the grid plate under these conditions.

In order to obtain an insight into the lateral temperature distribution effect due to the fuel element pins, a so-called "single-cell" thermal model was devised and studied. It consists of a thermal model of a single fuel element and the portion of the grid plate directly associated with it. Figure 19 indicates the portion of the reactor core which is considered in the "single cell" thermal model. Heat is input at the outer surface of the grid plate. No heat is considered to be transferred laterally into or out of the fuel element (as if this typical fuel element is near the center of the core), though lateral transfer within the element occurs.

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(This Sketch is
not to Scale)

FIGURE 19

PORTION OF REACTOR CORE
CONSIDERED IN
"SINGLE CELL" THERMAL MODEL

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FIGURE 21-a
"SINGLE CELL"
THERMAL MODEL
GEOMETRY

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NODE (2) = AMBIENT ($T_2 = 0^\circ R$)

NODE NUMBERS - CIRCLED

PATH NUMBERS - NOT CIRCLED

NODE NUMBERS:

LAST DIGIT = RING #

FIRST DIGITS = SLICE #

THERE ARE: 50 SURFACE NODES

63 VOLUME NODES

PATH NUMBERS:

CONDUCTIVE:

AXIAL: 1ST DIGIT, 3 or 4

2ND DIGIT, ADJACENT SLICE #

LAST DIGIT, RING #

RADIAL: 1ST DIGIT, 5 or 6

LAST DIGITS, ADJACENT NODE #

CONVECTIVE:

AXIAL: 1ST & 2ND DIGITS, 20 or 21

LAST DIGIT, RING #

RADIATIVE:

AXIAL: LAST DIGIT, RING #

PREFIX, 1 at outer Surface

25 in Grid Plate - Fuel Cap Gap

28 in H₂ Gap

THERE ARE: 143 CONDUCTIVE PATHS

27 RADIATIVE PATHS

17 CONVECTIVE PATHS

10 HEAT INPUT PATHS

FIGURE 21-b

"SINGLE CELL" PROBLEM
THERMAL MODEL

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The heat input load at the surface of the grid plate is arbitrarily chosen to be $1.0 \text{ Btu/sec in.}^2$ (144 Btu/sec ft^2), and is constant with time. It is not related to the aerodynamic heating functions discussed in Chapter III. Figure 20 shows how the assumed heat load for "single-cell" model compares with the actual heat load on the end of the cylindrical reactor core for various modes of reentry on the reference trajectory. The slight decrease of the heating load due to the "hot wall" correction factor is not taken into account in Figure 20.

The purpose of the computer calculation based on this thermal model is merely to investigate what magnitude of lateral temperature gradients might occur, and whether the effect should be considered when the thermal model of the entire core is being developed.

Figure 21-a indicates the assumed geometry on which the thermal model was based, and Figure 21-b shows the detail of the thermal model for the "single-cell" problem for use with the Thermal Analyzer Program (TAP-3E) computer code (see Reference 8). Thermal admittances, nodal capacitances, heat inputs, and other system parameters are shown in Figure 21-b and Appendix A.

Two different runs were made using this thermal model; (a) the grid plate separated from the fuel elements, with only radiation and convective heat transfer between the two surfaces except by conduction through the fuel element pin, and (b) the grid plate and fuel elements in perfect contact, in which case there is no lateral variation of geometry, thermal properties, temperature, or heat flow, which makes this essentially a one-dimensional problem. The results of the case in which the grid plate is separated from the fuel elements except for the fuel element pins (computer run 7323-18) are shown, in part, in Figures 22 and 23. Figures 22a and 22b show the temperature distribution at 12 and 14 seconds after the start. Notice the large lateral temperature gradient in the grid plate near the fuel element pin, with a temperature gradient through the thickness of the plate far away from the fuel element pin, the relatively high heat flux through the pin (indicated by the closeness

FIGURE 22a
TEMPERATURE DISTRIBUTION; "SINGLE CELL" PROBLEM
 $t = 12$ seconds $T = (^\circ\text{F})$

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FIGURE 22b

TEMPERATURE DISTRIBUTION; "SINGLE CELL" PROBLEM

$t = 14 \text{ seconds}$

$T = (^\circ\text{F})$

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of the isothermal lines), and the relatively small hinderance to heat flow offered by the hydrogen gap.

Figure 23 shows the temperature versus time plots for four different situations in the "single-cell" thermal model. Curves (a) and (b) represent the temperature versus time plots for nodes 20 and 29 from computer run 7323-18. These nodes are located at the mid-thickness of the grid plate, and represent the extremes of lateral position (near to, and at a distance from the fuel element pin; see Figure 21). Curve (c) shows the temperature of an equivalent point in the grid plate under the same thermal conditions, except that the grid plate and fuel element are in perfect thermal contact (computer run 7323-22). In curves (a), (b), and (c), radiation from the grid plate surface to space (at $T = -460^{\circ}\text{F}$) occurs with an emissivity, ϵ , of 0.333. Curves (a'), (b'), and (c') are for the same conditions as curves (a), (b), and (c), except that there is no radiation from the grid plate surface to space ($\epsilon = 0$), (computer runs 7323-02 and 7323-08).

It is pointed out once more that the temperature distributions indicated in Figures 22 and 23 are not directly applicable to the thermal problem of the reentering reactor core. This is because of the completely arbitrary heat input rate assumed. (A heat load of $Q = 1.0 \text{ Btu/in.}^2 \text{ sec} = 144 \text{ Btu/ft}^2 \text{ sec}$ was assumed here. During reentry, the aerodynamic heat input to the grid plate varies with time and position on the grid plate, as well as being partially dependent on the temperature of the grid plate surface.) Nevertheless, the results of the "single cell" problem (Figures 20 through 23) are indicative of the thermal responses that one might expect with the reentering reactor core. The sharp lateral temperature differences that occur in the grid plate are very important. This indicates that if the grid plate is kept separated from the fuel elements, hot regions can be expected to occur in the area of the grid plate corresponding to the edge of the fuel elements. Thus, the grid plate could break up, without the necessity of the entire plate being melted. Furthermore, one notes that if the grid plate is in good thermal contact with the

FIGURE 23
"SINGLE CELL" PROBLEM.
TEMPERATURE VS. TIME
(Temperature at mid-thickness
of Grid Plate)

Radiation to Ambient at -460°F
Initial Temperature 0°F

- a, a') Grid Plate non-contact
Away from Fuel Pin
- b, b') Grid Plate non-contact
Near Fuel Pin
- c, c') Grid Plate Contact
Representative Point

a, b, c $\epsilon = 1/3$

a', b', c' $\epsilon = 0$

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fuel elements, not only is the grid plate temperature more nearly uniform, but more importantly, it runs considerably cooler as the fuel elements are acting as a more effective heat sink.

Curves (a), (b), and (c) include the effect of thermal radiation from the grid plate surface to space with an emissivity of 0.333, while curves (a'), (b'), and (c') include no such radiative effect. Thus, Figure 23 gives some indication of the effect of surface emissivity on the thermal response of the grid plate to aerodynamic heating. The effect appears to be noticeable, but somewhat limited.

The thermal model discussed in the foregoing is concerned only with one fuel element and the portion of the grid plate associated with it. In the following section, a thermal model representative of the entire core (designated the "3-D core" thermal model) is developed and studied. The new thermal model has the important advantage of taking the entire core into consideration, but does not have the local detail of the "single cell" model discussed above. Thus, the results of the analysis reported in this section is of value in interpreting the results obtained from the "3-D core" model.

V. TEMPERATURE DISTRIBUTION IN REENTERING REACTOR CORE

("3-D Core" Thermal Model)

In order to investigate the transient temperature distribution in the reentering reactor core, a thermal model is developed to represent it. The nodal thermal model and the obtained results are presented here.

In the previous section, a thermal model was presented which took into account only one fuel element and the portion of the grid plate associated with it. The fuel element was assumed to be isolated from adjacent elements. The model was essentially two dimensional, (radial and axial). In this section, a thermal model is presented which shows

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considerably less local detail,* but which represents the entire core, and considers three dimensional variation (radial, angular, and axial).

A general end view of the reactor core is shown in Figure 2a. It is observed that symmetry allows the core to be represented by a 30° wedge. Accordingly, the thermal model represents a 30° wedge-shaped section of the core, as shown in Figure 24. Axial symmetry with respect to the mid-plane is also assumed, which entails the assumption that both end grid plates are identical. The core model is divided into five slices, as shown in Figure 24c. The upper layer represents the grid plate and this is shown schematically in Figure 24a. All the nodes and conductances in this plane are designated by one or two digit numbers, (the 0xx series). The second layer is shown in Figure 24b. It represents the fuel element cap and the corresponding layer of the beryllium reflector. The nodes and conductances in this plane are designated by three digit numbers with 1 the initial digit (the 1xx series). The next three layers represent thicknesses of fuel material and beryllium, and are designated the 2xx, 3xx, and 4xx series. Figure 24b also describes these layers, except the node and conductance numbers are changed to correspond to the layer number. Axial conductances are designated the 5xx, 7xx, and 8xx series, radiation to the ambient is the 9xx series, and aerodynamic heat input is the 6xx series, as shown in Figure 24c. Numerical values of the model structure system parameters are given in Appendix B.

In order to employ the "3-D core" thermal model discussed above, an assumption must be made with respect to the aerodynamic heating to which the core is to be (mathematically) exposed. The thermal calculations made are based on the reentry trajectory having a ballistic coefficient of

*A comparison of the "single cell" thermal model (Figure 21) and the "3-D Core" thermal model (Figure 24) indicates this. For example, the portion of the grid plate represented by a single node (e.g., node 6) in Figure 24a, is represented by twenty-one nodes in Figure 21 (surface nodes 10 through 16 and 30 through 36, and volume nodes 20 through 26).

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FIGURE 24a

"3-D CORE" NODAL THERMAL MODEL
(30° Wedge)

VIEW OF GRID PLATE

NODE NUMBERS - CIRCLED
PATH NUMBERS - NOT CIRCLED

AMBIENT = NODE 99
 $T_{99} = -460^{\circ}\text{F}$
HEAT INPUT FROM NODE 100

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FIGURE 24b
 "3-D CORE" NODAL THERMAL MODEL
 (30° Wedge)

FUEL ELEMENT CAPS & UPPER LAYER
 OF BERYLLIUM REFLECTORS.

(SUCCEEDING LAYERS OF FUEL HAVE A
 SIMILAR NODAL LAYOUT, EXCEPT
 NODE AND ADMITTANCE DESIGNATIONS
 ARE IN THE 200's, 300's, & 400's.)

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o Ambient = Node 99

FIGURE 24c

"3-D CORE" NODAL THERMAL MODEL

"SIDE - VIEW"

SHOWS NODE & THERMAL PATH
NUMBERING SYSTEM.

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165.5, and an initial altitude of 250,000 feet.* This trajectory was discussed earlier, and some data regarding it are given in Figures 11 through 17 and Tables VII, VIII, and IX. This information is for a reactor core tumbling randomly. Based on this trajectory, a table of stagnation temperatures and reference heating factors (Table X) has been compiled for use in the calculation of aerodynamic heat input by means of Equation (III-46),

$$Q_N \left(\frac{\text{BTU}}{\text{sec}} \right) = \left\{ \left(\frac{q_{\text{Ref}}}{T_s - 540^\circ \text{R}} \right) \left(\sqrt{\frac{R_o}{R}} A_N \mathcal{F} \right) \right\} (T_s - T_N) \quad \dots (\text{III-46a})$$

Tables of stagnation temperature, T_s , and the reference heating factor, $q_{\text{Ref}}/(T_s - 540)$, as a function of time is included in the TAP-3E code input data. This means, of course, that the computer code is set up for the random tumbling reentry, so that it could not rigorously be employed for end-on or side-on reentry trajectory cases. However, Table IV indicates that the drag coefficient, and hence the ballistic coefficient for the core varies only slightly with the various flight orientations (except for the side-on case).

From Table IV:

Orientation	C_D	$W/C_D A$
End-On	2.0	163.9
Side-On	2.515	130.4
End-Over-End	1.916	171.1
Random Tumbling	1.981	165.5

*The starting conditions of the trajectory at 250,000 feet altitude are based on a prior base trajectory starting at 400,000 feet with a $W/C_D A = 100$.

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TABLE X
REFERENCE HEATING AND STAGNATION TEMPERATURE

DATA FOR REFERENCE TRAJECTORY

$Alt_0 = 250,000 \text{ ft}$ $W/C_D A = 165.5$

Reactor Core, Random Tumbling

t sec	H_s $\frac{\text{Btu}}{\text{lbm}}$	q_{Ref} $\frac{\text{Btu}}{\text{ft}^2 \text{ sec}}$	q_{Ref}	T_s
			$T_s - T_{540}$ $\frac{\text{Btu}}{\text{ft}^2 \text{ } ^\circ\text{F sec}}$	$\frac{H_s}{C_p} - 460$ $^\circ\text{F}$
0	12,616	84.87	.00170	50,004
10	12,576	90.18	.00181	49,844
20	12,529	96.16	.00194	49,656
30	12,475	102.88	.00208	49,440
40	12,412	110.04	.00224	49,188
50	12,339	118.02	.00242	48,896
60	12,253	126.88	.00262	48,549
70	12,151	136.34	.00283	48,144
80	12,031	146.94	.00308	47,664
90	11,888	158.12	.00336	47,092
100	11,717	170.47	.00368	46,408
110	11,512	183.51	.00403	45,588
120	11,265	197.77	.00444	44,600
130	10,962	213.45	.00493	43,388
140	10,591	229.41	.00549	41,904
150	10,135	244.92	.00612	40,080

Values for $t > 150 \text{ sec}$
are available from
Runs: 7323-01c
7323-28a
7248-72

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Accordingly, the simplifying approximation was made that random tumbling stagnation temperature and reference heating also applied for the trajectories with a different flight orientation, but same initial altitude. However, in each case, the $\bar{F}$ factors (see Tables V and VI) were determined on the basis of the particular flight orientation involved (end-on, side-on, or random tumbling). The $\bar{F}$ factors used to determine the aerodynamic heat input to each node in the various flight orientations are tabulated in Appendix C.

In any event, the approximation of using T_s and q_{Ref} data from the random tumbling trajectory is not a crucial one. Most of the calculations made and reported are for random tumbling.

As indicated in Appendix B and the foregoing discussion, the "3-D core" thermal model allows the option of specifying whether the grid plate is separated from, or in perfect thermal contact with the fuel elements. When the grid plate is assumed to be separated from the fuel elements, heat transfer between the two surfaces is by radiation and convection, except for the heat conducted through the fuel element pins. When the grid plate and fuel are in contact, heat transfer is by conduction over the entire area of the fuel element cap.

The thermal model has no provision included in it to take into account the latent heat of fusion of the stainless steel, though the TAP-3E code allows this to be included if desired. Rather, for simplicity, it is assumed that the melting temperature of stainless steel is 2600°F, and that a temperature rise of approximately an additional 100°F is considered to be equivalent to the additional heat required to bring about a sufficient degree of melting to destroy the structural strength of the stainless steel alloy.

In all, six different runs were made using the "3-D core" thermal model and the TAP-3E code, (see Reference 8). These are listed in Table XI. The results of these computer runs are on printout sheets and are quite voluminous, and so are not included in this report. They are

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TABLE XI
"3-D Core" Thermal Model Computer Runs

Case	Computer Run No.	Grid Plate and Fuel Elements	Flight Configuration
a)	7323-26	Non-Contact*	Random Tumbling
b)	7323-27	Contact**	Random Tumbling
c)	7323-19	Non-Contact	End-on
d)	7323-23	Contact	End-on
e)	7323-25	Non-Contact	Side-on
f)	7323-24	Contact	Side-on

Trajectory based on $W/C_D A = 165.5$, $Alt_0 = 250,000$ feet.

*Non-Contact: Grid plate and fuel element caps are separated, except for the fuel element pin.

**Contact: Grid plate and fuel element caps are in perfect thermal contact.

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available, if needed, from the author. However, a graphical summary of the results are presented here.

Figure 25 shows a 30° wedge portion of the grid plate, with nodal numbers indicated. Circles drawn in lightly dashed lines indicate the position of the fuel elements beneath the plate. A heavy double dashed line is indicated which is assumed to constitute a reasonably typical radial path temperature traverse or temperature profile line of the grid plate. (This line connects nodes 1, 22, 2, 42, 3, 62, 5, and 9 as it goes from the center of the grid plate to the periphery.) It traverses points on the grid plate corresponding to the center and outer edges of the fuel elements, and should thus include the local minimum and maximum temperatures existing in the grid plate at any particular time. Nodes 1, 2, 3, and 5 represent points near the fuel element pins, and nodes 22, 42, 62, and 9 represent points near the edge of the fuel elements.

In Figures 26a through 26f, temperature profiles as a function of time are shown for the six cases of Table XI. The initial temperature of the system is assumed to be 0°F. The radiation heat transfer from the surface is to the space environment (-460°F). A number of interesting qualitative observations can be made from these plots. The cases in which the grid plate is separated from the fuel elements show a much more rapid temperature rise than when the grid plate is in contact with the fuel. Even the low points in the temperature profile in the "non-contact" cases rise more rapidly than in the "contact" cases, (e.g., compare the temperature versus time performance of nodes 1, 2, 3, and 5 in Figures 26a and 26b, Figures 26c and 26d, or Figures 26e and 26f).

From the temperature profile plots of Figure 26 and altitude-time curve of Figure 13, one can estimate the time and altitude drop required to release the first two rings of fuel elements. Referring to Figure 25, let it be assumed that when node 62 indicates a temperature of about 2700°F, the beryllium reflector and the outer ring of fuel elements are released. Assume, further, that when node 42 indicates $T \cong 2700^\circ\text{F}$, that the second ring of fuel elements is released. From Figures 26a through 26f, the time

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FIGURE 25

TEMPERATURE PROFILE LINE ON
GRID PLATE

Double Dashed Line Indicates
Line Along Which Temperature
Profiles of Figure 26 are Shown.

Outline of Fuel Elements and
Reflector Behind Grid Plate.

TEMPERATURE
PROFILE
LINE

CLASSIFICATION	RD / DI
SIGNATURE	DATE
AUTHORIZED CLASSIFIER

FIGURE 26 a

TRANSIENT TEMPERATURE PROFILE
(On Grid Plate Along Line of Figure 25)

Run 7323 - 26

Random Tumbling
Grid Plate Apart

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McLain
McLain
 FD / PI
4/16/66

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FIGURE 26 b

TRANSIENT TEMPERATURE PROFILE
 (On Grid Plate Along Line of Figure 25)
 Run 7323 - 27

Random Tumbling
 Grid Plate Contact

FIGURE 26 c

TRANSIENT TEMPERATURE PROFILE
(On Grid Plate Along Line of Figure 25)

Run 7323 - 19

End - on
Grid Plate Apart

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FIGURE 26 d

TRANSIENT TEMPERATURE PROFILE
(On Grid Plate Along Line of Figure 25)

Run 7323 - 23

End - on
Grid Plate Contact

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FIGURE 26 e

TRANSIENT TEMPERATURE PROFILE
(On Grid Plate Along Line of Figure 25)

Run 7323 - 25

Side - on
Grid Plate Apart

Name: *W. L. ...*
 Classification: *Secret*
 Date: *3/1/66*
 RD / DI

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FIGURE 26 f

TRANSIENT TEMPERATURE PROFILE
(On Grid Plate Along Line of Figure 25)

Run 7323 - 24

Side - on
Grid Plate Contact

CLASSIFICATION	SECRET
DATE	3/18/66
SIGNATURE	<i>[Signature]</i>

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at which each ring of fuel elements is released is estimated, and the corresponding altitude is determined from Figure 13. These results are shown in Tables XII-a, XII-b, XII-c, and Figure 27.

Table XII-a lists the time, altitude, and altitude drop required for the release of the first and second rings of fuel elements according to the criteria set up above, and the curves of Figure 26. In Tables XII-b and XII-c, the difference in time and altitude drop (shown in seconds, kilofeet, and percentage) between the release of the first and second rings of fuel elements is shown, as well as the difference in release time and altitude between the grid plate-fuel element contact and non-contact cases. Figure 27 shows the data of Table XII in graphical form.

Several things are made evident from Table XII and Figure 27. Once the grid plate has melted sufficiently to release the first ring of fuel elements, it takes a relatively small amount of additional time to release the second ring, (according to Tables XII-b and XII-c, the additional time is approximately 20%, which is roughly equivalent to a 30% additional altitude drop). On the other hand, whether or not the grid plate is in thermal contact with the fuel elements makes a considerable difference in the time required to release the fuel elements; approximately an additional sixty seconds, which means more than double the altitude drop in the random tumbling flight orientation, (Cases a and b of Table XII).

At this point, a particular feature of the reentry trajectory should be given particular attention. As the projectile is reentering, it is decelerating due to aerodynamic drag; that is, its velocity is decreasing. However, the vertical component of its velocity is actually increasing, so that it is losing altitude at an increasing rate. This can be noted from the altitude versus time curve for the reference trajectory shown in Figure 13. Thus it may be seen, for instance, that an additional 20% time in the reentry trajectory can mean an additional 30% in altitude drop.

The limitations of the data of Tables XII and Figures 26 and 27 should be borne in mind. The stagnation temperature and reference heating

FIGURE 27

TIME & ALTITUDE DROP FOR
FUEL ELEMENT RELEASE

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TABLE XII-a

TIME AND ALTITUDE OF FUEL ELEMENT RELEASE
(For Reference Trajectory)

Case	Configuration* Orientation**	Time (1) Release of Outer Ring $T_{62} \cong 2700^\circ\text{F}$ (sec)	Altitude kft	Altitude Drop kft	Time (2) Release Of 2nd Ring $T_{42} \cong 2700^\circ\text{F}$ (sec)	Altitude kft	Altitude Drop kft
a	$\frac{\text{NC}}{\text{RT}}$	70	224.9	25.1	84	217.5	32.5
b	$\frac{\text{C}}{\text{RT}}$	135	188.9	61.1	165	165.8	84.2
c	$\frac{\text{NC}}{\text{EO}}$	28	241.3	8.7	34	239.1	10.9
d	$\frac{\text{C}}{\text{EO}}$	90	215.5	34.5	105	207.6	42.4
e	$\frac{\text{NC}}{\text{SO}}$	140	185.5	64.5	156	173.3	76.7
f	$\frac{\text{C}}{\text{SO}}$	190	142.0	108.0	225	103.2	146.8

*NC = Non-Contact

C = Contact

**RT = Random Tumbling

EO = End-On

SO = Side-On

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TABLE XII-b

Difference in Time for Fuel Element Release

Difference in time for release of the first and second ring of fuel elements.
Percentage differences are based on the shorter of the two times involved.

Case	Configuration* Orientation**	Time 1 sec	Difference (sec/%)	Time 2 sec
a	NC RT	70 ↑ ($\frac{65 \text{ sec}}{93\%$)	← ($\frac{14 \text{ sec}}{20\%$) →	84 ↑ ($\frac{81 \text{ sec}}{96\%$)
b	C RT	135 ↓ ($\frac{65 \text{ sec}}{93\%$)	← ($\frac{30 \text{ sec}}{22\%$) →	165 ↓ ($\frac{81 \text{ sec}}{96\%$)
c	NC EO	28 ↑ ($\frac{62 \text{ sec}}{220\%$)	← ($\frac{6 \text{ sec}}{21\%$) →	34 ↑ ($\frac{71 \text{ sec}}{210\%$)
d	C EO	90 ↓ ($\frac{62 \text{ sec}}{220\%$)	← ($\frac{15 \text{ sec}}{17\%$) →	105 ↓ ($\frac{71 \text{ sec}}{210\%$)
e	NC SO	140 ↑ ($\frac{50 \text{ sec}}{36\%$)	← ($\frac{16 \text{ sec}}{11\%$) →	156 ↑ ($\frac{69 \text{ sec}}{44\%$)
f	C SO	190 ↓ ($\frac{50 \text{ sec}}{36\%$)	← ($\frac{35 \text{ sec}}{18\%$) →	225 ↓ ($\frac{69 \text{ sec}}{44\%$)

*NC = Non-Contact C = Contact
**RT = Random Tumbling EO = End-On SO = Side-On

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TABLE XII-c

Difference in Altitude Drop for Fuel Element Release

Difference in altitude drop for release of the first and second ring of fuel elements.

Percentage differences are based on the shorter of the two distances involved.

Case	Configuration* Orientation**	Altitude Drop 1	Difference	Altitude Drop 2
		kft	$\frac{\text{kft}}{\%}$	kft
a	$\frac{\text{NC}}{\text{RT}}$	25.1	$\left(\frac{7.4 \text{ kft}}{30\%} \right)$	32.5
		$\uparrow$ $\left(\frac{36.0 \text{ kft}}{143\%} \right)$		$\uparrow$ $\left(\frac{51.7 \text{ kft}}{159\%} \right)$
b	$\frac{\text{C}}{\text{RT}}$	61.1	$\left(\frac{23.1 \text{ kft}}{38\%} \right)$	84.2
c	$\frac{\text{NC}}{\text{EO}}$	8.7	$\left(\frac{2.2 \text{ kft}}{25\%} \right)$	10.9
		$\uparrow$ $\left(\frac{25.8 \text{ kft}}{310\%} \right)$		$\uparrow$ $\left(\frac{31.5 \text{ kft}}{290\%} \right)$
d	$\frac{\text{C}}{\text{EO}}$	34.5	$\left(\frac{6.9 \text{ kft}}{20\%} \right)$	42.4
e	$\frac{\text{NC}}{\text{SO}}$	64.5	$\left(\frac{12.2 \text{ kft}}{19\%} \right)$	76.7
		$\uparrow$ $\left(\frac{43.5 \text{ kft}}{68\%} \right)$		$\uparrow$ $\left(\frac{70.1 \text{ kft}}{91\%} \right)$
f	$\frac{\text{C}}{\text{SO}}$	108.0	$\left(\frac{38.8 \text{ kft}}{36\%} \right)$	146.8

*NC = Non-Contact
**RT = Random Tumbling

C = Contact
EO = End-On

SO = Side-On

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data on which the calculations were based are for a random tumbling trajectory. Comparing the ballistic coefficients of the different flight orientations (see Table IV), end-on reentry differs little from random tumbling ($W/C_D A_{\text{Ran Tum}} = 165.5$, $W/C_D A_{\text{end-on}} = 163.9$), but side-on reentry shows a considerable discrepancy ($W/C_D A_{\text{side-on}} = 130.4$). The lower ballistic coefficient of side-on reentry indicates that, in fact, aerodynamic heating would be higher in the initial phase, and release time (though not necessarily altitude drop) would be less than indicated in Table XII. Table XII-a indicates that with end-on reentry, the grid plate is melted away in a relatively short time. However, this is misleading because it is based on the temperature distribution in the forward grid plate, which would receive a far greater aerodynamic heating load than the trailing edge grid plate.

Of the three flight orientations considered (random tumbling, end-on, and side-on), the random tumbling is probably more nearly representative of circumstances as they actually would occur. End-on or side-on reentry seem to be special orientations and somewhat unlikely.

The transient temperature distribution in the grid plate for the case of random tumbling and grid plate "non-contact" (Case a of Tables XI and XII) is shown in considerably more detail in Figures 28a through 28h. The temperature distribution in the form of "contour maps" at 12 second intervals are shown. By observing the successive diagrams, the buildup of the temperature pattern can be seen. Notice particularly how the temperature rises most rapidly in the regions along the lines between the NaK flow holes in the grid plate. These are the regions corresponding to the outer edges of the fuel elements (see Figures 25 and 28i). One might expect that the grid plate will break up along these lines. The low temperature areas in the vicinity of the fuel elements pins can be seen. It can also be seen that the temperature rises more rapidly at the periphery of the grid plate than toward the center. This is a result of the fact that the aerodynamic heat input to the end of a cylinder is greater near the edge. This is accounted for by the factor F_b of Table V and Equation III-31,

FIGURE 28-a TEMPERATURE DISTRIBUTION IN GRID PLATE

ALT₀ = 250,000 ft.

$$\frac{W}{C_b A} = 165.5$$

RUN 7323-26

$t = 12$ SECONDS

Alt = 246.4 k.ft.

RANDOM TUMBLING
GRID PLATE NOT IN CONTACT
WITH FUEL ELEMENTS

FIGURE 28-b

TEMPERATURE DISTRIBUTION IN GRID PLATE

ALT_o = 250,000 ft.

$$\frac{W}{C_A} = 165.5$$

RUN 7323-26

$t = 24$ SECONDS

Alt = 242.6 K.ft.

RANDOM TUMBLING
GRID PLATE NOT IN CONTACT
WITH FUEL ELEMENTS

FIGURE 28 - c

TEMPERATURE DISTRIBUTION IN GRID PLATE

$ALT_0 = 250,000 \text{ ft.}$

$$\frac{W}{C_b A} = 165.5$$

RUN 7323-26

$t = 36 \text{ SECONDS}$

$Alt = 238.4 \text{ K.ft.}$

RANDOM TUMBLING
GRID PLATE NOT IN CONTACT
WITH FUEL ELEMENTS

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FIGURE 28- d

TEMPERATURE DISTRIBUTION IN GRID PLATE

$$ALT_0 = 250,000 \text{ ft.}$$

$$\frac{W}{C_A} = 165.5$$

RUN 7323-26

$$t = 48 \text{ SECONDS}$$

$$Alt = 234.0 \text{ K.ft.}$$

RANDOM TUMBLING
GRID PLATE NOT IN CONTACT
WITH FUEL ELEMENTS

FIGURE 28- e

TEMPERATURE DISTRIBUTION IN GRID PLATE

ALT₀ = 250,000 ft.

$$\frac{W}{C_A} = 165.5$$

RUN 7323-26

$t = 60$ SECONDS

Alt = 229.2 K.ft.

RANDOM TUMBLING
GRID PLATE NOT IN CONTACT
WITH FUEL ELEMENTS

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FIGURE 28-f

TEMPERATURE DISTRIBUTION IN GRID PLATE

ALT₀ = 250,000 ft.

$$\frac{W}{C_A} = 165.5$$

RUN 7323-26

$t = 72$ SECONDS

Alt = 224.0 K.ft.

RANDOM TUMBLING
GRID PLATE NOT IN CONTACT
WITH FUEL ELEMENTS

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FIGURE 28-9 TEMPERATURE DISTRIBUTION IN GRID PLATE

$ALT_0 = 250,000 \text{ ft.}$

$\frac{W}{C_p A} = 165.5$

RUN 7323-26

$t = 84 \text{ SECONDS}$

$Alt = 218.4 \text{ K.ft.}$

RANDOM TUMBLING
GRID PLATE NOT IN CONTACT
WITH FUEL ELEMENTS

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FIGURE 28-h

TEMPERATURE DISTRIBUTION IN GRID PLATE

$$ALT_0 = 250,000 \text{ ft.}$$

$$\frac{W}{C_p A} = 165.5$$

RUN 7323-26

$$t = 96 \text{ SECONDS}$$

$$Alt = 213.4 \text{ K.ft.}$$

RANDOM TUMBLING
GRID PLATE NOT IN CONTACT
WITH FUEL ELEMENTS

FIGURE 28-i
TEMPERATURE DISTRIBUTION
IN GRID PLATE

LOCATION OF FUEL ELEMENTS
BEHIND GRID PLATE

$$F_b = \frac{\text{Local heat, cylinder end, } \alpha=0}{\text{Stag. Pt. heat, cylinder end, } \alpha=0} = \frac{q_{L \alpha=0}^{\text{end}}}{q_{SP}} = \left[1.0 + 0.6 \left(\frac{x}{R} \right)^{3.3} \right],$$

...(III-31)

from which it can be seen that the heat input rate at the periphery of the grid plate, ($x = R$), is 60% higher than at the center, ($x = 0$). In Figures 26a through 26f, it can be noted that the temperature rise near the periphery is roughly 1.6 times that at the center, discounting the local "heat sink" effects of the fuel element pins.

VI. DISCUSSION AND RECOMMENDATIONS

A. Assumptions

The assumptions made concerning the behavior of the reactor core system, and the thermal model representing it, have been indicated in the body of this report. However, so that one can realistically evaluate the results of the calculations, these assumptions and their significance are discussed here.

The primary assumption concerns the mode of reactor disintegration and fuel element separation. It is envisioned that because of fuel element swelling or warping, the grid plates may not be able to freely fall off the fuel element pins as soon as the reactor core is released from the containment vessel. In this event, it would be necessary for the grid plates to melt to a sufficient extent to free the fuel element pins. This is the mode of reactor disintegration that has been assumed and investigated.

The reactor core geometry on which the calculations of this report are based is shown in Figures 1, 2, 3, and 4, and Table I. Trajectory calculations and aerodynamic reference heating data are obtained from the

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RESTORE reentry trajectory code, (see References 6 and 7). For simplicity, constant thermal properties (invariant with temperature) were assumed, as indicated in Table II. The initial temperature of the reactor core (at the moment of release from the reactor vessel) is taken as 0°F , even though it is probable that the reactor core may be at a slightly higher temperature because of heat absorbed during the reactor vessel meltdown phase. It is further assumed that heat is rejected from the reactor vessel by thermal radiation to the effective temperature of outer space, -460°F .

The geometric symmetry of the reactor core was noted and taken into account in devising the thermal model. The hypothesis of length-wise symmetry requires the assumption that the upper and lower grid plates have identical thermal characteristics. This allowed use of a thermal model which considered only one end of the core. Furthermore, the radial and angular symmetry allowed the circular end of the cylindrical core to be represented by a 30° wedge, (see Figure 2a).

The distribution of aerodynamic heating input on the reactor core surface was based on the heating factor tabulated in Tables V and VI (see References 4 and 5). The reference trajectory (on which the aerodynamic heating calculations were based) is for a randomly tumbling reentering reactor core ($W/C_D A = 165.5$), with an initial release altitude of 250,000 feet. Several other trajectories were also considered to determine the effect of varying initial trajectory conditions. The RESTORE computer code was employed to make the trajectory calculations. The initial conditions for this reference trajectory were determined for a projectile descending from a polar orbit flight path, with an initial altitude of 400,000 feet and $W/C_D A = 100$. The assumption was made that the aerodynamic heating factors, $\mathcal{F}$, (see Tables V and VI) were constant with time, and were at the mean value for the particular flight orientation in question. (This is not to say that the heat input at each point is constant, but merely the distribution of the heat load. See Equation III-46 and Tables V and VI for the significance of the $\mathcal{F}$ factor.)

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There is evidence to indicate that these heating factors may be variables, (with air density, for example), but for the range in air densities in question, they hold reasonably constant.

In the "3-D core" thermal model, the temperature gradient through the thickness of the grid plate (axial direction) is not determined since each node of the grid plate layer is the thickness of the plate. The "single-cell" thermal model shows considerably more detail in the vicinity of the grid plate and gives an indication of this axial temperature gradient.

In the thermal models considered, no heat transfer barrier is assumed to exist between the surface of the fuel element pin and the inner surface of the pin hole in the grid plate. A thermal barrier here would result in the grid plate heating up somewhat more rapidly, since the heat transfer into the fuel element would be impeded.

B. Discussion

The reactor disintegration model considered in this report is predicted on the occurrence of a series of idealized (though not necessarily desired) events. These are: (1) following the release of the reactor-core from the containment vessel, the grid plates bind and are not free to fall off, (2) aerodynamic heating raises the temperature of the grid plates until the outer edge reaches the melting temperature, (3) the grid plate melting is assumed to occur symmetrically so that as the melting front of the grid plate moves toward the interior, all the fuel elements in the outer ring are released and fall away simultaneously, and, (4) later, the next ring of fuel elements are released simultaneously, etc.

This simplified model was assumed in order to have a basis for quantitative determinations of temperatures, release times, and other parameters of interest. However, one must remember that this represents only a preliminary, first phase approach to the analytical description of the fuel element separation which must be refined. It is necessary to keep in mind the many possible modes of behavior of the reentering core.

It is possible, of course, that when the reactor core is released, the fit of the grid plates on the fuel element pins may be loose enough so that the tumbling of the core would be sufficient to throw them off, and the fuel elements would all be released immediately. It would be most desirable if this were to happen, but one cannot be certain about it occurring. Swelling or warping of the fuel elements or grid plates may bind the core together. However, it is a further possibility that when partial melting of the grid plate has occurred, the fuel elements that were causing the binding may be released, and the remaining portions of the grid plates may fall off immediately. Further, the temperature differences occurring during the reentry heating may cause differential thermal stresses and strains which could either alleviate or make more severe the forces holding together the components of the core. The effect of this phenomenon is also unpredictable.

The grid plates are composed of stainless steel. As an alloy, it has some melting characteristics which are different from those of the pure constituents. In the first place, it does not have a definite melting temperature as a pure element or compound might (e.g., pure iron or ice). It melts over a certain temperature range, as indicated on a phase diagram for the particular alloy. In this report, the melting temperature of the stainless steel of the grid plate has been assumed to be 2600°F, which approximates the melting range of SS 316.

When the "melting temperature" of an alloy is reached, melting starts in the grain boundaries, since the lower melting constituents tend to collect there. The result is that an alloy will lose all strength much more quickly than a pure substance when melting starts, because it tends to break up along the grain boundaries. This would indicate that, in order to destroy a portion of the grid plate, it may not be necessary to supply the entire "latent heat" to melt it away, but merely a relatively small amount of heat to initiate the melting at the grain boundaries.

On the other hand, the above description of melting and the phase diagram of an alloy system is based on considering the specimen as being at an equilibrium temperature. In reality, during reentry, core tem-

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peratures are not at equilibrium. The grid plate may have a temperature gradient through its thickness such that the outer surface is actually melting while the interior may still be somewhat below the "melting temperature." In this event, the outer surface would have no structural strength but may still be absorbing heat, while the somewhat cooler interior retains sufficient mechanical strength to hold the fuel elements together while being partially shielded from direct aerodynamic heating by the outer molten layer. The result would be that a somewhat greater quantity of heat (hence, time) might be required for the destruction of the grid plates and release of the fuel elements.

When the stainless steel is in a heated and weakened condition, portions of the grid plate may just break off or be torn off by aerodynamic shear stresses, or bearing stresses of the fuel element pin on the grid plate hole.

The aerodynamic heating calculations presented in this report are, for the most part, based on a reentry trajectory for a reactor tumbling randomly which is probably the most reasonable flight orientation to expect. However, it is at least possible that a less desirable orientation might occur, (with regard to delivering heat to the reactor core grid plates). Such an orientation is the side-on and spinning, but this seems to be an unlikely reentry mode for the reactor core.

The effect on aerodynamic drag and heating of the grid plate NaK flow holes and the longitudinal spaces between the fuel elements has not been considered in this report. The partial "porosity" of the reactor core probably acts to slightly decrease the drag coefficient, C_D , with a resulting increase in the ballistic coefficient, $W/C_D A$, and an increase in the reference heating, q_{Ref} . Since the outer dimensions of the core are unchanged, the "size correction factor," $\sqrt{\frac{R_o}{R}}$, would not cancel out the increase in reference heating in the manner shown in Figure 15 and 16 for the changing radius situation. In any event, the additional aerodynamic heating that could be claimed because of this is slight.

A discontinuity on the surface of a reentering body generally results in an increase in the intensity of the local aerodynamic heating. The NaK flow holes in the grid plates are such discontinuities, and this could indicate that local heating in the vicinity of the edges of these holes may be greater than assumed (by the heating factors of Tables V and VI). Thus, the local "hot spot" effect already noted in the vicinity of the flow holes might actually be somewhat intensified.

For the sake of simplicity, it is assumed that all the fuel elements in a particular ring are released simultaneously, such that symmetry is maintained. In reality, the individual fuel elements may come off at different times.

As the reactor grid plates are melting, most of the molten steel will be swept away by the flow stream. However, it is possible that some of it may flow down between the fuel elements. There, since the fuel elements are at a temperature well below the melting point of the steel, the molten steel may solidify, and "weld" the fuel elements together. Whether this would happen, and to what extent it could happen, is not predictable analytically, but an experimental study may provide the insight needed to evaluate this event.

C. Conclusions and Recommendations

It is possible that the reactor core grid plates might freely fall away and release the individual fuel elements when the core is ejected from the containment vessel. However, due to warping or fuel element swelling, the grid plates could bind on the fuel element pins and separation may not readily occur. Reactor core disintegration and fuel element separation can be brought about by melting away the grid plates at the ends of the core by aerodynamic heating. The analytical investigation presented in this report indicates that if the grid plate is in good contact with the end surfaces of the fuel elements, the temperatures of the plate rises much more slowly than if the surfaces were apart, as the fuel

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elements act as a "heat sink". This "heat sink" effect of the fuel elements can be considerable, as indicated by the analysis, (see Figures 26).

If the grid plate and fuel elements are not in good thermal contact, the fuel element pins cause a local "heat-sink" effect; that is, the region of the grid plate surrounding the pin runs at a lower temperature than the rest of the plate. The result could be that the grid plate will break apart along lines roughly corresponding to the outer boundaries of the fuel elements (see Figures 26 and 28).

These results suggest that steps be taken to assure that the grid plate and fuel elements always remain separated. This can be done by notching the fuel element pin and the grid plate hole in such a way as to maintain a small gap. One may even go so far as to place a thin layer of insulation between the grid plate and fuel elements.

Of the aerodynamic heat deposited in the grid plate, the more that can be retained in the plate, the more rapidly its temperature will rise, and the sooner melting will commence. In the same regard, applying a low emissivity coating to the outer surface of the grid plate will reduce the quantity of heat lost by radiation to space. Of course, the retention of a low emissivity coating on grid plates exposed to NaK flow for a period of one year may be difficult, and as indicated by Figure 23, the thermal advantage may be slight.

The upper grid plate has a thickness of 1/8 inch. If this entire thickness is not necessary for structural strength, then it might be reduced to facilitate its meltdown by aerodynamic heating. If fabricating a plate of varying thickness would not be excessively difficult, the plate might be made thinner in regions where its strength would not be significantly reduced, but where meltdown might be enhanced. That is, the plate might be made thinner near the NaK flow holes, where the melting leading to grid plate break up is expected to occur. The outer edge of the grid plate might be made thinner so that the melting front from the periphery may move inward more rapidly. This might be permissible if stress analysis indicates that the outer edges of the plate are subjected to less bending moment resulting from the fuel element load.

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Insulating the fuel element pin from the circumference of the grid plate hole would impede the flow of heat from the grid plate into the fuel element, though such an arrangement may be difficult to make.

Of course, the obvious basic principles to bear in mind are:

(1) the less heat required to melt the grid plate, the more rapidly disintegration can occur, and (2) the higher the fraction of the heat deposited in the grid plate which is retained in the plate, the earlier the melting can occur.

The many uncertainties involved in the analysis presented in this report indicate that experimental investigation may be needed. A mockup of the reactor core might be placed in an "arc-jet" gas flow stream (arc-heated wind tunnel) and rotated end over end. Analytical calculations by means of the thermal models discussed in this report could be performed for the particular conditions of the experiment. Comparison of analytical and experimental results would give an indication of the validity of the thermal model and the aerodynamic heat distribution factors, would show whether the "welding" together of the fuel elements by the molten grid plate material might occur and, of course, would give further insight into the nature of the phenomena acting during the reactor disintegration phase of reentry.

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APPENDIX A

"Single-Cell" Thermal Model

The "single-cell" thermal model is presented and discussed in Chapter IV, and the nodal network is shown in Figure 21. The values of the various system parameters are tabulated in the following pages by means of a listing of the network input cards for the TAP-3E code of computer run 7323-18. The details involved in the calculation of these input parameters are not included, but are available from the author.

ALL NEW INPUT DATA FOR THIS RUN

* 4	-0	-0	-0.	-0.	-0	-0	-0	-0	00000040	
				SINGLE FUEL CELL PROBLEM					100	
				AIR GAP CONDUCTANCE = FINITE					200	
				INITIAL TEMP = 0 DEG F					00000300	
				Q = 1.0 BTU/SEC SQ IN					00000400	
* 10	-0	-0	-0.	-0.	-0	-0	-0	-0	00100000	
				NETWORK DESCRIPTION						
Y 10	Y 19	-0	-0.	-0.	10	2	1	0	RAD PATHS TO AMB	00100100
Y203	-0	-0	0.942000E-06	-0.	33	53	-0	-0	CONDUCTIVE PATHS	00102030
Y204	-0	-0	0.154600E-05	-0.	34	54	-0	-0	BTU / SEC DEG F	00102040
Y205	-0	-0	0.237600E-05	-0.	35	55	-0	-0		00102050
Y206	-0	-0	0.299000E-05	-0.	36	56	-0	-0		00102060
Y207	-0	-0	0.417000E-05	-0.	37	57	-0	-0		00102070
Y208	-0	-0	0.498000E-05	-0.	38	58	-0	-0		00102080
Y209	-0	-0	0.656000E-05	-0.	39	59	-0	-0		00102090
Y210	-0	-0	0.900000E-05	-0.	70	80	-0	-0		00102100
Y211	-0	-0	0.786000E-04	-0.	71	81	-0	-0		00102110
Y212	-0	-0	0.157000E-03	-0.	72	82	-0	-0		00102120
Y213	-0	-0	0.236000E-03	-0.	73	83	-0	-0		00102130
Y214	-0	-0	0.387000E-03	-0.	74	84	-0	-0		00102140
Y215	-0	-0	0.594000E-03	-0.	75	85	-0	-0		00102150
Y216	-0	-0	0.748000E-03	-0.	76	86	-0	-0		00102160
Y217	-0	-0	0.104000E-02	-0.	77	87	-0	-0		00102170
Y218	-0	-0	0.124000E-02	-0.	78	88	-0	-0		00102180
Y219	-0	-0	0.164000E-02	-0.	79	89	-0	-0	END COND PATHS	00102190
Y253	Y259	-0	-0.	-0.	33	53	1	1	RAD PATHS	00102530
Y280	Y289	-0	-0.	-0.	70	80	1	1	RAD PATHS	00102800
Y320	-0	-0	0.107000E-04	-0.	10	20	-0	-0	AXIAL CONDUCTIVE	00103200
Y321	-0	-0	0.855000E-04	-0.	11	21	-0	-0	PATHS	00103210
Y322	-0	-0	0.171000E-03	-0.	12	22	-0	-0		00103220
Y323	-0	-0	0.256000E-03	-0.	13	23	-0	-0		00103230
Y324	-0	-0	0.421000E-03	-0.	14	24	-0	-0		00103240
Y325	-0	-0	0.647000E-03	-0.	15	25	-0	-0		00103250
Y326	-0	-0	0.814000E-03	-0.	16	26	-0	-0		00103260
Y327	-0	-0	0.113000E-02	-0.	17	27	-0	-0		00103270
Y328	-0	-0	0.135000E-02	-0.	18	28	-0	-0		00103280
Y329	-0	-0	0.178000E-02	-0.	19	29	-0	-0		00103290
Y330	-0	-0	0.107000E-04	-0.	20	30	-0	-0		00103300
Y331	-0	-0	0.855000E-04	-0.	21	31	-0	-0		00103310
Y332	-0	-0	0.117000E-03	-0.	22	32	-0	-0		00103320
Y333	-0	-0	0.256000E-03	-0.	23	33	-0	-0		00103330
Y334	-0	-0	0.421000E-03	-0.	24	34	-0	-0		00103340

Y335	-0	-0	0.647000E-03	-0.	25	35	-0	-0	00103350
Y336	-0	-0	0.814000E-03	-0.	26	36	-0	-0	00103360
Y337	-0	-0	0.113000E-02	-0.	27	37	-0	-0	00103370
Y338	-0	-0	0.135000E-02	-0.	28	38	-0	-0	00103380
Y339	-0	-0	0.178000E-02	-0.	29	39	-0	-0	00103390
Y340	-0	-0	0.214000E-04	-0.	30	40	-0	-0	00103400
Y341	-0	-0	0.117000E-03	-0.	31	41	-0	-0	00103410
Y342	-0	-0	0.342000E-03	-0.	32	42	-0	-0	00103420
Y350	-0	-0	0.214000E-04	-0.	40	50	-0	-0	00103500
Y351	-0	-0	0.117000E-03	-0.	41	51	-0	-0	00103510
Y352	-0	-0	0.342000E-03	-0.	42	52	-0	-0	00103520
Y360	-0	-0	0.148000E-04	-0.	50	60	-0	-0	00103600
Y361	-0	-0	0.118000E-03	-0.	51	61	-0	-0	00103610
Y362	-0	-0	0.238000E-03	-0.	52	62	-0	-0	00103620
Y363	-0	-0	0.356000E-03	-0.	53	63	-0	-0	00103630
Y364	-0	-0	0.585000E-03	-0.	54	64	-0	-0	00103640
Y365	-0	-0	0.897000E-03	-0.	55	65	-0	-0	00103650
Y366	-0	-0	0.113000E-02	-0.	56	66	-0	-0	00103660
Y367	-0	-0	0.158000E-02	-0.	57	67	-0	-0	00103670
Y368	-0	-0	0.188000E-02	-0.	58	68	-0	-0	00103680
Y369	-0	-0	0.248000E-02	-0.	59	69	-0	-0	00103690
Y370	-0	-0	0.148000E-04	-0.	60	70	-0	-0	00103700
Y371	-0	-0	0.118000E-03	-0.	61	71	-0	-0	00103710
Y372	-0	-0	0.238000E-03	-0.	62	72	-0	-0	00103720
Y373	-0	-0	0.356000E-03	-0.	63	73	-0	-0	00103730
Y374	-0	-0	0.585000E-03	-0.	64	74	-0	-0	00103740
Y375	-0	-0	0.897000E-03	-0.	65	75	-0	-0	00103750
Y376	-0	-0	0.113000E-02	-0.	66	76	-0	-0	00103760
Y377	-0	-0	0.158000E-02	-0.	67	77	-0	-0	00103770
Y378	-0	-0	0.188000E-02	-0.	68	78	-0	-0	00103780
Y379	-0	-0	0.248000E-02	-0.	69	79	-0	-0	00103790
Y389	-0	-0	0.380000E-03	-0.	79	89	-0	-0	00103890
Y390	-0	-0	0.975000E-05	-0.	80	90	-0	-0	00103900
Y391	-0	-0	0.779000E-04	-0.	81	91	-0	-0	00103910
Y392	-0	-0	0.156000E-03	-0.	82	92	-0	-0	00103920
Y393	-0	-0	0.234000E-03	-0.	83	93	-0	-0	00103930
Y394	-0	-0	0.383000E-03	-0.	84	94	-0	-0	00103940
Y395	-0	-0	0.590000E-03	-0.	85	95	-0	-0	00103950
Y396	-0	-0	0.742000E-03	-0.	86	96	-0	-0	00103960
Y397	-0	-0	0.103000E-02	-0.	87	97	-0	-0	00103970
Y398	-0	-0	0.123000E-02	-0.	88	98	-0	-0	00103980
Y399	-0	-0	0.163000E-02	-0.	89	99	-0	-0	00103990
Y400	-0	-0	0.487000E-05	-0.	90	100	-0	-0	00104000
Y401	-0	-0	0.390000E-04	-0.	91	101	-0	-0	00104010

Y402	-0	-0	0.780000E-04	-0.	92	102	-0	-0	00104020
Y403	-0	-0	0.117000E-03	-0.	93	103	-0	-0	00104030
Y404	-0	-0	0.192000E-03	-0.	94	104	-0	-0	00104040
Y405	-0	-0	0.294000E-03	-0.	95	105	-0	-0	00104050
Y406	-0	-0	0.371000E-03	-0.	96	106	-0	-0	00104060
Y407	-0	-0	0.517000E-03	-0.	97	107	-0	-0	00104070
Y408	-0	-0	0.617000E-03	-0.	98	108	-0	-0	00104080
Y409	-0	-0	0.814000E-03	-0.	99	109	-0	-0	00104090
Y410	-0	-0	0.324000E-05	-0.	100	110	-0	-0	00104100
Y411	-0	-0	0.260000E-04	-0.	101	111	-0	-0	00104110
Y412	-0	-0	0.520000E-04	-0.	102	112	-0	-0	00104120
Y413	-0	-0	0.780000E-04	-0.	103	113	-0	-0	00104130
Y414	-0	-0	0.127000E-03	-0.	104	114	-0	-0	00104140
Y415	-0	-0	0.197000E-03	-0.	105	115	-0	-0	00104150
Y416	-0	-0	0.249000E-03	-0.	106	116	-0	-0	00104160
Y417	-0	-0	0.345000E-03	-0.	107	117	-0	-0	00104170
Y418	-0	-0	0.412000E-03	-0.	108	118	-0	-0	00104180
Y419	-0	-0	0.543000E-03	-0.	109	119	-0	-0	00104190
Y450	-0	-0	0.162000E-05	-0.	110	150	-0	-0	00104500
Y451	-0	-0	0.130000E-04	-0.	111	151	-0	-0	00104510
Y452	-0	-0	0.260000E-04	-0.	112	152	-0	-0	00104520
Y453	-0	-0	0.390000E-04	-0.	113	153	-0	-0	00104530
Y454	-0	-0	0.635000E-04	-0.	114	154	-0	-0	00104540
Y455	-0	-0	0.985000E-04	-0.	115	155	-0	-0	00104550
Y456	-0	-0	0.124000E-03	-0.	116	156	-0	-0	00104560
Y457	-0	-0	0.173000E-03	-0.	117	157	-0	-0	00104570
Y458	-0	-0	0.206000E-03	-0.	118	158	-0	-0	00104580
Y459	-0	-0	0.271000E-03	-0.	119	159	-0	-0	00104590
Y521	-0	-0	0.133000E-03	-0.	20	21	-0	-0	00105210
Y522	-0	-0	0.400000E-03	-0.	21	22	-0	-0	00105220
Y523	-0	-0	0.669000E-03	-0.	22	23	-0	-0	00105230
Y524	-0	-0	0.861000E-03	-0.	23	24	-0	-0	00105240
Y525	-0	-0	0.975000E-03	-0.	24	25	-0	-0	00105250
Y526	-0	-0	0.109000E-02	-0.	25	26	-0	-0	00105260
Y527	-0	-0	0.134000E-02	-0.	26	27	-0	-0	00105270
Y528	-0	-0	0.152000E-02	-0.	27	28	-0	-0	00105280
Y529	-0	-0	0.169000E-02	-0.	28	29	-0	-0	00105290
Y541	-0	-0	0.666000E-04	-0.	40	41	-0	-0	00105410
Y542	-0	-0	0.200000E-03	-0.	41	42	-0	-0	00105420
Y561	-0	-0	0.963000E-04	-0.	60	61	-0	-0	00105610
Y562	-0	-0	0.288000E-03	-0.	61	62	-0	-0	00105620
Y563	-0	-0	0.481000E-03	-0.	62	63	-0	-0	00105630
Y564	-0	-0	0.620000E-03	-0.	63	64	-0	-0	00105640
Y565	-0	-0	0.702000E-03	-0.	64	65	-0	-0	00105650

END OF AXIAL
CONDUCTIVE PATHS
RADIAL CONDUCTIVE
PATHS

Y566	-0	-0	0.838000E-03	-0.	65	66	-0	-0	00105660
Y567	-0	-0	0.967000E-03	-0.	66	67	-0	-0	00105670
Y568	-0	-0	0.109000E-02	-0.	67	68	-0	-0	00105680
Y569	-0	-0	0.122000E-02	-0.	68	69	-0	-0	00105690
Y591	-0	-0	0.122000E-03	-0.	90	91	-0	-0	00105910
Y592	-0	-0	0.366000E-03	-0.	91	92	-0	-0	00105920
Y593	-0	-0	0.610000E-03	-0.	92	93	-0	-0	00105930
Y594	-0	-0	0.786000E-03	-0.	93	94	-0	-0	00105940
Y595	-0	-0	0.890000E-03	-0.	94	95	-0	-0	00105950
Y596	-0	-0	0.103000E-02	-0.	95	96	-0	-0	00105960
Y597	-0	-0	0.123000E-02	-0.	96	97	-0	-0	00105970
Y598	-0	-0	0.138000E-02	-0.	97	98	-0	-0	00105980
Y599	-0	-0	0.154000E-02	-0.	98	99	-0	-0	00105990
Y601	-0	-0	0.122000E-03	-0.	100	101	-0	-0	00106010
Y602	-0	-0	0.366000E-03	-0.	101	102	-0	-0	00106020
Y603	-0	-0	0.610000E-03	-0.	102	103	-0	-0	00106030
Y604	-0	-0	0.786000E-03	-0.	103	104	-0	-0	00106040
Y605	-0	-0	0.890000E-03	-0.	104	105	-0	-0	00106050
Y606	-0	-0	0.103000E-02	-0.	105	106	-0	-0	00106060
Y607	-0	-0	0.123000E-02	-0.	106	107	-0	-0	00106070
Y608	-0	-0	0.138000E-02	-0.	107	108	-0	-0	00106080
Y609	-0	-0	0.154000E-02	-0.	108	109	-0	-0	00106090
Y611	-0	-0	0.244000E-03	-0.	110	111	-0	-0	00106110
Y612	-0	-0	0.730000E-03	-0.	111	112	-0	-0	00106120
Y613	-0	-0	0.122000E-02	-0.	112	113	-0	-0	00106130
Y614	-0	-0	0.157000E-02	-0.	113	114	-0	-0	00106140
Y615	-0	-0	0.178000E-02	-0.	114	115	-0	-0	00106150
Y616	-0	-0	0.212000E-02	-0.	115	116	-0	-0	00106160
Y617	-0	-0	0.245000E-02	-0.	116	117	-0	-0	00106170
Y618	-0	-0	0.277000E-02	-0.	117	118	-0	-0	00106180
Y619	-0	-0	0.308000E-02	-0.	118	119	-0	-0	00106190
Y651	-0	-0	0.366000E-03	-0.	150	151	-0	-0	00106510
Y652	-0	-0	0.110000E-02	-0.	151	152	-0	-0	00106520
Y653	-0	-0	0.183000E-02	-0.	152	153	-0	-0	00106530
Y654	-0	-0	0.236000E-02	-0.	153	154	-0	-0	00106540
Y655	-0	-0	0.267000E-02	-0.	154	155	-0	-0	00106550
Y656	-0	-0	0.315000E-02	-0.	155	156	-0	-0	00106560
Y657	-0	-0	0.368000E-02	-0.	156	157	-0	-0	00106570
Y658	-0	-0	0.415000E-02	-0.	157	158	-0	-0	00106580
Y659	-0	-0	0.462000E-02	-0.	158	159	-0	-0	00106590
* 20	-0	-0	-0.	-0.	-0	-0	-0	-0	00200000
INITIAL VALUES									
Q 10	-0	-0	0.196000E-02	-0.	-0	-0	-0	-0	00200100
Q 11	-0	-0	0.157000E-01	-0.	-0	-0	-0	-0	00200110
OUTER SURFACE									
HEAT FLUX									

Q 12	-0	-0	0.314000E-01	-0.	-0	-0	-0	-0		00200120
Q 13	-0	-0	0.471000E-01	-0.	-0	-0	-0	-0	C = 1.0	00200130
Q 14	-0	-0	0.773000E-01	-0.	-0	-0	-0	-0	BTU / SEC SQ IN	00200140
Q 15	-0	-0	0.119000E-00	-0.	-0	-0	-0	-0		00200150
Q 16	-0	-0	0.149000E-00	-0.	-0	-0	-0	-0		00200160
Q 17	-0	-0	0.209000E-00	-0.	-0	-0	-0	-0		00200170
Q 18	-0	-0	0.249000E-00	-0.	-0	-0	-0	-0		00200180
Q 19	-0	-0	0.328000E-00	-0.	-0	-0	-0	-0		00200190
C 20	-0	-0	0.906000E-05	-0.	-0	-0	-0	-0	THERMAL	00210200
C 21	-0	-0	0.725000E-04	-0.	-0	-0	-0	-0	CAPACITIES	00210210
C 22	-0	-0	0.145000E-03	-0.	-0	-0	-0	-0		00210220
C 23	-0	-0	0.218000E-03	-0.	-0	-0	-0	-0		00210230
C 24	-0	-0	0.357000E-03	-0.	-0	-0	-0	-0		00210240
C 25	-0	-0	0.550000E-03	-0.	-0	-0	-0	-0		00210250
C 26	-0	-0	0.691000E-03	-0.	-0	-0	-0	-0		00210260
C 27	-0	-0	0.966000E-03	-0.	-0	-0	-0	-0		00210270
C 28	-0	-0	0.115000E-02	-0.	-0	-0	-0	-0		00210280
C 29	-0	-0	0.152000E-02	-0.	-0	-0	-0	-0		00210290
C 40	-0	-0	0.455000E-05	-0.	-0	-0	-0	-0		00210400
C 41	-0	-0	0.362000E-04	-0.	-0	-0	-0	-0		00210410
C 42	-0	-0	0.725000E-04	-0.	-0	-0	-0	-0		00210420
C 60	-0	-0	0.651000E-05	-0.	-0	-0	-0	-0		00210600
C 61	-0	-0	0.521000E-04	-0.	-0	-0	-0	-0		00210610
C 62	-0	-0	0.105000E-03	-0.	-0	-0	-0	-0		00210620
C 63	-0	-0	0.157000E-03	-0.	-0	-0	-0	-0		00210630
C 64	-0	-0	0.258000E-03	-0.	-0	-0	-0	-0		00210640
C 65	-0	-0	0.395000E-03	-0.	-0	-0	-0	-0		00210650
C 66	-0	-0	0.500000E-03	-0.	-0	-0	-0	-0		00210660
C 67	-0	-0	0.695000E-03	-0.	-0	-0	-0	-0		00210670
C 68	-0	-0	0.829000E-03	-0.	-0	-0	-0	-0		00210680
C 69	-0	-0	0.137000E-02	-0.	-0	-0	-0	-0		00210690
C 90	-0	-0	0.137000E-04	-0.	-0	-0	-0	-0		00210900
C 91	-0	-0	0.110000E-03	-0.	-0	-0	-0	-0		00210910
C 92	-0	-0	0.220000E-03	-0.	-0	-0	-0	-0		00210920
C 93	-0	-0	0.330000E-03	-0.	-0	-0	-0	-0		00210930
C 94	-0	-0	0.541000E-03	-0.	-0	-0	-0	-0		00210940
C 95	-0	-0	0.832000E-03	-0.	-0	-0	-0	-0		00210950
C 96	-0	-0	0.105000E-02	-0.	-0	-0	-0	-0		00210960
C 97	-0	-0	0.146000E-02	-0.	-0	-0	-0	-0		00210970
C 98	-0	-0	0.174000E-02	-0.	-0	-0	-0	-0		00210980
C 99	-0	-0	0.230000E-02	-0.	-0	-0	-0	-0		00210990
C100	-0	-0	0.137000E-04	-0.	-0	-0	-0	-0		00211000
C101	-0	-0	0.110000E-03	-0.	-0	-0	-0	-0		00211010
C102	-0	-0	0.220000E-03	-0.	-0	-0	-0	-0		00211020

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C103	-0	-0	0.330000E-03	-0.	-0	-0	-0	-0	00211030
C104	-0	-0	0.541000E-03	-0.	-0	-0	-0	-0	00211040
C105	-0	-0	0.832000E-03	-0.	-0	-0	-0	-0	00211050
C106	-0	-0	0.105000E-02	-0.	-0	-0	-0	-0	00211060
C107	-0	-0	0.146000E-02	-0.	-0	-0	-0	-0	00211070
C108	-0	-0	0.174000E-02	-0.	-0	-0	-0	-0	00211080
C109	-0	-0	0.230000E-02	-0.	-0	-0	-0	-0	00211090
C110	-0	-0	0.274000E-04	-0.	-0	-0	-0	-0	00211100
C111	-0	-0	0.220000E-03	-0.	-0	-0	-0	-0	00211110
C112	-0	-0	0.440000E-03	-0.	-0	-0	-0	-0	00211120
C113	-0	-0	0.660000E-03	-0.	-0	-0	-0	-0	00211130
C114	-0	-0	0.108000E-02	-0.	-0	-0	-0	-0	00211140
C115	-0	-0	0.166000E-02	-0.	-0	-0	-0	-0	00211150
C116	-0	-0	0.210000E-02	-0.	-0	-0	-0	-0	00211160
C117	-0	-0	0.292000E-02	-0.	-0	-0	-0	-0	00211170
C118	-0	-0	0.348000E-02	-0.	-0	-0	-0	-0	00211180
C119	-0	-0	0.460000E-02	-0.	-0	-0	-0	-0	00211190
C150	-0	-0	0.548000E-04	-0.	-0	-0	-0	-0	00211500
C151	-0	-0	0.440000E-03	-0.	-0	-0	-0	-0	00211510
C152	-0	-0	0.880000E-03	-0.	-0	-0	-0	-0	00211520
C153	-0	-0	0.132000E-02	-0.	-0	-0	-0	-0	00211530
C154	-0	-0	0.216000E-02	-0.	-0	-0	-0	-0	00211540
C155	-0	-0	0.322000E-02	-0.	-0	-0	-0	-0	00211550
C156	-0	-0	0.410000E-02	-0.	-0	-0	-0	-0	00211560
C157	-0	-0	0.584000E-02	-0.	-0	-0	-0	-0	00211570
C158	-0	-0	0.696000E-02	-0.	-0	-0	-0	-0	00211580
C159	-0	-0	0.920000E-02	-0.	-0	-0	-0	-0	00211590
T 10 T159	-0	0.	-0.	-0.	-0	-0	-0	-0	INT. TEMP = 0 F 00220100
T 1	-0	-1	0.	-0.	-0	-0	-0	-0	ORIGINAL TEMP = 0 00220110
T 2	-0	-1	-0.459700E 03	-0.	-0	-0	-0	-0	AMB TEMP = -459.7F 00220120
D100	-0	-0	0.	-0.	-0	-0	-0	-0	00230010
D101	-0	-0	1.000000E-02	-0.	-0	-0	-0	-0	D101 = ZERO 00230020
D102	-0	-0	0.340000E 04	-0.	-0	-0	-0	-0	MELT TEMP = 3400 00230031
* 30	-0	-0	-0.	-0.	-0	-0	-0	-0	00300000
FUNCTIONS									
Y 10	-0	49	-0.	0.454000E-05	-0	-0	-0	-0	RAD TO AMB 00300100
Y 11	-0	49	-0.	0.363000E-04	-0	-0	-0	-0	R 00300110
Y 12	-0	49	-0.	0.726000E-04	-0	-0	-0	-0	R 00300120
Y 13	-0	49	-0.	0.109000E-03	-0	-0	-0	-0	R 00300130
Y 14	-0	49	-0.	0.179000E-03	-0	-0	-0	-0	R 00300140
Y 15	-0	49	-0.	0.275000E-03	-0	-0	-0	-0	R 00300150
Y 16	-0	49	-0.	0.346000E-03	-0	-0	-0	-0	R 00300160
Y 17	-0	49	-0.	0.483000E-03	-0	-0	-0	-0	R 00300170
Y 18	-0	49	-0.	0.576000E-03	-0	-0	-0	-0	R 00300180

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Y 19	-0	49	-0.	0.759000E-03	-0	-0	-0	-0	RAD TO AMB	00300190
Y253	-0	49	-0.	0.654000E-04	-0	-0	-0	-0		00302530
Y254	-0	49	-0.	0.107000E-03	-0	-0	-0	-0		00302540
Y255	-0	49	-0.	0.165000E-03	-0	-0	-0	-0		00302550
Y256	-0	49	-0.	0.208000E-03	-0	-0	-0	-0		00302560
Y257	-0	49	-0.	0.290000E-03	-0	-0	-0	-0		00302570
Y258	-0	49	-0.	0.346000E-03	-0	-0	-0	-0		00302580
Y259	-0	49	-0.	0.456000E-03	-0	-0	-0	-0		00302590
Y280	-0	49	-0.	0.272000E-05	-0	-0	-0	-0		00302800
Y281	-0	49	-0.	0.218000E-05	-0	-0	-0	-0		00302810
Y282	-0	49	-0.	0.436000E-04	-0	-0	-0	-0		00302820
Y283	-0	49	-0.	0.654000E-04	-0	-0	-0	-0		00302830
Y284	-0	49	-0.	0.107000E-03	-0	-0	-0	-0		00302840
Y285	-0	49	-0.	0.165000E-03	-0	-0	-0	-0		00302850
Y286	-0	49	-0.	0.208000E-03	-0	-0	-0	-0		00302860
Y287	-0	49	-0.	0.290000E-03	-0	-0	-0	-0		00302870
Y288	-0	49	-0.	0.346000E-03	-0	-0	-0	-0		00302880
Y289	-0	49	-0.	0.456000E-03	-0	-0	-0	-0		00302890
D 99	-0	99	-0.	-0.	T 19 D102	-0	-0	-0	STOP RUN AT T MELT	00310050
* 70	-0	-0	-0.	-0.		-0	-0	-0		00700000
SPECIAL CONSTANT VALUES										
1			0.400000E-01	SPECIFIED DELTA-TIME						00700010
2			0.200000E-02	MINIMUM ALLOWED DELTA-TIME						00700020
* 80										00800000
PRINT OUT SPECIFICATIONS										
T 10 T 42	-0	-0.	-0.		-0	-0	-0	-0		00800100
T 1	-0	-0	-0.	-0.	-0	-0	-0	-0		00800200
D102	-0	-0	-0.	-0.	-0	-0	-0	-0		00800300
T 50 T119	-0	-0.	-0.	-0.	-0	-0	-0	-0		00800400
T150 T159	-0	-0.	-0.	-0.	-0	-0	-0	-0		00800500
T 1 T 2	-0	-0.	-0.	-0.	-0	-0	-0	-0		00800650
* 90	-0	-0	-0.	-0.	-0	-0	-0	-0		00900000
RUN CONTROL										
-0	-0	-0	0.	0.200000E 01	-0	-0	-0	-0		00900100
-0	-0	-0	0.360000E 02	-0.	-0	-0	-0	-0		00900200
* 99	-0	-0	-0.	-0.	-0	-0	-0	-0		99999999

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APPENDIX B

"3-D Core" Thermal Model

The "3-D Core" thermal model is presented and discussed in Chapter V, and the nodal network is shown in Figures 24a, b, and c. The values of the system parameters are tabulated in the following pages by means of a listing of the network input cards for the TAP-3E code of computer run 7323-26, which is for the case of random tumbling reentry flight configuration with the grid plate separated from the fuel elements. There are many details involved in the calculation of these input parameters which are not shown here. Information relating to this is available from the author. Of particular interest might be the geometrical aspects of determining the thermal conductances.

THERMAL ANALYZER PROGRAM, TAP-3, RUN SUBMITTED BY OE M MOURADIAN H05

ALL NEW INPUT DATA FOR THIS RUN

* 7	-0	-0	-0.	-0.	-0	-0	-0	-0		00000070
	30 DEG WEDGE 3-D CORE MODEL									00001000
	FUEL DISINTEGRATION - REACTOR SEPARATION									00002000
	INITIAL TEMPERATURE = 0 F									00003000
	GRID PLATE - FUEL CAP = APART (REMOVE 2108210-8870, ADD 3908212-8872)									00004020
	RANDOM TUMBLING HEAT. ADD(2500010-860) OUT(2300010-860, 2400010-840)									00005040
	STARTING ALTITUDE = 250 KFT TRAJECTORY OF RUN 7323-01 C									00006010
	AMBIENT TEMPERATURE = 0.0 R = -460 F									00007000

* 10	-0	-0	-0.	-0.	-0	-0	-0	-0	NETWORK CONNECTIONS	01000000
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NETWORK DESCRIPTION

Y 1	-0	-0	0.179000E-04	-0.	1	21	-0	-0	CD	01000010
Y 2	-0	-0	0.357000E-04	-0.	2	23	-0	-0	CD	01000020
Y 3	-0	-0	0.357000E-04	-0.	2	26	-0	-0	CD	01000030
Y 4	-0	-0	0.357000E-04	-0.	2	41	-0	-0	CD	01000040
Y 5	-0	-0	0.357000E-04	-0.	3	43	-0	-0	CD	01000050
Y 6	-0	-0	0.357000E-04	-0.	3	52	-0	-0	CD	01000060
Y 7	-0	-0	0.357000E-04	-0.	3	61	-0	-0	CD	01000070
Y 8	-0	-0	0.179000E-04	-0.	4	28	-0	-0	CD	01000080
Y 9	-0	-0	0.179000E-04	-0.	4	29	-0	-0	CD	01000090
Y 10	-0	-0	0.357000E-04	-0.	4	45	-0	-0	CD	01000100
Y 11	-0	-0	0.357000E-04	-0.	4	56	-0	-0	CD	01000110
Y 12	-0	-0	0.245000E-04	-0.	5	7	-0	-0	CD	01000120
Y 13	-0	-0	0.140000E-04	-0.	5	9	-0	-0	CD	01000130
Y 14	-0	-0	0.357000E-04	-0.	5	63	-0	-0	CD	01000140
Y 15	-0	-0	0.245000E-04	-0.	6	7	-0	-0	CD	01000150
Y 16	-0	-0	0.245000E-04	-0.	6	8	-0	-0	CD	01000160
Y 17	-0	-0	0.245000E-04	-0.	6	11	-0	-0	CD	01000170
Y 18	-0	-0	0.357000E-04	-0.	6	31	-0	-0	CD	01000180
Y 19	-0	-0	0.357000E-04	-0.	6	54	-0	-0	CD	01000190
Y 20	-0	-0	0.357000E-04	-0.	6	65	-0	-0	CD	01000200
Y 21	-0	-0	0.242000E-04	-0.	7	9	-0	-0	CD	01000210
Y 22	-0	-0	0.331000E-04	-0.	7	10	-0	-0	CD	01000220
Y 23	-0	-0	0.245000E-04	-0.	7	11	-0	-0	CD	01000230
Y 24	-0	-0	0.357000E-04	-0.	7	64	-0	-0	CD	01000240
Y 25	-0	-0	0.245000E-04	-0.	8	11	-0	-0	CD	01000250
Y 26	-0	-0	0.298000E-04	-0.	8	12	-0	-0	CD	01000260
Y 27	-0	-0	0.179000E-04	-0.	8	32	-0	-0	CD	01000270
Y 28	-0	-0	0.110000E-04	-0.	9	10	-0	-0	CD	01000280
Y 29	-0	-0	0.187000E-04	-0.	10	11	-0	-0	CD	01000290
Y 30	-0	-0	0.161000E-04	-0.	11	12	-0	-0	CD	01000300
Y 31	-0	-0	0.283000E-04	-0.	21	22	-0	-0	CD	01000310
Y 32	-0	-0	0.283000E-04	-0.	22	23	-0	-0	CD	01000320

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Y 33	-0	-0	0.283000E-04	-0.	23	24	-0	-0	CD	01000330
Y 34	-0	-0	0.656000E-04	-0.	24	25	-0	-0	CD	01000340
Y 35	-0	-0	0.283000E-04	-0.	25	26	-0	-0	CD	01000350
Y 36	-0	-0	0.283000E-04	-0.	26	27	-0	-0	CD	01000360
Y 37	-0	-0	0.283000E-04	-0.	27	28	-0	-0	CD	01000370
Y 38	-0	-0	0.656000E-04	-0.	27	46	-0	-0	CD	01000380
Y 39	-0	-0	0.283000E-04	-0.	29	30	-0	-0	CD	01000390
Y 40	-0	-0	0.283000E-04	-0.	30	31	-0	-0	CD	01000400
Y 41	-0	-0	0.656000E-04	-0.	30	55	-0	-0	CD	01000410
Y 42	-0	-0	0.283000E-04	-0.	31	32	-0	-0	CD	01000420
Y 43	-0	-0	0.283000E-04	-0.	41	42	-0	-0	CD	01000430
Y 44	-0	-0	0.283000E-04	-0.	41	46	-0	-0	CD	01000440
Y 45	-0	-0	0.283000E-04	-0.	42	43	-0	-0	CD	01000450
Y 46	-0	-0	0.283000E-04	-0.	43	44	-0	-0	CD	01000460
Y 47	-0	-0	0.283000E-04	-0.	44	45	-0	-0	CD	01000470
Y 48	-0	-0	0.656000E-04	-0.	44	51	-0	-0	CD	01000480
Y 49	-0	-0	0.283000E-04	-0.	45	46	-0	-0	CD	01000490
Y 50	-0	-0	0.283000E-04	-0.	51	52	-0	-0	CD	01000500
Y 51	-0	-0	0.283000E-04	-0.	51	56	-0	-0	CD	01000510
Y 52	-0	-0	0.283000E-04	-0.	52	53	-0	-0	CD	01000520
Y 53	-0	-0	0.283000E-04	-0.	53	54	-0	-0	CD	01000530
Y 54	-0	-0	0.656000E-04	-0.	53	66	-0	-0	CD	01000540
Y 55	-0	-0	0.283000E-04	-0.	54	55	-0	-0	CD	01000550
Y 56	-0	-0	0.283000E-04	-0.	55	56	-0	-0	CD	01000560
Y 57	-0	-0	0.283000E-04	-0.	61	62	-0	-0	CD	01000570
Y 58	-0	-0	0.283000E-04	-0.	61	66	-0	-0	CD	01000580
Y 59	-0	-0	0.283000E-04	-0.	62	63	-0	-0	CD	01000590
Y 60	-0	-0	0.283000E-04	-0.	63	64	-0	-0	CD	01000600
Y 61	-0	-0	0.283000E-04	-0.	64	65	-0	-0	CD	01000610
Y 62	-0	-0	0.283000E-04	-0.	65	66	-0	-0	CD	01000620
Y101	-0	-0	0.283000E-04	-0.	101	114	-0	-0	CD	01001010
Y102	-0	-0	0.283000E-04	-0.	102	121	-0	-0	CD	01001020
Y103	-0	-0	0.567000E-04	-0.	102	122	-0	-0	CD	01001030
Y104	-0	-0	0.567000E-04	-0.	102	123	-0	-0	CD	01001040
Y105	-0	-0	0.283000E-04	-0.	102	124	-0	-0	CD	01001050
Y106	-0	-0	0.283000E-04	-0.	103	131	-0	-0	CD	01001060
Y107	-0	-0	0.567000E-04	-0.	103	132	-0	-0	CD	01001070
Y108	-0	-0	0.567000E-04	-0.	103	133	-0	-0	CD	01001080
Y109	-0	-0	0.283000E-04	-0.	103	134	-0	-0	CD	01001090
Y110	-0	-0	0.567000E-04	-0.	104	146	-0	-0	CD	01001100
Y111	-0	-0	0.567000E-04	-0.	104	145	-0	-0	CD	01001110
Y112	-0	-0	0.567000E-04	-0.	104	144	-0	-0	CD	01001120
Y113	-0	-0	0.283000E-04	-0.	105	151	-0	-0	CD	01001130
Y114	-0	-0	0.567000E-04	-0.	105	152	-0	-0	CD	01001140

Y115	-0	-0	0.567000E-04	-0.	105	153	-0	-0	CD	01001150
Y116	-0	-0	0.283000E-04	-0.	105	154	-0	-0	CD	01001160
Y117	Y122	-0	0.567000E-04	-0.	106	161	0	1	CD	01001170
Y140	-0	-0	0.248000E-03	-0.	107	171	-0	-0	CD	01001400
Y141	-0	-0	0.274000E-03	-0.	107	110	-0	-0	CD	01001410
Y142	-0	-0	0.106000E-03	-0.	107	108	-0	-0	CD	01001420
Y143	-0	-0	0.414000E-03	-0.	108	172	-0	-0	CD	01001430
Y144	-0	-0	0.270000E-03	-0.	109	173	-0	-0	CD	01001440
Y145	-0	-0	0.492000E-04	-0.	108	109	-0	-0	CD	01001450
Y146	-0	-0	0.282000E-03	-0.	109	112	-0	-0	CD	01001460
Y147	-0	-0	0.258000E-03	-0.	108	111	-0	-0	CD	01001470
Y148	-0	-0	0.154000E-04	-0.	110	111	-0	-0	CD	01001480
Y149	-0	-0	0.154000E-04	-0.	111	112	-0	-0	CD	01001490
Y161	-0	-0	-0.	-0.	114	121	-0	-0	R	01001610
Y162	-0	-0	-0.	-0.	124	131	-0	-0	R	01001620
Y163	-0	-0	-0.	-0.	123	146	-0	-0	R	01001630
Y164	-0	-0	-0.	-0.	132	145	-0	-0	R	01001640
Y165	-0	-0	-0.	-0.	134	151	-0	-0	R	01001650
Y166	-0	-0	-0.	-0.	133	166	-0	-0	R	01001660
Y167	-0	-0	-0.	-0.	144	161	-0	-0	R	01001670
Y168	-0	-0	-0.	-0.	152	165	-0	-0	R	01001680
Y169	-0	-0	-0.	-0.	153	171	-0	-0	R	01001690
Y170	-0	-0	-0.	-0.	164	172	-0	-0	R	01001700
Y171	-0	-0	-0.	-0.	163	173	-0	-0	R	01001710
Y172	-0	-0	-0.	-0.	154	99	-0	-0	R	01001720
Y173	-0	-0	-0.	-0.	110	99	-0	-0	R	01001730
Y174	-0	-0	-0.	-0.	111	99	-0	-0	R	01001740
Y175	-0	-0	-0.	-0.	112	99	-0	-0	R	01001750
Y181	-0	-0	0.125000E-05	-0.	114	121	-0	-0	CV	01001810
Y182	-0	-0	0.125000E-05	-0.	124	131	-0	-0	CV	01001820
Y183	-0	-0	0.125000E-05	-0.	123	146	-0	-0	CV	01001830
Y184	-0	-0	0.125000E-05	-0.	132	145	-0	-0	CV	01001840
Y185	-0	-0	0.125000E-05	-0.	134	151	-0	-0	CV	01001850
Y186	-0	-0	0.125000E-05	-0.	133	166	-0	-0	CV	01001860
Y187	-0	-0	0.125000E-05	-0.	144	161	-0	-0	CV	01001870
Y188	-0	-0	0.125000E-05	-0.	152	165	-0	-0	CV	01001880
Y189	-0	-0	0.125000E-05	-0.	153	171	-0	-0	CV	01001890
Y190	-0	-0	0.125000E-05	-0.	164	172	-0	-0	CV	01001900
Y191	-0	-0	0.125000E-05	-0.	163	173	-0	-0	CV	01001910
Y201	-0	-0	0.724000E-04	-0.	201	214	-0	-0	CD	01002010
Y202	-0	-0	0.724000E-04	-0.	202	221	-0	-0	CD	01002020
Y203	-0	-0	0.144800E-03	-0.	202	222	-0	-0	CD	01002030
Y204	-0	-0	0.144800E-03	-0.	202	223	-0	-0	CD	01002040
Y205	-0	-0	0.724000E-04	-0.	202	224	-0	-0	CD	01002050

Y117-Y122

Y206	-0	-0	0.724000E-04	-0.	203	231	-0	-0	CD	01002060
Y207	-0	-0	0.144800E-03	-0.	203	232	-0	-0	CD	01002070
Y208	-0	-0	0.144800E-03	-0.	203	233	-0	-0	CD	01002080
Y209	-0	-0	0.724000E-04	-0.	203	234	-0	-0	CD	01002090
Y210	-0	-0	0.144800E-03	-0.	204	246	-0	-0	CD	01002100
Y211	-0	-0	0.144800E-03	-0.	204	245	-0	-0	CD	01002110
Y212	-0	-0	0.144800E-03	-0.	204	244	-0	-0	CD	01002120
Y213	-0	-0	0.724000E-04	-0.	205	251	-0	-0	CD	01002130
Y214	-0	-0	0.144800E-03	-0.	205	252	-0	-0	CD	01002140
Y215	-0	-0	0.144800E-03	-0.	205	253	-0	-0	CD	01002150
Y216	-0	-0	0.724000E-04	-0.	205	254	-0	-0	CD	01002160
Y217 Y222	-0	-0	0.144800E-03	-0.	206	261	0	1	CD	01002170
Y240	-0	-0	0.992000E-03	-0.	207	271	-0	-0	CD	01002400
Y241	-0	-0	0.109600E-02	-0.	207	210	-0	-0	CD	01002410
Y242	-0	-0	0.424000E-03	-0.	207	208	-0	-0	CD	01002420
Y243	-0	-0	0.165600E-02	-0.	208	272	-0	-0	CD	01002430
Y244	-0	-0	0.108000E-02	-0.	209	273	-0	-0	CD	01002440
Y245	-0	-0	0.197000E-03	-0.	208	209	-0	-0	CD	01002450
Y246	-0	-0	0.112800E-02	-0.	209	212	-0	-0	CD	01002460
Y247	-0	-0	0.103200E-02	-0.	208	211	-0	-0	CD	01002470
Y248	-0	-0	0.616000E-04	-0.	210	211	-0	-0	CD	01002480
Y249	-0	-0	0.616000E-04	-0.	211	212	-0	-0	CD	01002490
Y261	-0	-0	-0.	-0.	214	221	-0	-0	R	01002610
Y262	-0	-0	-0.	-0.	224	231	-0	-0	R	01002620
Y263	-0	-0	-0.	-0.	223	246	-0	-0	R	01002630
Y264	-0	-0	-0.	-0.	232	245	-0	-0	R	01002640
Y265	-0	-0	-0.	-0.	234	251	-0	-0	R	01002650
Y266	-0	-0	-0.	-0.	233	266	-0	-0	R	01002660
Y267	-0	-0	-0.	-0.	244	261	-0	-0	R	01002670
Y268	-0	-0	-0.	-0.	252	265	-0	-0	R	01002680
Y269	-0	-0	-0.	-0.	253	271	-0	-0	R	01002690
Y270	-0	-0	-0.	-0.	264	272	-0	-0	R	01002700
Y271	-0	-0	-0.	-0.	263	273	-0	-0	R	01002710
Y272	-0	-0	-0.	-0.	254	99	-0	-0	R	01002720
Y273	-0	-0	-0.	-0.	210	99	-0	-0	R	01002730
Y274	-0	-0	-0.	-0.	211	99	-0	-0	R	01002740
Y275	-0	-0	-0.	-0.	212	99	-0	-0	R	01002750
Y281	-0	-0	0.500000E-05	-0.	214	221	-0	-0	CV	01002810
Y282	-0	-0	0.500000E-05	-0.	224	231	-0	-0	CV	01002820
Y283	-0	-0	0.500000E-05	-0.	223	246	-0	-0	CV	01002830
Y284	-0	-0	0.500000E-05	-0.	232	245	-0	-0	CV	01002840
Y285	-0	-0	0.500000E-05	-0.	234	251	-0	-0	CV	01002850
Y286	-0	-0	0.500000E-05	-0.	233	266	-0	-0	CV	01002860
Y287	-0	-0	0.500000E-05	-0.	244	261	-0	-0	CV	01002870

Y217-Y222

Y288	-0	-0	0.500000E-05	-0.	252	265	-0	-0	CV	01002880
Y289	-0	-0	0.500000E-05	-0.	253	271	-0	-0	CV	01002890
Y290	-0	-0	0.500000E-05	-0.	264	272	-0	-0	CV	01002900
Y291	-0	-0	0.500000E-05	-0.	263	273	-0	-0	CV	01002910
Y301	-0	-0	0.724000E-04	-0.	301	314	-0	-0	CD	01003010
Y302	-0	-0	0.724000E-04	-0.	302	321	-0	-0	CD	01003020
Y303	-0	-0	0.144800E-03	-0.	302	322	-0	-0	CD	01003030
Y304	-0	-0	0.144800E-03	-0.	302	323	-0	-0	CD	01003040
Y305	-0	-0	0.724000E-04	-0.	302	324	-0	-0	CD	01003050
Y306	-0	-0	0.724000E-04	-0.	303	331	-0	-0	CD	01003060
Y307	-0	-0	0.144800E-03	-0.	303	332	-0	-0	CD	01003070
Y308	-0	-0	0.144800E-03	-0.	303	333	-0	-0	CD	01003080
Y309	-0	-0	0.724000E-04	-0.	303	334	-0	-0	CD	01003090
Y310	-0	-0	0.144800E-03	-0.	304	346	-0	-0	CD	01003100
Y311	-0	-0	0.144800E-03	-0.	304	345	-0	-0	CD	01003110
Y312	-0	-0	0.144800E-03	-0.	304	344	-0	-0	CD	01003120
Y313	-0	-0	0.724000E-04	-0.	305	351	-0	-0	CD	01003130
Y314	-0	-0	0.144800E-03	-0.	305	352	-0	-0	CD	01003140
Y315	-0	-0	0.144800E-03	-0.	305	353	-0	-0	CD	01003150
Y316	-0	-0	0.724000E-04	-0.	305	354	-0	-0	CD	01003160
Y317 Y322	-0	-0	0.144800E-03	-0.	306	361	0	1	CD	01003170
Y340	-0	-0	0.992000E-03	-0.	307	371	-0	-0	CD	01003400
Y341	-0	-0	0.109600E-02	-0.	307	310	-0	-0	CD	01003410
Y342	-0	-0	0.424000E-03	-0.	307	308	-0	-0	CD	01003420
Y343	-0	-0	0.165600E-02	-0.	308	372	-0	-0	CD	01003430
Y344	-0	-0	0.108000E-02	-0.	309	373	-0	-0	CD	01003440
Y345	-0	-0	0.197000E-03	-0.	308	309	-0	-0	CD	01003450
Y346	-0	-0	0.112800E-02	-0.	309	312	-0	-0	CD	01003460
Y347	-0	-0	0.103200E-02	-0.	308	311	-0	-0	CD	01003470
Y348	-0	-0	0.616000E-04	-0.	310	311	-0	-0	CD	01003480
Y349	-0	-0	0.616000E-04	-0.	311	312	-0	-0	CD	01003490
Y361	-0	-0	-0.	-0.	314	321	-0	-0	R	01003610
Y362	-0	-0	-0.	-0.	324	331	-0	-0	R	01003620
Y363	-0	-0	-0.	-0.	323	346	-0	-0	R	01003630
Y364	-0	-0	-0.	-0.	332	345	-0	-0	R	01003640
Y365	-0	-0	-0.	-0.	334	351	-0	-0	R	01003650
Y366	-0	-0	-0.	-0.	333	366	-0	-0	R	01003660
Y367	-0	-0	-0.	-0.	344	361	-0	-0	R	01003670
Y368	-0	-0	-0.	-0.	352	365	-0	-0	R	01003680
Y369	-0	-0	-0.	-0.	353	371	-0	-0	R	01003690
Y370	-0	-0	-0.	-0.	364	372	-0	-0	R	01003700
Y371	-0	-0	-0.	-0.	363	373	-0	-0	R	01003710
Y372	-0	-0	-0.	-0.	354	99	-0	-0	R	01003720
Y373	-0	-0	-0.	-0.	310	99	-0	-0	R	01003730

Y374	-0	-0	-0.	-0.	311	99	-0	-0	R	01003740
Y375	-0	-0	-0.	-0.	312	99	-0	-0	R	01003750
Y381	-0	-0	0.500000E-05	-0.	314	321	-0	-0	CV	01003810
Y382	-0	-0	0.500000E-05	-0.	324	331	-0	-0	CV	01003820
Y383	-0	-0	0.500000E-05	-0.	323	346	-0	-0	CV	01003830
Y384	-0	-0	0.500000E-05	-0.	332	345	-0	-0	CV	01003840
Y385	-0	-0	0.500000E-05	-0.	334	351	-0	-0	CV	01003850
Y386	-0	-0	0.500000E-05	-0.	333	366	-0	-0	CV	01003860
Y387	-0	-0	0.500000E-05	-0.	344	361	-0	-0	CV	01003870
Y388	-0	-0	0.500000E-05	-0.	352	365	-0	-0	CV	01003880
Y389	-0	-0	0.500000E-05	-0.	353	371	-0	-0	CV	01003890
Y390	-0	-0	0.500000E-05	-0.	364	372	-0	-0	CV	01003900
Y391	-0	-0	0.500000E-05	-0.	363	373	-0	-0	CV	01003910
Y401	-0	-0	0.724000E-04	-0.	401	414	-0	-0	CD	01004010
Y402	-0	-0	0.724000E-04	-0.	402	421	-0	-0	CD	01004020
Y403	-0	-0	0.144800E-03	-0.	402	422	-0	-0	CD	01004030
Y404	-0	-0	0.144800E-03	-0.	402	423	-0	-0	CD	01004040
Y405	-0	-0	0.724000E-04	-0.	402	424	-0	-0	CD	01004050
Y406	-0	-0	0.724000E-04	-0.	403	431	-0	-0	CD	01004060
Y407	-0	-0	0.144800E-03	-0.	403	432	-0	-0	CD	01004070
Y408	-0	-0	0.144800E-03	-0.	403	433	-0	-0	CD	01004080
Y409	-0	-0	0.724000E-04	-0.	403	434	-0	-0	CD	01004090
Y410	-0	-0	0.144800E-03	-0.	404	446	-0	-0	CD	01004100
Y411	-0	-0	0.144800E-03	-0.	404	445	-0	-0	CD	01004110
Y412	-0	-0	0.144800E-03	-0.	404	444	-0	-0	CD	01004120
Y413	-0	-0	0.724000E-04	-0.	405	451	-0	-0	CD	01004130
Y414	-0	-0	0.144800E-03	-0.	405	452	-0	-0	CD	01004140
Y415	-0	-0	0.144800E-03	-0.	405	453	-0	-0	CD	01004150
Y416	-0	-0	0.724000E-04	-0.	405	454	-0	-0	CD	01004160
Y417 Y422	-0	-0	0.144800E-03	-0.	406	461	0	1	CD	01004170
Y440	-0	-0	0.992000E-03	-0.	407	471	-0	-0	CD	01004400
Y441	-0	-0	0.109600E-02	-0.	407	410	-0	-0	CD	01004410
Y442	-0	-0	0.424000E-03	-0.	407	408	-0	-0	CD	01004420
Y443	-0	-0	0.165600E-02	-0.	408	472	-0	-0	CD	01004430
Y444	-0	-0	0.108000E-02	-0.	409	473	-0	-0	CD	01004440
Y445	-0	-0	0.197000E-03	-0.	408	409	-0	-0	CD	01004450
Y446	-0	-0	0.112800E-02	-0.	409	412	-0	-0	CD	01004460
Y447	-0	-0	0.103200E-02	-0.	408	411	-0	-0	CD	01004470
Y448	-0	-0	0.616000E-04	-0.	410	411	-0	-0	CD	01004480
Y449	-0	-0	0.616000E-04	-0.	411	412	-0	-0	CD	1004490
Y461	-0	-0	-0.	-0.	414	421	-0	-0	R	01004610
Y462	-0	-0	-0.	-0.	424	431	-0	-0	R	01004620
Y463	-0	-0	-0.	-0.	423	446	-0	-0	R	01004630
Y464	-0	-0	-0.	-0.	432	445	-0	-0	R	01004640

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Y465	-0	-0	-0.	-0.	434	451	-0	-0	R	01004650
Y466	-0	-0	-0.	-0.	433	466	-0	-0	R	01004660
Y467	-0	-0	-0.	-0.	444	461	-0	-0	R	01004670
Y468	-0	-0	-0.	-0.	452	465	-0	-0	R	01004680
Y469	-0	-0	-0.	-0.	453	471	-0	-0	R	01004690
Y470	-0	-0	-0.	-0.	464	472	-0	-0	R	01004700
Y471	-0	-0	-0.	-0.	463	473	-0	-0	R	01004710
Y472	-0	-0	-0.	-0.	454	99	-0	-0	R	01004720
Y473	-0	-0	-0.	-0.	410	99	-0	-0	R	01004730
Y474	-0	-0	-0.	-0.	411	99	-0	-0	R	01004740
Y475	-0	-0	-0.	-0.	412	99	-0	-0	R	01004750
Y481	-0	-0	0.500000E-05	-0.	414	421	-0	-0	CV	01004810
Y482	-0	-0	0.500000E-05	-0.	424	431	-0	-0	CV	01004820
Y483	-0	-0	0.500000E-05	-0.	423	446	-0	-0	CV	01004830
Y484	-0	-0	0.500000E-05	-0.	432	445	-0	-0	CV	01004840
Y485	-0	-0	0.500000E-05	-0.	434	451	-0	-0	CV	01004850
Y486	-0	-0	0.500000E-05	-0.	433	466	-0	-0	CV	01004860
Y487	-0	-0	0.500000E-05	-0.	444	461	-0	-0	CV	01004870
Y488	-0	-0	0.500000E-05	-0.	452	465	-0	-0	CV	01004880
Y489	-0	-0	0.500000E-05	-0.	453	471	-0	-0	CV	01004890
Y490	-0	-0	0.500000E-05	-0.	464	472	-0	-0	CV	01004900
Y491	-0	-0	0.500000E-05	-0.	463	473	-0	-0	CV	01004910
Y501	-0	-0	0.943000E-04	-0.	301	401	-0	-0	CD	01005010
Y502 Y505	-0	-0	0.566000E-03	-0.	302	402	1	1	CD	01005020
Y506	-0	-0	0.113200E-02	-0.	306	406	-0	-0	CD	01005060
Y507	-0	-0	0.439000E-03	-0.	307	407	-0	-0	CD	01005070
Y508	-0	-0	0.878000E-03	-0.	308	408	-0	-0	CD	01005080
Y509	-0	-0	0.108800E-02	-0.	309	409	-0	-0	CD	01005090
Y510	-0	-0	0.211000E-03	-0.	310	410	-0	-0	CD	01005100
Y511	-0	-0	0.230000E-03	-0.	311	411	-0	-0	CD	01005110
Y512	-0	-0	0.230000E-03	-0.	312	412	-0	-0	CD	01005120
Y521	-0	-0	0.943000E-04	-0.	201	301	-0	-0	CD	01005210
Y522 Y525	-0	-0	0.566000E-03	-0.	202	302	1	1	CD	01005220
Y526	-0	-0	0.113200E-02	-0.	206	306	-0	-0	CD	01005260
Y527	-0	-0	0.439000E-03	-0.	207	307	-0	-0	CD	01005270
Y528	-0	-0	0.878000E-03	-0.	208	308	-0	-0	CD	01005280
Y529	-0	-0	0.108800E-02	-0.	209	309	-0	-0	CD	01005290
Y530	-0	-0	0.211000E-03	-0.	210	310	-0	-0	CD	01005300
Y531	-0	-0	0.230000E-03	-0.	211	311	-0	-0	CD	01005310
Y532	-0	-0	0.230000E-03	-0.	212	312	-0	-0	CD	01005320
Y601 Y612	-0	-0.	-0.	-0.	1	100	1	0	HT INPUT	01006010
Y621 Y632	-0	-0.	-0.	-0.	21	100	1	0	HT INPUT	01006210
Y641 Y646	-0	-0.	-0.	-0.	41	100	1	0	HT INPUT	01006410
Y651 Y656	-0	-0.	-0.	-0.	51	100	1	0	HT INPUT	01006510

Y502-Y505

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Y661	Y666	-0	-0.	-0.	61	100	1	0	HT	INPUT	01006610
Y671	Y674	-0	-0.	-0.	154	100	100	0	HT	INPUT	01006710
Y675	Y678	-0	-0.	-0.	110	100	100	0	HT	INPUT	01006750
Y679	Y682	-0	-0.	-0.	111	100	100	0	HT	INPUT	01006790
Y683	Y686	-0	-0.	-0.	112	100	100	0	HT	INPUT	01006830
Y701	-0	-0	0.118000E-03	-0.	101	201	-0	-0	CD		01007010
Y702	Y705	-0	0.710000E-03	-0.	102	202	1	1	CD	Y702-Y705	01007020
Y706	-0	-0	0.142000E-02	-0.	106	206	-0	-0	CD		01007060
Y707	-0	-0	0.701000E-03	-0.	107	207	-0	-0	CD		01007070
Y708	-0	-0	0.140200E-02	-0.	108	208	-0	-0	CD		01007080
Y709	-0	-0	0.174000E-02	-0.	109	209	-0	-0	CD		01007090
Y710	-0	-0	0.338000E-03	-0.	110	210	-0	-0	CD		01007100
Y711	-0	-0	0.368000E-03	-0.	111	211	-0	-0	CD		01007110
Y712	-0	-0	0.368000E-03	-0.	112	212	-0	-0	CD		01007120
Y801	-0	-0	0.420000E-04	-0.	1	101	-0	-0	CD	PIN Y801	01008010
Y802	Y805	-0	0.126000E-03	-0.	2	102	1	1	CD	PINS Y802-Y805	01008020
Y806	-0	-0	0.252000E-03	-0.	6	106	-0	-0	CD	PIN Y806	01008060
Y807	-0	-0	0.138000E-04	-0.	7	108	-0	-0	CD	PIN	01008070
Y808	-0	-0	0.192000E-04	-0.	8	109	-0	-0	CD	PIN	01008080
Y809	-0	-0	0.276000E-04	-0.	10	108	-0	-0	CD	PIN	01008090
Y810	-0	-0	0.276000E-04	-0.	11	108	-0	-0	CD	PIN	01008100
Y811	-0	-0	0.576000E-04	-0.	11	109	-0	-0	CD	PIN	01008110
Y812	-0	-0	0.115200E-03	-0.	12	109	-0	-0	CD	PIN	01008120
Y821	-0	-0	-0.	-0.	1	101	-0	-0	R/CD		01008210
Y822	-0	-0	-0.	-0.	2	102	-0	-0	R/CD		01008220
Y823	-0	-0	-0.	-0.	3	103	-0	-0	R/CD		01008230
Y824	-0	-0	-0.	-0.	4	104	-0	-0	R/CD		01008240
Y825	-0	-0	-0.	-0.	5	105	-0	-0	R/CD		01008250
Y826	-0	-0	-0.	-0.	6	106	-0	-0	R/CD		01008260
Y827	-0	-0	-0.	-0.	7	108	-0	-0	R/CD		01008270
Y828	-0	-0	-0.	-0.	8	109	-0	-0	R/CD		01008280
Y829	-0	-0	-0.	-0.	10	108	-0	-0	R/CD		01008290
Y830	-0	-0	-0.	-0.	11	108	-0	-0	R/CD		01008300
Y831	-0	-0	-0.	-0.	11	109	-0	-0	R/CD		01008310
Y832	-0	-0	-0.	-0.	12	109	-0	-0	R/CD		01008320
Y833	-0	-0	-0.	-0.	7	105	-0	-0	R/CD		01008330
Y834	-0	-0	-0.	-0.	7	106	-0	-0	R/CD		01008340
Y835	-0	-0	-0.	-0.	7	107	-0	-0	R/CD		01008350
Y836	-0	-0	-0.	-0.	8	106	-0	-0	R/CD		01008360
Y837	-0	-0	-0.	-0.	9	105	-0	-0	R/CD		01008370
Y838	-0	-0	-0.	-0.	9	107	-0	-0	R/CD		01008380
Y839	-0	-0	-0.	-0.	9	110	-0	-0	R/CD		01008390
Y840	-0	-0	-0.	-0.	10	107	-0	-0	R/CD		01008400
Y841	-0	-0	-0.	-0.	10	110	-0	-0	R/CD		01008410

Y842	-0	-0	-0.	-0.	10	111	-0	-0	R/CD	01008420
Y843	-0	-0	-0.	-0.	11	106	-0	-0	R/CD	01008430
Y844	-0	-0	-0.	-0.	11	111	-0	-0	R/CD	01008440
Y845	-0	-0	-0.	-0.	11	112	-0	-0	R/CD	01008450
Y846	-0	-0	-0.	-0.	12	112	-0	-0	R/CD	01008460
Y847	-0	-0	-0.	-0.	21	101	-0	-0	R/CD	01008470
Y848	-0	-0	-0.	-0.	22	101	-0	-0	R/CD	01008480
Y849	-0	-0	-0.	-0.	22	102	-0	-0	R/CD	01008490
Y850	-0	-0	-0.	-0.	23	102	-0	-0	R/CD	01008500
Y851	-0	-0	-0.	-0.	24	102	-0	-0	R/CD	01008510
Y852	-0	-0	-0.	-0.	25	102	-0	-0	R/CD	01008520
Y853	-0	-0	-0.	-0.	26	102	-0	-0	R/CD	01008530
Y854	-0	-0	-0.	-0.	27	102	-0	-0	R/CD	01008540
Y855	-0	-0	-0.	-0.	27	104	-0	-0	R/CD	01008550
Y856	-0	-0	-0.	-0.	28	104	-0	-0	R/CD	01008560
Y857	-0	-0	-0.	-0.	29	104	-0	-0	R/CD	01008570
Y858	-0	-0	-0.	-0.	30	104	-0	-0	R/CD	01008580
Y859	-0	-0	-0.	-0.	30	106	-0	-0	R/CD	01008590
Y860	-0	-0	-0.	-0.	31	106	-0	-0	R/CD	01008600
Y861	-0	-0	-0.	-0.	32	106	-0	-0	R/CD	01008610
Y862	-0	-0	-0.	-0.	41	102	-0	-0	R/CD	01008620
Y863	-0	-0	-0.	-0.	42	102	-0	-0	R/CD	01008630
Y864	-0	-0	-0.	-0.	42	103	-0	-0	R/CD	01008640
Y865	-0	-0	-0.	-0.	43	103	-0	-0	R/CD	01008650
Y866	-0	-0	-0.	-0.	44	103	-0	-0	R/CD	01008660
Y867	-0	-0	-0.	-0.	44	104	-0	-0	R/CD	01008670
Y868	-0	-0	-0.	-0.	45	104	-0	-0	R/CD	01008680
Y869	-0	-0	-0.	-0.	46	102	-0	-0	R/CD	01008690
Y870	-0	-0	-0.	-0.	46	104	-0	-0	R/CD	01008700
Y871	-0	-0	-0.	-0.	51	103	-0	-0	R/CD	01008710
Y872	-0	-0	-0.	-0.	51	104	-0	-0	R/CD	01008720
Y873	-0	-0	-0.	-0.	52	103	-0	-0	R/CD	01008730
Y874	-0	-0	-0.	-0.	53	103	-0	-0	R/CD	01008740
Y875	-0	-0	-0.	-0.	53	106	-0	-0	R/CD	01008750
Y876	-0	-0	-0.	-0.	54	106	-0	-0	R/CD	01008760
Y877	-0	-0	-0.	-0.	55	104	-0	-0	R/CD	01008770
Y878	-0	-0	-0.	-0.	55	106	-0	-0	R/CD	01008780
Y879	-0	-0	-0.	-0.	56	104	-0	-0	R/CD	01008790
Y880	-0	-0	-0.	-0.	61	103	-0	-0	R/CD	01008800
Y881	-0	-0	-0.	-0.	62	103	-0	-0	R/CD	01008810
Y882	-0	-0	-0.	-0.	62	105	-0	-0	R/CD	01008820
Y883	-0	-0	-0.	-0.	63	105	-0	-0	R/CD	01008830
Y884	-0	-0	-0.	-0.	64	105	-0	-0	R/CD	01008840
Y885	-0	-0	-0.	-0.	64	106	-0	-0	R/CD	01008850

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Y886	-0	-0	-0.	-0.	65	106	-0	-0	R/CD	01008860
Y887	-0	-0	-0.	-0.	66	103	-0	-0	R/CD	01008870
Y888	-0	-0	-0.	-0.	66	106	-0	-0	R/CD	01008880
Y901	Y912	-0	-0.	-0.	1	99	1	0	R Y901-Y912	01009010
Y921	Y932	-0	-0.	-0.	21	99	1	0	R Y921-Y932	01009210
Y941	Y946	-0	-0.	-0.	41	99	1	0	R Y941-Y946	01009410
Y951	Y956	-0	-0.	-0.	51	99	1	0	R Y951-Y956	01009510
Y961	Y966	-0	-0.	-0.	61	99	1	0	R Y961-Y966	01009610
* 20	-0	-0	-0.	-0.	-0	-0	-0	-0	INT + CONST VALUES	02000000

INITIAL VALUES

C 1	-0	-0	0.181000E-03	-0.	-0	-0	-0	-0	02000010
C 2 C 5	-0	-0	0.109000E-02	-0.	-0	-0	-0	-0	02000020
C 6 C 7	-0	-0	0.218000E-02	-0.	-0	-0	-0	-0	02000060
C 8	-0	-0	0.109000E-02	-0.	-0	-0	-0	-0	02000080
C 9	-0	-0	0.108000E-02	-0.	-0	-0	-0	-0	02000090
C 10	-0	-0	0.620000E-03	-0.	-0	-0	-0	-0	02000100
C 11	-0	-0	0.218000E-02	-0.	-0	-0	-0	-0	02000110
C 12	-0	-0	0.550000E-03	-0.	-0	-0	-0	-0	02000120
C 21	-0	-0	0.138000E-03	-0.	-0	-0	-0	-0	02000210
C 22 C 23	-0	-0	0.276000E-03	-0.	-0	-0	-0	-0	02000220
C 24 C 25	-0	-0	0.138000E-03	-0.	-0	-0	-0	-0	02000240
C 26 C 27	-0	-0	0.276000E-03	-0.	-0	-0	-0	-0	02000260
C 28 C 29	-0	-0	0.138000E-03	-0.	-0	-0	-0	-0	02000280
C 30 C 31	-0	-0	0.276000E-03	-0.	-0	-0	-0	-0	02000300
C 32	-0	-0	0.138000E-03	-0.	-0	-0	-0	-0	02000320
C 41 C 46	-0	-0	0.276000E-03	-0.	-0	-0	-0	-0	02000410
C 51 C 56	-0	-0	0.276000E-03	-0.	-0	-0	-0	-0	02000510
C 61 C 66	-0	-0	0.276000E-03	-0.	-0	-0	-0	-0	02000610
C101	-0	-0	0.323000E-03	-0.	-0	-0	-0	-0	02001010
C102 C105	-0	-0	0.194000E-02	-0.	-0	-0	-0	-0	02001020
C106	-0	-0	0.388000E-02	-0.	-0	-0	-0	-0	02001060
C107	-0	-0	0.432000E-03	-0.	-0	-0	-0	-0	02001070
C108	-0	-0	0.855000E-03	-0.	-0	-0	-0	-0	02001080
C109	-0	-0	0.107000E-02	-0.	-0	-0	-0	-0	02001090
C110	-0	-0	0.206000E-03	-0.	-0	-0	-0	-0	02001100
C111 C112	-0	-0	0.225000E-03	-0.	-0	-0	-0	-0	02001110
C201	-0	-0	0.121000E-02	-0.	-0	-0	-0	-0	02002010
C202 C205	-0	-0	0.726000E-02	-0.	-0	-0	-0	-0	02002020
C206	-0	-0	0.145200E-01	-0.	-0	-0	-0	-0	02002060
C207	-0	-0	0.173000E-02	-0.	-0	-0	-0	-0	02002070
C208	-0	-0	0.346000E-02	-0.	-0	-0	-0	-0	02002080
C209	-0	-0	0.428000E-02	-0.	-0	-0	-0	-0	02002090
C210	-0	-0	0.825000E-03	-0.	-0	-0	-0	-0	02002100
C211 C212	-0	-0	0.900000E-03	-0.	-0	-0	-0	-0	02002110

C301	-0	-0	0.121000E-02	-0.	-0	-0	-0	-0	02003010
C302	C305	-0	0.726000E-02	-0.	-0	-0	-0	-0	02003020
C306	-0	-0	0.145200E-01	-0.	-0	-0	-0	-0	02003060
C307	-0	-0	0.173000E-02	-0.	-0	-0	-0	-0	02003070
C308	-0	-0	0.346000E-02	-0.	-0	-0	-0	-0	02003080
C309	-0	-0	0.428000E-02	-0.	-0	-0	-0	-0	02003090
C310	-0	-0	0.825000E-03	-0.	-0	-0	-0	-0	02003100
C311	C312	-0	0.900000E-03	-0.	-0	-0	-0	-0	02003110
C401	-0	-0	0.121000E-02	-0.	-0	-0	-0	-0	02004010
C402	C405	-0	0.726000E-02	-0.	-0	-0	-0	-0	02004020
C406	-0	-0	0.145200E-01	-0.	-0	-0	-0	-0	02004060
C407	-0	-0	0.173000E-02	-0.	-0	-0	-0	-0	02004070
C408	-0	-0	0.346000E-02	-0.	-0	-0	-0	-0	02004080
C409	-0	-0	0.428000E-02	-0.	-0	-0	-0	-0	02004090
C410	-0	-0	0.825000E-03	-0.	-0	-0	-0	-0	02004100
C411	C412	-0	0.900000E-03	-0.	-0	-0	-0	-0	02004110
T 1	T 66	-0	0.	-0.	-0	-0	-0	-0	T INT = 0 DEG F 02200010
T 99	-0	-1	-0.460000E 03	-0.	-0	-0	-0	-0	T AMB = -460F = 0 R 02200990
T101	T473	-0	0.	-0.	-0	-0	-0	-0	T INT = 0 02201010
D100	-0	-0	0.300000E 04	-0.	-0	-0	-0	-0	T MELT=D100=3000F 02301000
D 1	-0	-0	0.116000E-03	-0.	-0	-0	-0	-0	RANDOM TUMBLING HEAT 02500010
D 2	-0	-0	0.695000E-03	-0.	-0	-0	-0	-0	02500020
D 3	-0	-0	0.750000E-03	-0.	-0	-0	-0	-0	02500030
D 4	-0	-0	0.725000E-03	-0.	-0	-0	-0	-0	02500040
D 5	-0	-0	0.932000E-03	-0.	-0	-0	-0	-0	02500050
D 6	-0	-0	0.171000E-02	-0.	-0	-0	-0	-0	02500060
D 7	-0	-0	0.190000E-02	-0.	-0	-0	-0	-0	02500070
D 8	-0	-0	0.906000E-03	-0.	-0	-0	-0	-0	02500080
D 9	-0	-0	0.129800E-02	-0.	-0	-0	-0	-0	02500090
D 10	-0	-0	0.824000E-03	-0.	-0	-0	-0	-0	02500100
D 11	-0	-0	0.213000E-02	-0.	-0	-0	-0	-0	02500110
D 12	-0	-0	0.656000E-03	-0.	-0	-0	-0	-0	02500120
D 21	-0	-0	0.860000E-04	-0.	-0	-0	-0	-0	02500210
D 22	-0	-0	0.172000E-03	-0.	-0	-0	-0	-0	02500220
D 23	-0	-0	0.178000E-03	-0.	-0	-0	-0	-0	02500230
D 24	-0	-0	0.870000E-04	-0.	-0	-0	-0	-0	02500240
D 25	-0	-0	0.870000E-04	-0.	-0	-0	-0	-0	02500250
D 26	-0	-0	0.175000E-03	-0.	-0	-0	-0	-0	02500260
D 27	-0	-0	0.177000E-03	-0.	-0	-0	-0	-0	02500270
D 28	-0	-0	0.880000E-04	-0.	-0	-0	-0	-0	02500280
D 29	-0	-0	0.960000E-04	-0.	-0	-0	-0	-0	02500290
D 30	-0	-0	0.196000E-03	-0.	-0	-0	-0	-0	02500300
D 31	-0	-0	0.204000E-03	-0.	-0	-0	-0	-0	02500310
D 32	-0	-0	0.104000E-03	-0.	-0	-0	-0	-0	02500320

D 41	-0	-0	0.177000E-03	-0.	-0	-0	-0	-0	02500410
D 42	-0	-0	0.178000E-03	-0.	-0	-0	-0	-0	02500420
D 43	-0	-0	0.182000E-03	-0.	-0	-0	-0	-0	02500430
D 44	-0	-0	0.183000E-03	-0.	-0	-0	-0	-0	02500440
D 45	-0	-0	0.182000E-03	-0.	-0	-0	-0	-0	02500450
D 46	-0	-0	0.177000E-03	-0.	-0	-0	-0	-0	02500460
D 51	-0	-0	0.185000E-03	-0.	-0	-0	-0	-0	02500510
D 52	-0	-0	0.190000E-03	-0.	-0	-0	-0	-0	02500520
D 53	-0	-0	0.196000E-03	-0.	-0	-0	-0	-0	02500530
D 54	-0	-0	0.198000E-03	-0.	-0	-0	-0	-0	02500540
D 55	-0	-0	0.196000E-03	-0.	-0	-0	-0	-0	02500550
D 56	-0	-0	0.187000E-03	-0.	-0	-0	-0	-0	02500560
D 61	-0	-0	0.199000E-03	-0.	-0	-0	-0	-0	02500610
D 62	-0	-0	0.206000E-03	-0.	-0	-0	-0	-0	02500620
D 63	-0	-0	0.216000E-03	-0.	-0	-0	-0	-0	02500630
D 64	-0	-0	0.218000E-03	-0.	-0	-0	-0	-0	02500640
D 65	-0	-0	0.209000E-03	-0.	-0	-0	-0	-0	02500650
D 66	-0	-0	0.197000E-03	-0.	-0	-0	-0	-0	02500660
D 71	-0	-0	0.490000E-04	-0.	-0	-0	-0	-0	02500710
D 72	-0	-0	0.198000E-03	-0.	-0	-0	-0	-0	02500720
D 73	-0	-0	0.198000E-03	-0.	-0	-0	-0	-0	02500730
D 74	-0	-0	0.198000E-03	-0.	-0	-0	-0	-0	02500740
D 75	-0	-0	0.133000E-03	-0.	-0	-0	-0	-0	02500750
D 76	-0	-0	0.534000E-03	-0.	-0	-0	-0	-0	02500760
D 77	-0	-0	0.534000E-03	-0.	-0	-0	-0	-0	02500770
D 78	-0	-0	0.534000E-03	-0.	-0	-0	-0	-0	02500780
D 79	-0	-0	0.133000E-03	-0.	-0	-0	-0	-0	02500790
D 80	-0	-0	0.534000E-03	-0.	-0	-0	-0	-0	02500800
D 81	-0	-0	0.534000E-03	-0.	-0	-0	-0	-0	02500810
D 82	-0	-0	0.534000E-03	-0.	-0	-0	-0	-0	02500820
D 83	-0	-0	0.133000E-03	-0.	-0	-0	-0	-0	02500830
D 84	-0	-0	0.534000E-03	-0.	-0	-0	-0	-0	02500840
D 85	-0	-0	0.534000E-03	-0.	-0	-0	-0	-0	02500850
D 86	-0	-0	0.534000E-03	-0.	-0	-0	-0	-0	02500860
* 30	-0	-0	-0.	-0.	-0	-0	-0	-0	03000000

FUNCTIONS

Y161	Y171	49	-0.	0.758000E-04	-0	-0	-0	-0	R	03001610
Y172	-0	49	-0.	0.463000E-04	-0	-0	-0	-0	R	03001720
Y173	Y175	49	-0.	0.124400E-03	-0	-0	-0	-0	R	03001730
Y261	Y271	49	-0.	0.303200E-03	-0	-0	-0	-0	R	03002610
Y272	-0	49	-0.	0.185200E-03	-0	-0	-0	-0	R	03002720
Y273	Y275	49	-0.	0.497600E-03	-0	-0	-0	-0	R	03002730
Y361	Y371	49	-0.	0.303200E-03	-0	-0	-0	-0	R	03003610
Y372	-0	49	-0.	0.185200E-03	-0	-0	-0	-0	R	03003720

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Y373	Y375	49	-0.	0.497600E-03	-0	-0	-0	-0	R	03003730
Y461	Y471	49	-0.	0.303200E-03	-0	-0	-0	-0	R	03004610
Y472	-0	49	-0.	0.185200E-03	-0	-0	-0	-0	R	03004720
Y473	Y475	49	-0.	0.497600E-03	-0	-0	-0	-0	R	03004730
Y901	-0	49	-0.	0.883000E-04	-0	-0	-0	-0	R	03009010
Y902	Y905	49	-0.	0.530000E-03	-0	-0	-0	-0	R	03009020
Y906	Y907	49	-0.	0.106000E-02	-0	-0	-0	-0	R	03009060
Y908	-0	49	-0.	0.530000E-03	-0	-0	-0	-0	R	03009080
Y909	-0	49	-0.	0.506000E-03	-0	-0	-0	-0	R	03009090
Y910	-0	49	-0.	0.289000E-03	-0	-0	-0	-0	R	03009100
Y911	-0	49	-0.	0.106000E-02	-0	-0	-0	-0	R	03009110
Y912	-0	49	-0.	0.303000E-03	-0	-0	-0	-0	R	03009120
Y921	-0	49	-0.	0.670000E-04	-0	-0	-0	-0	R	03009210
Y922	Y923	49	-0.	0.134000E-03	-0	-0	-0	-0	R	03009220
Y924	Y925	49	-0.	0.670000E-04	-0	-0	-0	-0	R	03009240
Y926	Y927	49	-0.	0.134000E-03	-0	-0	-0	-0	R	03009260
Y928	Y929	49	-0.	0.670000E-04	-0	-0	-0	-0	R	03009280
Y930	Y931	49	-0.	0.134000E-03	-0	-0	-0	-0	R	03009300
Y932	-0	49	-0.	0.670000E-04	-0	-0	-0	-0	R	03009320
Y941	Y946	49	-0.	0.134000E-03	-0	-0	-0	-0	R	03009410
Y951	Y956	49	-0.	0.134000E-03	-0	-0	-0	-0	R	03009510
Y961	Y966	49	-0.	0.134000E-03	-0	-0	-0	-0	R	03009610
D 99	-0	99	-0.	-0.	T 1	D100	-0	-0	STOP AT T001=T MELT	03100990
T100	-0	-1	-0.	-0.	-0	-0	-0	-0	TABLE 1=T100=T STAG	03101000
D200	-0	-2	-0.	-0.	-0	-0	-0	-0	TBL2=D200=Q/TS-540	03102000
Y601	Y612	52	-0.	-0.	D200	D 1	0	1	Y601=D200 X D001	03106010
Y621	Y632	52	-0.	-0.	D200	D 21	0	1	Q REF/TS-540 X	03106210
Y641	Y646	52	-0.	-0.	D200	D 41	0	1	X.824FA = Y	03106410
Y651	Y656	52	-0.	-0.	D200	D 51	0	1		03106510
Y661	Y666	52	-0.	-0.	D200	D 61	0	1		03106610
Y671	Y686	52	-0.	-0.	D200	D 71	0	1	600 SERIES Y	03106710
D301	D386	40	-0.	0.100000E 01	Y601	-0	1	-0	INDIVID HEAT INPUT	03203010
D400	-0	58	-0.	-0.860000E 02	D301	D386	-0	-0	TOTAL HEAT INPUT	03204001
Y821	-0	49	-0.	0.764000E-04	-0	-0	-0	-0	R	03908212
Y822	Y825	49	-0.	0.459000E-03	-0	-0	-0	-0	R	03908222
Y826	-0	49	-0.	0.918000E-03	-0	-0	-0	-0	R	03908262
Y827	-0	49	-0.	0.148000E-03	-0	-0	-0	-0	R	03908272
Y828	-0	49	-0.	0.184000E-03	-0	-0	-0	-0	R	03908282
Y829	-0	49	-0.	0.980000E-04	-0	-0	-0	-0	R	03908292
Y830	-0	49	-0.	0.250000E-03	-0	-0	-0	-0	R	03908302
Y831	-0	49	-0.	0.246000E-03	-0	-0	-0	-0	R	03908312
Y832	-0	49	-0.	0.184000E-03	-0	-0	-0	-0	R	03908322
Y833	Y834	49	-0.	0.306000E-03	-0	-0	-0	-0	R	03908332
Y835	-0	49	-0.	0.148000E-03	-0	-0	-0	-0	R	03908352

Y836	Y837	49	-0.	0.306000E-03	-0	-0	-0	-0	R	03908362
Y838	-0	49	-0.	0.640000E-04	-0	-0	-0	-0	R	03908382
Y839	-0	49	-0.	0.666000E-04	-0	-0	-0	-0	R	03908392
Y840	-0	49	-0.	0.360000E-04	-0	-0	-0	-0	R	03908402
Y841	-0	49	-0.	0.526000E-04	-0	-0	-0	-0	R	03908412
Y842	-0	49	-0.	0.714000E-04	-0	-0	-0	-0	R	03908422
Y843	-0	49	-0.	0.306000E-03	-0	-0	-0	-0	R	03908432
Y844	Y845	49	-0.	0.584000E-04	-0	-0	-0	-0	R	03908442
Y846	-0	49	-0.	0.714000E-04	-0	-0	-0	-0	R	03908462
Y847	Y849	49	-0.	0.580000E-04	-0	-0	-0	-0	R	03908472
Y850	-0	49	-0.	0.116000E-03	-0	-0	-0	-0	R	03908502
Y851	Y852	49	-0.	0.580000E-04	-0	-0	-0	-0	R	03908512
Y853	-0	49	-0.	0.116000E-03	-0	-0	-0	-0	R	03908532
Y854	Y859	49	-0.	0.580000E-04	-0	-0	-0	-0	R	03908542
Y860	-0	49	-0.	0.116000E-03	-0	-0	-0	-0	R	03908602
Y861	-0	49	-0.	0.580000E-04	-0	-0	-0	-0	R	03908612
Y862	-0	49	-0.	0.116000E-03	-0	-0	-0	-0	R	03908622
Y863	Y864	49	-0.	0.580000E-04	-0	-0	-0	-0	R	03908632
Y865	-0	49	-0.	0.116000E-03	-0	-0	-0	-0	R	03908652
Y866	Y867	49	-0.	0.580000E-04	-0	-0	-0	-0	R	03908662
Y868	-0	49	-0.	0.116000E-03	-0	-0	-0	-0	R	03908682
Y869	Y872	49	-0.	0.580000E-04	-0	-0	-0	-0	R	03908692
Y873	-0	49	-0.	0.116000E-03	-0	-0	-0	-0	R	03908732
Y874	Y875	49	-0.	0.580000E-04	-0	-0	-0	-0	R	03908742
Y876	-0	49	-0.	0.116000E-03	-0	-0	-0	-0	R	03908762
Y877	Y878	49	-0.	0.580000E-04	-0	-0	-0	-0	R	03908772
Y879	Y880	49	-0.	0.116000E-03	-0	-0	-0	-0	R	03908792
Y881	Y882	49	-0.	0.580000E-04	-0	-0	-0	-0	R	03908812
Y883	-0	49	-0.	0.116000E-03	-0	-0	-0	-0	R	03908832
Y884	Y885	49	-0.	0.580000E-04	-0	-0	-0	-0	R	03908842
Y886	-0	49	-0.	0.116000E-03	-0	-0	-0	-0	R	03908862
Y887	Y888	49	-0.	0.580000E-04	-0	-0	-0	-0	R	03908872
* 40	-0	-0	-0.	-0.	-0	-0	-0	-0	TABLES	04000000

MONOVARIATE TABLE DATA

TABLE			X		Z							
1	-0	-0	0.	0.500040E 05	-0	-0	-0	-0	TABLE ONE		04100000	
-0	-0	-0	0.100000E 02	0.498440E 05	-0	-0	-0	-0	T STAG	DEG F	04100100	
-0	-0	-0	0.200000E 02	0.496560E 05	-0	-0	-0	-0			04100200	
-0	-0	-0	0.300000E 02	0.494400E 05	-0	-0	-0	-0			04100300	
-0	-0	-0	0.400000E 02	0.491880E 05	-0	-0	-0	-0			04100400	
-0	-0	-0	0.500000E 02	0.488960E 05	-0	-0	-0	-0			04100500	
-0	-0	-0	0.600000E 02	0.485490E 05	-0	-0	-0	-0			04100600	
-0	-0	-0	0.700000E 02	0.481440E 05	-0	-0	-0	-0			04100700	

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-0	-0	-0	0.800000E 02	0.476640E 05	-0	-0	-0	-0	04100800
-0	-0	-0	0.900000E 02	0.470920E 05	-0	-0	-0	-0	04100900
-0	-0	-0	0.100000E 03	0.464080E 05	-0	-0	-0	-0	04101000
-0	-0	-0	0.110000E 03	0.455880E 05	-0	-0	-0	-0	04101100
-0	-0	-0	0.120000E 03	0.446000E 05	-0	-0	-0	-0	04101200
-0	-0	-0	0.130000E 03	0.433880E 05	-0	-0	-0	-0	04101300
-0	-0	-0	0.140000E 03	0.419040E 05	-0	-0	-0	-0	04101400
-0	-0	-0	0.150000E 03	0.400800E 05	-0	-0	-0	-0	04101500
-0	-0	-0	0.160000E 03	0.378360E 05	-0	-0	-0	-0	04101600
-0	-0	-0	0.170000E 03	0.350480E 05	-0	-0	-0	-0	04101700
-0	-0	-0	0.180000E 03	0.315840E 05	-0	-0	-0	-0	04101800
-0	-0	-0	0.190000E 03	0.273000E 05	-0	-0	-0	-0	04101900
-0	-0	-0	0.200000E 03	0.221520E 05	-0	-0	-0	-0	04102000
2	-0	-0	0.	0.170000E-02	-0	-0	-0	-0	04200000
-0	-0	-0	0.100000E 02	0.181000E-02	-0	-0	-0	-0	04200100
-0	-0	-0	0.200000E 02	0.194000E-02	-0	-0	-0	-0	04200200
-0	-0	-0	0.300000E 02	0.208000E-02	-0	-0	-0	-0	04200300
-0	-0	-0	0.400000E 02	0.224000E-02	-0	-0	-0	-0	04200400
-0	-0	-0	0.500000E 02	0.242000E-02	-0	-0	-0	-0	04200500
-0	-0	-0	0.600000E 02	0.262000E-02	-0	-0	-0	-0	04200600
-0	-0	-0	0.700000E 02	0.283000E-02	-0	-0	-0	-0	04200700
-0	-0	-0	0.800000E 02	0.308000E-02	-0	-0	-0	-0	04200800
-0	-0	-0	0.900000E 02	0.336000E-02	-0	-0	-0	-0	04200900
-0	-0	-0	0.100000E 03	0.368000E-02	-0	-0	-0	-0	04201000
-0	-0	-0	0.110000E 03	0.403000E-02	-0	-0	-0	-0	04201100
-0	-0	-0	0.120000E 03	0.444000E-02	-0	-0	-0	-0	04201200
-0	-0	-0	0.130000E 03	0.493000E-02	-0	-0	-0	-0	04201300
-0	-0	-0	0.140000E 03	0.549000E-02	-0	-0	-0	-0	04201400
-0	-0	-0	0.150000E 03	0.612000E-02	-0	-0	-0	-0	04201500
-0	-0	-0	0.160000E 03	0.685000E-02	-0	-0	-0	-0	04201600
-0	-0	-0	0.170000E 03	0.808000E-02	-0	-0	-0	-0	04201700
-0	-0	-0	0.180000E 03	0.876000E-02	-0	-0	-0	-0	04201800
-0	-0	-0	0.190000E 03	0.995000E-02	-0	-0	-0	-0	04201900
-0	-0	-0	0.200000E 03	0.111800E-01	-0	-0	-0	-0	04202000
* 70	-0	-0	-0.	-0.	-0	-0	-0	-0	07000000

TABLE TWO
Q REF / TS - 540

SPECIAL CONSTANT VALUES

1	0.245000E-00	SPECIFIED DELTA-TIME	07000011
2	0.500000E-01	MINIMUM ALLOWED DELTA-TIME	07000020
7	0.100000E 01	FLAG +1.0 FOR COMPLETE CORE DUMP ATEND OF RUN	

*99 RUNS ONLY

* 80

PRINT OUT SPECIFICATIONS

T 1 T 12	-0	-0.	-0.	-0	-0	-0	-0	08000010
T 21 T 32	-0	-0.	-0.	-0	-0	-0	-0	08000210

07000070
08000000

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T 41	T 46	-0	-0.	-0.	-0	-0	-0	-0	08000410
T 51	T 56	-0	-0.	-0.	-0	-0	-0	-0	08000510
T 61	T 66	-0	-0.	-0.	-0	-0	-0	-0	08000610
T 99	T100	-0	-0.	-0.	-0	-0	-0	-0	08000990
T401	-0	-0	-0.	-0.	-0	-0	-0	-0	08004011
D400	-0	-0	-0.	-0.	-0	-0	-0	-0	TOTAL HEAT INPUT 08104000
* 90	-0	-0	-0.	-0.	-0	-0	-0	-0	TIME TO PRINT 09000000
RUN CONTROL									
-0	-0	-0	-0.	0.100000E 01	-0	-0	-0	-0	PRINT EVERY SECOND 09000011
-0	-0	-0	0.180000E 03	-0.	-0	-0	-0	-0	STOP AT TIME = 180 09000020
* 99	-0	-0	-0.	-0.	-0	-0	-0	-0	99999999

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APPENDIX C

Aerodynamic Heating Factors

The geometric aerodynamic heating factors for the random tumbling, side-on, and end-on flight configurations are tabulated in the following pages. The values have been calculated on the basis of Tables V and VI and were used with the "3-D core" thermal model of Chapter V for computer runs 7323-19, 23, 24, 25, 26, and 27.

TABLE C-a

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 F_b FACTORS

NODE	X (in)	$\frac{X}{R}$	F_b	NODE	X	$\frac{X}{R}$	F_b
1	0	0	1.0	41	1.67	.378	1.024
2	1.26	.0286	1.0096	42	1.89	.428	1.036
3	2.51	.569	1.0936	43	2.12	.480	1.054
4	2.18	.494	1.0585	44	2.18	.493	1.058
5	3.77	.854	1.356	45	2.00	.453	1.044
6	3.35	.759	1.241	46	1.72	.389	1.026
7	3.86	.875	1.386				
8	3.65	.827	1.320	51	2.36	.534	1.076
9	4.27	.966	1.535	52	2.56	.580	1.100
10	4.31	.976	1.554	53	2.83	.641	1.138
11	4.07	.921	1.457	54	2.90	.656	1.149
12	4.20	.951	1.508	55	2.72	.638	1.136
				56	2.45	.554	1.085
21	0.46	.104	1.00	61	2.92	.661	1.153
22	0.64	.145	1.001	62	3.14	.711	1.194
23	0.92	.208	1.034	63	3.40	.770	1.253
24	1.01	.229	1.0046	64	3.43	.776	1.260
25	1.19	.270	1.0079	65	3.22	.729	1.211
26	1.34	.304	1.0118	66	2.86	.647	1.143
27	1.62	.367	1.022				
28	1.73	.392	1.027	LAYER			Kemp, Rose, Detra
29	2.64	.598	1.110	OXX	4.478	1.014	0.58
30	2.79	.632	1.132				
31	3.07	.695	1.180	1XX	4.623	1.047	0.48
32	3.19	.722	1.205				
				2XX	4.661	1.056	0.45
				3XX	5.144	1.166	0.35
				4XX	5.475	1.241	0.28

TABLE C-6
 Σ FACTORS (RANDOM TUMBLING)

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NODE	$\Sigma \mathcal{F}A \times 10^3$ ft ²	NODE	$\Sigma \mathcal{F}A \times 10^3$ ft ²
1	.116	51	.185
2	.695	52	.190
3	.750	53	.196
4	.725	54	.198
5	.932	55	.196
6	.710	56	.187
7	.900		
8	.906	61	.199
9	1.298	62	.206
10	.824	63	.216
11	2.130	64	.218
12	.656	65	.209
		66	.197
21	.086		
22	.172	154	.049
23	.178	254	.198
24	.087	354	.198
25	.087	454	.198
26	.175	110	.133
27	.177	210	.534
28	.088	310	.534
29	.096	410	.534
30	.196	111	.133
31	.204	211	.534
32	.104	311	.534
		411	.534
41	.177	112	.133
42	.178	212	.534
43	.182	312	.534
44	.183	412	.534
45	.182		
46	.177		

TABLE C-C

$\sum F$ FACTORS (SIDE-ON)

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NODE	$\sum F A \times 10^3$ ft ²	NODE	$\sum F A \times 10^3$ ft ²
1	0.065	51	.01
2	.39	52	.01
3	.39	53	.01
4	.39	54	.01
5	.39	55	.01
6	.78	56	.01
7	.78		
8	.39	61	.01
9	.70	62	.01
10	.51	63	.01
11	.95	64	.01
12	.38	65	.01
		66	.01
21	0.05		
22	.10	154	.066
23	.10	254	.274
24	.05	354	.274
25	.05	454	.274
26	.10	110	.177
27	.10	210	.71
28	.05	310	.71
29	.05	410	.71
30	.10	111	.177
31	.10	211	.71
32	.05	311	.71
		411	.71
41	.10	112	.177
42	.10	212	.71
43	.10	312	.71
44	.10	412	.71
45	.10		
46	.10		

TABLE C-d

F FACTORS (END-ON)

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NODE	$\sum F A \times 10^3$ ft ²	NODE	$\sum F A \times 10^3$ ft ²
1	.22	51	.354
2	1.33	52	.362
3	1.43	53	.375
4	1.38	54	.379
5	1.78	55	.374
6	3.27	56	.358
7	3.64		
8	1.73	61	.380
9	2.01	62	.394
10	1.15	63	.413
11	3.82	64	.415
12	1.0	65	.398
		66	.378
21	.165		
22	.33	0xx	.066 .179
23	.34		
24	.166	1xx	.055 .148
25	.166		
26	.334	2xx	.204 .552
27	.338		
28	.169	3xx	.160 .432
29	.183		
30	.374	4xx	.128 .344
31	.389		
32	.199		
41	.338		
42	.341		
43	.348		
44	.348		
45	.344		
46	.338		

ATOMICS INTERNATIONAL

A Division of North American Aviation, Inc.

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1. Design Drawings of SNAP 10A Reactor Core:
 - (a) 10FS-10004 Core Installation - Final
 - (b) 10FSM2-15002 Plate Assy-Upper Grid, Reactor Vessel
 - (c) 10FSM2-15003 Plate Assy-Lower Grid, Reactor Vessel
 - (d) 7580 - 18020 SNAP 10A Assembly-Fuel Element
 - (e) 10PSM1-12006 Detail-Reflector and Element
2. R. W. Detra and H. Hidalgo, "Generalized Heat Transfer Formulas and Graphs for Nose Cone Reentry Into the Atmosphere," American Rocket Society Journal, March 1961, Pages 318-321
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NOMENCLATURE

A	Area	ft ²
A _N	Nodal Area	ft ²
A _{Ref}	Reference Area (End of Cylinder)	
	$A_{Ref} = \frac{\pi D^2}{4}$ Eq. (III-14)	ft ²
Alt _o	Initial Altitude of Trajectory	ft or kft
C	Thermal Capacitance of Node, C = m c _p	Btu/°F
C _D	Drag Coefficient on Body,	
	$C_D = \frac{F}{\left(\frac{\rho V^2}{2g_c}\right) A}$, Eq. (III-3)	
$\bar{C}_D$	Mean Drag Coefficient of a Tumbling Body,	
	$\bar{C}_D = \frac{\int C_D d\alpha}{\int d\alpha}$ or $\frac{\int C_D dA}{\int dA}$	
C _P	Drag Coefficient on a Point	
C _{P_s}	Drag Coefficient on the Stagnation Point	
c _p	Specific Heat (Table II)	Btu/lb _m °F
D	Diameter	ft or in.
F	Force	lb _F
F _A , F _N , F _D	Axial, Normal (to axis), and Drag Force (Figure 5-c)	lb _F
F _a → F _k	Aerodynamic Heating Correlation Factors (Table V)	
$\mathcal{F}$	Aerodynamic Heating Correlation Factors (Table VI, Eq. III-46)	
$\mathcal{F}$	Radiation Factors, $\mathcal{F} = \mathcal{F}(\epsilon, \text{Geometry})$	
g _c	Gravitational Constant, = 32.2	$\frac{\text{ft lb}_m}{\text{sec}^2 \text{ lb}_F}$

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h	Heat Transfer Coefficient	$\frac{\text{Btu}}{\text{ft}^2 \text{ sec } ^\circ\text{F}}$
H	Enthalpy	$\frac{\text{Btu}}{\text{lb}_m}$
H_s, H_w, H_{540}	Stagnation Enthalpy, Air Enthalpy at Wall Temperature, Air Enthalpy at $T = 540^\circ\text{R}$	$\frac{\text{Btu}}{\text{lb}_m}$
(HWCf)	Hot Wall Correction Factor (Eq. III-27a) $(\text{HWCf}) = \frac{H_s - H_w}{H_s - H_{540}}$	
k	Thermal Conductivity, (Table II)	$\frac{\text{Btu}}{\text{sec ft } ^\circ\text{F}}$
L	Length	ft
L_m	Latent Heat of Fusion	$\frac{\text{Btu}}{\text{lb}_m}$
m	Mass	lb_m
q_{Ref}	Reference Heating, (Eq. III-29)	$\frac{\text{Btu}}{\text{sec ft}^2}$
q_{ss}	Spherical Stagnation Point Heating (Eq. III-26)	$\frac{\text{Btu}}{\text{sec ft}^2}$
q_{sp}	Stagnation Point Heating, End of Cylinder	$\frac{\text{Btu}}{\text{sec ft}^2}$
q_{sl}	Stagnation Line Heating, on Side of Cylinder	$\frac{\text{Btu}}{\text{sec ft}^2}$
Q_{INT}	Integrated Reference Heating $Q_{\text{INT}} = \int_{t_0}^t q_{\text{Ref}} dt \quad (\text{Eq. III-47})$	$\frac{\text{Btu}}{\text{ft}^2}$
Q_N	Heat Input into Node	$\frac{\text{Btu}}{\text{sec}}$
r	Radial Distance	ft or in.
R	Radius	ft or in.

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R_o	Reference Radius, $R_o = 12 \text{ inches} = 1 \text{ ft}$	
(SCF)	Size Correction Factor, (Eq. III-28)	
	$(\text{SCF}) = \sqrt{\frac{R_o}{R}}$	
t	Time Measured from Initiation of Reentry Trajectory	sec
T_m	Melting Temperature, (Table II)	°F
T_N	Nodal Temperature	°F
T_s	Stagnation Temperature	°F
T_w	Wall Temperature	°F
V	Flow Stream (or Projectile) Velocity	ft/sec
V_o	Reference Velocity, $V_o = 10,000 \text{ ft/sec}$	
W	Projectile Mass	lb_m
$W/C_D A$	Ballistic Coefficient	$\frac{\text{lb}_m}{\text{ft}^2}$
x	Radial Distance	ft or in.
α	Angle of Attack	deg.
$\beta, \gamma, \eta, \theta$	Angles	deg.
ϵ	Radiative Emissivity	
ρ	Atmospheric Density, Material Density (Table II)	$\frac{\text{lb}_m}{\text{ft}^3}$
ρ_o, ρ_{sl}	Atmospheric Density at Sea Level	
	$\rho_o = 0.07647 \frac{\text{lb}_m}{\text{ft}^3}$	
ϕ	Surface Heating Parameter, Figure 18	

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SUBSCRIPTS

E/E	End-Over-End
EO	End-On
N	Node or Normal
o	Initial or Reference
RT	Random Tumbling
SO	Side-On