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PAGE 1 OF 44

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TITLE

Thermal Behavior of Manned Orbiting Research
Laboratory and Lunar Base Reactor Systems During
Atmospheric Reentry

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STATEMENT OF PROBLEM

Conduct a thermal analysis of the M.O.R.L. and lunar base reactor system to determine their probable configuration and impact

ABSTRACT:

A thermal analysis was carried out to determine the thermal behavior of the M.O.R.L and lunar base reactor systems during atmospheric reentry. Of particular interest are the configurations of the various reactor systems at impact and the effect of the presence of a ⁴ Pi neutron shield upon the reactor thermal behavior.

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ATOMICS INTERNATIONAL

A Division of North American Aviation, Inc.

NO. NAA-SR-TDR-12623

DATE 12/14/67

PAGE 2 OF 44

I. Introduction

An analysis was performed to simulate the thermal behavior of the Manned Orbiting Research Laboratory (MORL) and the lunar base reactor system during reentry into the earth's atmosphere. The objective of this analysis was to determine the probable configuration of the reactor systems after reentry with initial flight angles of both 0.0 and -3.0 degrees. In addition, the MORL reactor was investigated under the same conditions with and without the presence of a 4-pi shield.

The analysis concerned the heating and subsequent removal of the various systems' components during the two reentry trajectories. During both trajectories each MORL reactor system analyzed was assumed to be fastened to the neutron shadow shield assembly, to be spinning about its longitudinal axis, and have a constant 0.0° angle of attack. Since the cases investigated were based on the assumption of a constant angle of attack, it was possible to determine the relative effect of reentry flight angle on thermal behavior.

The lunar base reactor was assumed to be tumbling at random during reentry. This assumption was based upon the symmetric nature of the system with respect to its core and LiH shield components. The reactor's primary NaK equipment and associated shield was omitted from the analytical model since its presence has little effect upon the ablation characteristics of the reactor core and neutron shield.

In this analysis, the assumption was made that as the various systems reenter, direct aerodynamic heating occurs only on those portions which are actually exposed to the flow stream. During the first phase of each case heating of the internal portions of each reactor takes place only indirectly, that is by internal conduction and radiation. Eventually, sufficient heating may have occurred to melt through exterior portions of the reactors, exposing internal core components to direct aerodynamic heating.

ATOMICS INTERNATIONAL

A Division of North American Aviation, Inc.

NO. NAA-SR-TDR-12623

DATE 12/14/67

PAGE 3 OF 44

II. Reference Reentry Trajectories

The RESTORE (Reentering SNAP Trajectory on an Oblate Rotating Earth) computer program (see Reference 1) was used to calculate the trajectories of the various reentering systems. The trajectory for each reactor system depends on the body's ballistic coefficient, as well as its initial velocity, position, and orientation. Initial flight angles of 0.0 and -3.0 degrees were considered for each of the three reactor systems analyzed. The ballistic coefficient of each reactor is dependent upon the body's weight, W ; projected area, A ; and drag coefficient, C_d . In order to determine these aerodynamics coefficient, an approximation of each system's reactor-shield assembly geometry were made as shown in Figure 1.

The drag coefficients acting on the configurations shown in Figure 1 were determined by the NEWTON Code. The Newton Code, devised by Nelson (Reference 2) is a computer program formulated to calculate the force and moment coefficients on axisymmetric bodies in hypersonic flow based on Newtonian flow theory. The results of the NEWTON Code calculations, for zero angle of attack, and the corresponding $W/C_d A_{ref}$ (lbm/ft²) for each system are listed in Table I.

TABLE I
Drag and Ballistic Coefficient used in RESTORE
Reentry Trajectory Calculations

	MORL (w/o Shield)	MORL (w/Shield)	Lunar Base Reactor
C_d	0.33	0.776	1.0
$W/C_d A$ (lbm/ft ²)	1077.8	555.3	530.0

The $W/C_d A$ values given in Table I for the two MORL reactors neglect the presence of the large thermal radiation skirt behind the reactor systems. The skirt extends the conical shape of the reactor base an additional 140 inches below the geometries shown in Figure 1. The presence of

Figure - 1

External Geometry Approximations used in NEWTON Code

M.O.R.L. 4-Pi
Shielded Reactor

M.O.R.L. Reactor Without
4-Pi Shield

Lunar Base Reactor

ATOMICS INTERNATIONAL

A Division of North American Aviation, Inc.

NO. NAA-SR-TDR-12623

DATE 12/14/67

PAGE 5 OF 44

this skirt behind the reentering system lowers the respective $W/C_d A$ values. The $W/C_d A$ value for the MORL reactor without 4-Pi shielding becomes 265.4 lb/ft^2 while that for the 4-Pi shielded reactor is 420.7 lb/ft^2 . Using these drag coefficients and those listed in Table I, two trajectories were calculated for each reactor system. Each reactor system was considered having initial flight angles of 0.0 and -3.0 degrees and the following initial conditions:

Altitude	400,000 ft
Longitude	0.0 degrees
Latitude	90.0 degrees
Velocity	25,694 ft/sec
Azimuth	+ 180.0 degrees

Upon comparison of the MORL reactor trajectories with and without the radiator skirt attached to the reactor systems, it was found that the skirt could be neglected. The aerodynamic heat to the MORL systems with and without radiation skirt attached as functions of altitude were almost identical. For this reason all MORL trajectories used in this analysis assumed that the thermal radiator skirt was not attached to the reactor systems during reentry.

The results of the various RESTORE calculations, altitude and reference heating versus time, and reference heating versus altitude, used in this analysis are shown in the figures as tabulated in Table II.

TABLE II
Results of RESTORE Calculations

Trace	Initial Flight Angle					
	8.0 Degrees			-3.0 Degrees		
	MORL w/o Shield	MORL w/Shield	Lunar Base	MORL w/oShield	MORL w/Shield	Lunar Base
Altitude in Time	Fig 2	Fig 2	Fig 2	Fig 5	Fig 4	Fig 6
Reference Heating vs Time	Fig 2	Fig 2	Fig 2	Fig 5	Fig 4	Fig 6
Reference Heating vs Altitude	Fig 3	Fig 3	Fig 3	Fig 7	Fig 7	Fig 7

FIGURE 2
REFERENCE TRAJECTORIES, 0.0 INITIAL FLIGHT ANGLE
A-MORL REACTOR WITH A-PI SHIELD
B-MORL REACTOR WITHOUT A-PI SHIELD
C-LUNAR BASE REACTOR
D-ALTITUDE VS TIME
E-REFERENCE HEAT RATE VS TIME

Figure 2

FIGURE-3

REFERENCE HEATING VS ALTITUDE
FOR THE REFERENCE TRAJECTORIES
OF INITIAL FLIGHT ANGLE

A-MODE REACTOR WITH APR SHIELD
B-MODE REACTOR WITHOUT APR SHIELD
C-LUNA BASE REACTOR

FIGURE-5
M.O.R.L. REACTOR WITHOUT
4-PI SHIELD REFERENCE TRAJECTORY
- 3.0 INITIAL FLIGHT ANGLE

FIGURE - 6
LUNAR BASE REACTOR
REFERENCE TRAJECTORY
- 8.3 INITIAL FLIGHT ANGLE

FIGURE 7
DIFFERENTIAL HEATING VS. ALTITUDE
FOR THE REFERENCE TRAJECTORIES
-3.0 INITIAL FLIGHT ANGLE

These reference trajectories have been used for all the reentry calculations presented in this report.

The actual aerodynamic heating on any point in the reentering vehicle is given by the expression:

$$Q_N \frac{\text{Btu}}{\text{sec}} = (q_{\text{Ref}}) \underbrace{\left[\sqrt{\frac{R_o}{R}} \frac{q_{\text{local}} (\text{radius} = R)}{q_{\text{stag}} (\text{radius} = R)} \right]}_{\phi} [\text{HWCR}] A_N$$

(See Reference 3, Equation (2), and Reference 4, Equations (III-26 to 29) and (III-46).

The hot wall correction factor (HWCR) has been neglected in the calculations reported herein, as it is consistently close to unity.

The heating loading factor, ϕ , is made up of the size correction factor,

R_o/R , and the location factor, q/q (See Reference 4, pages 27-39).

The local heating factors, ϕ , as applied to the thermal models presented in this report, are discussed in detail in Section V.

III. Geometric and Thermal Properties of Reactor Systems

The physical characteristics of the three reactor systems analyzed are shown in the design drawings listed in Reference 5. Design parameters were closely followed in the analytical model of both the shielded and unshielded MORL reactor systems, however, a simplified model was used in describing the lunar base reactor system. Due to the symmetric nature of the three reactor systems with regard to geometric configuration and aerodynamic heat distribution, some approximations were assumed for computational simplicity.

Only axial and radial variations of geometric parameters were taken into account. No circumferential variable was considered. The core and system components of both MORL reactors were treated as a series of concentric regions and a 45° circumferential segment was represented by the thermal models.

To describe the lunar base reactor system a one foot square section, composed of all materials to be thermally transversed was used in the analytical model. Since heating will be symmetrical over the whole system the "weakest" thermal path into the reactor will be from the bottom which

ATOMICS INTERNATIONAL

A Division of North American Aviation, Inc.

NO. NAA-SR-TDR-12623

DATE 12/14/67

PAGE 13 OF 44

will be a thinner LiH shield. (See Section IV on Analytical Models for details of the various thermal analogs).

The two MORL reactor systems are primarily composed of enlarged SNAP 8 type reactors mounted forward of a series of tungsten gamma and lithium hydride neutron shadow shields. Beryllium oxide neutron reflectors are located externally adjacent to the reactor vessel. The MORL 4-P1 shielded configuration has additional tungsten, lithium hydride and thermal shielding surrounding the reactor core and control drums.

The lunar base reactor system also consists of a SNAP type reactor using external beryllium reflectors surrounded by tungsten, Min-K insulation, and lithium hydride shield material. The lithium hydride shielding is enclosed in a truncated cone-shaped stainless steel shell.

The material properties used in the thermal analysis are given in Table III. All thermophysical properties used were assumed constant at values considered appropriate to yield correct thermal responses of the respective components.

Table III

Thermal Properties of Materials Used in Calculations

(A) Beryllium

1. Thermal Conductivity @ 1200°F

$$K = 15.0 \times 10^{-4} \text{ Btu/in-sec-}^{\circ}\text{F}$$

2. Density = $\rho = 0.067 \text{ lb/in}^3$

3. Specific Heat = $C_p = 0.7 \frac{\text{Btu}}{\text{lb-}^{\circ}\text{F}} @ 1200^{\circ}\text{F}$

4. Thermal Emissivity = $\epsilon = 0.61$

5. Melting Point = 2345°F

(B) Beryllium Oxide

1. Thermal Conductivity = $K =$

$$2.245 \times 10^{-4} \text{ Btu/sec-in-}^{\circ}\text{F} @ 2200^{\circ}\text{F}$$

2. Specific Heat = $C_p = 0.57 \text{ Btu/lb-}^{\circ}\text{F}$
@ 2200°F

3. Density = $\rho = 0.1085 \text{ lb/in}^3$

4. Thermal Emissivity = $\epsilon = 0.6$

5. Melting Point = 4658°F

ATOMICS INTERNATIONAL

A Division of North American Aviation, Inc.

NO. NAA-SR-TDR-12623

DATE 12/14/67

PAGE 14 OF 44

TABLE III
(Continued)

(C) Lithium Hydride

1. Thermal Conductivity =
 $K = 4.62 \times 10^{-5} \text{ Btu/sec-in-}^{\circ}\text{F}$
2. Specific Heat = $C_p = 1.00 \text{ Btu/lb-}^{\circ}\text{F}$
3. Density = $\rho = 0.297 \text{ lb/in}^3$
4. Thermal Emissivity = $\epsilon = 0.4$
5. Melting Point = 1255°F

(D) Min-K-2000

1. Thermal Conductivity =
 $K = 0.463 \times 10^{-5} \frac{\text{Btu}}{\text{sec in-}^{\circ}\text{F}} @ 1200^{\circ}\text{F}$
2. Specific Heat = $C_p = 0.27 \text{ Btu/lb-}^{\circ}\text{F} @ 1200^{\circ}\text{F}$
3. Density = $\rho = 0.0116 \text{ lb/in}^3$
4. Thermal Emissivity = $\epsilon = 0.4$

(E) Stainless Steel - 304

1. Thermal Conductivity = $K = 2.87 \times 10^{-4} \frac{\text{Btu}}{\text{sec-in-}^{\circ}\text{F}} @ 932^{\circ}\text{F}$
2. Specific Heat = $C_p = 0.12 \text{ Btu/lb}^{\circ}\text{F}$
3. Density = $\rho = 0.29 \text{ lb/in}^3$
4. Thermal Emissivity = $\epsilon = 0.7$
5. Melting Point = 2650°F

(F) Tungsten

1. Thermal Conductivity =
 $K = 1.51 \times 10^{-3} \text{ Btu/sec-in-}^{\circ}\text{F}$
2. Specific Heat = $C_p = 0.035 \text{ Btu/lb-}^{\circ}\text{F}$
3. Density = $\rho = 0.702 \text{ lb/in}^3$
4. Thermal Emissivity = $\epsilon = 0.4$

(G) Zirconium Hydride- Fuel Material

1. Thermal Conductivity =
 $K = 5.0 \times 10^{-4} \text{ Btu/in-sec-}^{\circ}\text{F}$

TABLE III
(Continued)

2. Specific Heat = $C_p = 0.2 \text{ Btu/lb-}^\circ\text{F}$
3. Density = $\rho = 0.22 \text{ lb/in}^3$
4. Thermal Emissivity = $\epsilon = 0.4$
5. Melting Point = 3280°F

IV. Analytical Models of Reentering Systems

Thermal models were devised to represent the various reactor systems during reentry to the earth's atmosphere. These analytical models were developed for use with the "Thermal Analyzer Program" (TAP) computer code (see Reference 6). The modes and paths of heat transfer on the models were represented by (thermal) resistors; and structural masses (thermal capacity) were represented by nodes and capacitors. Thus, a resistor-capacitor network was constructed, using structural lump sizes as required to properly account for the expected thermal gradients in the system.

The three analytical models employed in studying the behavior of the various reentering reactor systems are discussed below.

(1) MORL Reactor without 4-Pi Shield

The geometric configuration of this reactor is shown in Figure 8. The external NaK coolant flow tubes shown in Figure 8 were not included in the analytical representation. It is felt that these tubes will readily ablate upon reentry and therefore have little effect upon the thermal behavior of the reactor system.

The analytical model represents the top head, reactor vessel, internal core components and the external beryllium reflectors of the MORL reactor. A simplification was made in simulating the top head and upper grid plate of the reactor. The top head was considered as a single plate instead of the split one shown in Figure 8. The upper grid plate was assumed to be flat with a thickness equal to the average thickness of the rounded grid plate shown in Figure 8.

Figure 8

In devising this model, longitudinal and radial variations of parameters were taken into account, but circumferential variations were neglected. Thus, an annular model of the reactor system was set up. The radial annular division of the system is shown in Figure 9. This section was taken at the midplane of the reactor core. Due to the symmetric nature of the reactor system a 45° circumferential section was represented by the TAP analog.

The fuel material was divided into three radial portions, a central section with a 4.714 inch radius, and two concentric annuli with equal ΔR 's of 0.560 inch. The central portion served as a thermal heat sink with a mass equal to that of 30 fuel elements. Each of the two concentric rings contained mass equivalent to 7 fuel elements. A third concentric ring with a $\Delta R = 0.215$ inch was used to represent the reactor vessel wall. The external Be reflectors were simulated by a fourth concentric ring with a $\Delta R = 3.5$ ", which is the Be midplane thickness.

The longitudinal nodal division of the MORL reactor is shown in Figure 10. The total reactor length was simulated by the analytical model. Each node, located at the reactor midplane, represents a total depth of 17 inches. The upper head and grid plate was also divided into a series of concentric sections, as shown in Figure 10.

Aerodynamic heat loading was input to all exterior nodes which in turn radiated to space at a constant temperature of -460.0°F . Heat was transferred to the reactor system components via thermal conduction paths, shown as dashed lines in Figures 9 and 10 or by means of radiation paths which are shown as zig-zag lines in the same figures.

(2) MORL Reactor

The 4-Pi shielded MORL reactor system is shown in Figure 11. As can be seen in Figure 11 the reactor is essentially the same as that of the MORL reactor without 4-Pi shielding. The 4-Pi shielded configuration utilizes cylindrical BeO reflectors instead of the tapered pure beryllium

Figure - 9

Radial Annular Division of the M.O.R.L. Reactor
Analytical Model without 4-Pi Lithium Hydride Shield

ATOMICS INTERNATIONAL

A Division of North American Aviation, Inc.

NO. NAA-SR-TDR-12623

DATE 12/14/67

PAGE 19 OF 44

Figure - 10

Longitudinal Nodal Division of the M.O.R.L. Reactor
Analytical Model without 4-Pi Lithium Hydride Shield

FIGURE 11 PRELIMINARY REACTOR, T/O R P1 SHIELD, & PRIMARY COOLANT SYSTEM
ASSEMBLY USING E/M PUMPS & NAK TO NAK HEAT EXCHANGERS

ATOMICS INTERNATIONAL

A Division of North American Aviation, Inc.

NO. NAA-SR-TDR-12623

DATE 12/14/67

PAGE 21 OF 44

reflectors used with the unshielded reactor.

To represent this system a thermal network to simulate the tungsten, Min-K, and canned lithium hydride shielding material was added to the TAP analog described in Part I of this section. The 4-Pi shielding consists of 1.8 inch capped cylindrical tungsten gamma shield enclosing the reactor core, surrounded by a 0.75 inch layer of Min-K thermal insulation which is in turn surrounded by a canned lithium hydride neutron shield. The lithium hydride shield has the shape of a truncated core with an effective thickness of 8.6 inches. The material is encapsulated by a 0.10 inch thick SS-304 containment vessel.

The thermal network that was added to the analog of the MORL reactor to simulate the 4-Pi shielded system is illustrated in Figure 12. More detail was built into the forward section of the analytical model since that portion receives more intense aerodynamic heat loading when reentering with a 0.0° angle of attack. Each layer of the shielding material was considered as one thermal segment in depth with the exception of the LiH neutron shield. This material has a thickness of 8.6 inches and therefore was divided into four thermal segments, each 2.15 inches in depth. Each segment in the LiH shield consists of a central capacitance node and two non-capacitance nodes located at the segment interface, as shown in Figure 12.

Aerodynamic heating was again input to all external nodes and then transferred to internal system components via heat conduction or radiation paths. All analytical nodes in the various shielding materials were interconnected by both radial and longitudinal heat conduction paths (shown as dashed lines in Figure 12). Since no direct contact exists between the tungsten gamma shield and the reactor vessel the only means of heat transfer between the two was by radiation. The radiant heat transfer paths are shown as zig-zag lines in Figure 12.

3) Lunar Base Reactor System

A simplified schematic of the lunar base reactor system is shown in Figure 13. The primary NaK equipment and equipment shielding, located atop the system, was omitted from the analytical model. The basic consideration

ATOMICS INTERNATIONAL

A Division of North American Aviation, Inc.

NO. NAA-SR-TDR-12623

DATE 12/14/67

PAGE 22 OF 44

Figure - 12

Nodal Division of M.O.R.L. Reactor Analytical
Model with Lithium Hydride Shield

ATOMICS INTERNATIONAL

A Division of North American Aviation, Inc.

NO. NAA-SR-TDR-12623

DATE 12/14/67

PAGE 23 OF 44

Figure- 13
Simplified Schematic of Lunar Base Reactor System

ATOMICS INTERNATIONAL

A Division of North American Aviation, Inc.

NO. NAA-SR-TDR-12623

DATE 12/14/67

PAGE 24 OF 44

of the thermal analysis was to determine the extent of ablation of the reactor and shielding upon impact. It was felt that the presence of the primary NAK equipment would have little effect upon the thermal behavior of the basic reactor and shielding.

Due to the symmetric nature of these components the reactor was assumed to be tumbling at random during reentry. In this case, the aerodynamic heat loading would be evenly distributed over the exterior of the reentering body. That portion of the system protected by less shielding material would be most affected by the applied heating and therefore would represent the "weakest" thermal path into the reactor. The bottom of the reactor is protected by 14 inches of lithium hydride, as compared to approximately 20" of material located around the sides of the reactor. To simulate the "weakest" thermal path a one foot square section, taken from the base of the system, was used in the analytical mode.

Figure 14 illustrates the analytical model and shows the nodal division of the various materials comprising the reactor vessel and gamma, thermal, and neutron shielding. Due to the evenly distributed heat loading a one dimensional TAP network was considered to be an adequate representation of the lunar base reactor system. Again each layer of material was taken as one nodal segment with the exception of the lithium hydride. The lithium hydride was divided into seven segments, each two inches thick. As in the MORL 4-Pi shielded analog, each segment was represented by a central capacitant node and a non-capacitance node located at the interface between each segment.

V. Aerodynamic Heating Loading

As stated in Section II, the aerodynamic heating on the surface of a reentering body is expressed by:

$$Q_{in} \frac{\text{Btu}}{\text{Sec}} = (q_{Ref}) \left[\sqrt{\frac{R_o}{R}} \frac{q_{\text{local}} (\text{Radius} = R)}{q_{\text{sphere stag point}} (\text{Radius} = R)} \right] [HWCR] A_N$$

φ

ATOMICS INTERNATIONAL

A Division of North American Aviation, Inc.

NO. NAA-SR-TDR-12623

DATE 12/14/67

PAGE 25 OF 44

Figure- 14

Nodal Division of Lunar Base Reactor System
Analytical Model

ATOMICS INTERNATIONAL

A Division of North American Aviation, Inc.

NO. NAA-SR-TDR-12623

DATE 12/14/67

PAGE 26 OF 44

where:

q_{Ref} = Reference sphere stagnation point heating rate - $\frac{\text{Btu}}{\text{ft}^2\text{-sec}}$
obtained from RESTORE calculation for reentry body in question,

$\sqrt{\frac{R_o}{R}}$ = Size correction factor, ratio of reference sphere radius to equivalent reentry body sphere radius, in feet,

$\frac{q_{\text{local}} (\text{Radius} = R)}{q_{\text{sphere stag-point}} (\text{Radius} = R)}$ = Location factor, ratio of local heating rate at various positions on reentering body to sphere stagnation point heating rate of equivalent reentering body sphere

HWCR = Hot wall correction factor, neglected in these calculations, as it is consistently close to unity,

A_n = External surface area of given node, square feet.

The above equations must be multiplied by a further correction factor of 1/12 for both MORL reactor configurations. This factor converts the reference stagnation point heating rates on a 12-inch radius sphere to the stagnation point heating rates on a right cylinder with a radius of 12 inches.

The values of q_{Ref} as a function of time are given for each reactor system and initial flight angle considered in Section II of this report.

The size correction factor, $\sqrt{\frac{R_o}{R}}$, is different for each reactor system analyzed. The equivalent reentry body sphere radii for the various systems were taken as follows:

- (1) MORL reactor without 4-pi shielding = 0.508 ft
- (2) MORL reactor with 4-pi shielding = 1.75 ft
- (3) Lunar base reactor system = 2.83 ft.

The above radii represent the respective systems' mid-plane radius, in feet.

The location factor, q^1/q_s , is dependent upon the geometry and assumed mode of reentry of a given reactor system. Both MORL reactors were assumed to approximate truncated cones having cone half-angle of 17 degrees. The MORL reactor without a 4-pi shield was said to have a flat-faced front

ATOMICS INTERNATIONAL

A Division of North American Aviation, Inc.

NO. NAA-SR-TDR-12623

DATE 12/14/67

PAGE 27 OF 44

while the 4-pi shielded reactor was assumed to have a rounded face as shown in Figure 11. The q^1/q_s ratios used for various positions on the two MORL reactors are shown in Figure 15 (Ref. 7 and 8), Trace A (in Figure 15), having a higher and more sharply peaked q^1/q_s distribution at the periphery of the reactor's face, shows the marked influence of assuming a flat-faced front on the MORL reactor without a 4-pi shield. The rounded shoulders of the MORL 4-pi shielded reactor produced a larger shock standoff distance, and hence, a thicker boundary layer at the periphery of the reactor's front face. This resulted in the wider, less-peaked q^1/q_s distribution, as shown by Figure 15. The heat distributions shown in Figure 15 are symmetric about the system's axis, since they were assumed to reenter with a constant 0.0-degree angle of attack.

The lunar base reactor system was assumed to approximate a sphere spinning at random during reentry. Since the aerodynamic heat loading would be evenly distributed over the exterior of the reentering system, only two correction factors were necessary and

$$Q_{in} = 0.25 \sqrt{\frac{R_o}{R}} (q_{REF}) A_N,$$

where

$$0.25 = q^1/q_s \text{ for a random spinning sphere (See Ref. 3),}$$

$$\sqrt{\frac{R_o}{R}} = \text{Size correction factor, ratio of reference sphere radius to equivalent sphere radius of the lunar base reactor system.}$$

The heat loading factors, ϕA_N , for the external nodes of the various reactor systems are tabulated in Table IV. These factors, when used in the aerodynamic heating equation,

$$Q_N \frac{\text{Btu}}{\text{sec}} = (q_{REF}) \phi A_N,$$

give the heating applied to Node N as a function of time.

Figure- 15

Heating Rate Distribution on M.O.R.L. Reactor
Configurations

ATOMICS INTERNATIONAL

A Division of North American Aviation, Inc.

NO. NAA-SR-TDR-12623

DATE 12/14/67

PAGE 29 OF 44

TABLE IV
Aerodynamic Heating Factors

$$\underline{(\phi A_N) \text{ Ft}^2}$$

A. MORL reactor without 4-Pi shielding

Node No.	ϕA_N
1	0.0606
2	0.01886
3	0.0870
4	0.0275
5	0.00696
6	0.00766
13	0.0134

B. MORL reactor with 4-Pi shielding

Node No.	ϕA_N
34	0.03232
39	0.00746
44	0.7744
49	0.5989
54	0.02839
59	0.016183
64	0.010667

C. Lunar base reactor system

Node No.	ϕA_N
1	0.1485

ATOMICS INTERNATIONAL

A Division of North American Aviation, Inc.

NO. NAA-SR-TDR-12623
DATE 12/14/67
PAGE 30 OF 44

VI. Results

Two trajectory cases were considered for each reactor system investigated. The thermal behavior of each reactor system during reentry was determined for trajectories with 0.0 and -3.0 degree initial flight angles. Initial conditions of these calculations, at start of reentry, were as follows; time = 0 sec, altitude = 400,000 ft and temperature = 0°F. During these calculations, it was assumed that the two MORL reactor systems reentered with constant 0.0 degree angles of attack and were spinning about their axis so that no circumferential variation of aerodynamic heat loading existed. The lunar base reactor system was assumed to be spinning at random during trajectories so that the aerodynamic heat loading was evenly distributed over the exterior of the reentering body.

A. MORL Reactor without 4-Pi Shielding Cases

1) 0° Initial Flight Angle Case

Temperatures of representative portions of the MORL reactor without 4-Pi shielding are shown as function of time in Figure 16 for the 0° initial flight angle case. The locations of the respective nodes plotted in Figure 16 are shown in Figure 10. The number designation of the nodal temperatures shown in Figure 16 are as follows:

<u>Nodal Number</u>	<u>Location</u>
1	Central portion of top head
2	Periphery of top head
4	Vertical portion of top head above upper grid plate
6	Top of Be external reflector
7	Center of Be reflector at reactor mid-plane
9	Center of vessel wall at reactor mid-plane
10	Outer fuel annulus at reactor mid-plane
11	Inner fuel annulus at reactor mid-plane
13	Periphery of Be reflector at reactor mid-plane
14	Periphery of upper grid plate
15	Central portion of upper grid plate

12/14/67

Page 31 of 44

Figure 16

Temperatures of Representative Portions of the M.O.R.L. Reactor
without 4-Pi Shielding (0.0° Initial Flight Angle Case)

ATOMICS INTERNATIONAL

A Division of North American Aviation, Inc.

NO. NAA-SR-TDR-12623

DATE 12/14/67

PAGE 32 OF 44

Initial ablation of the system occurs at the periphery of the reactor's top head at ~3325 sec, 279,000 ft altitude. At this time, the central portion of the top head has not fully ablated and is assumed to be dispersed. The vertical portion of the top head above the grid plate attains ablation temperature at 3500 sec, an altitude of 262,000 ft. After the reactor's top head had ablated, the aerodynamic heat loading was applied directly to the upper grid plate in the analytical calculations. This was done at 3400 sec and is responsible for the sharp increase in the temperature-vs-time traces of the grid plate nodes, 14 and 15. The grid plate was fully ablated by 3825 sec, ~225,000 ft altitude. The upper portion of the external beryllium reflector reaches its melting temperature of 2345°F at time and altitude of peak heating, 4120 sec, ~111,000 ft, respectively. At time of impact, ~4200 sec, the reactor core components are at relatively low temperatures, fuel is in the 350-400°F, and vessel wall $\cong$ 350°F at the reactor mid-plane.

The characteristic temperature leveling or decrease which takes place at various reactor positions at 2200-2400 sec may be attributed to the corresponding decrease in aerodynamic heat loading to the system caused by the ablate earth.

2) -3.0-Degree Initial Flight Angle Case

Temperatures of the same portion of the MORL reactor as shown in Figure 16 are given in Figure 17. By plotting the temperatures of the same portions of the reactor for each reentry case, a basis of comparison is formed to determine the relative effect of increasing flight angle. The sequence of component ablation for the -3.0-degree initial flight angle case is the same as that for the 0.0-degree case. Times and altitudes of component ablation are as follows:

<u>Location</u>	<u>Time of Ablation (sec)</u>	<u>Altitude of Ablation (ft)</u>
Periphery of top head	147	~200,000
Vertical portion of top head	158	~185,000
Central portion of upper grid plate	190	~142,000
Periphery of upper grid plate	202	~128,000
Top of external Be reflector	217	~102,000

12/14/67

Page 33 of 44

Figure- 17
Temperatures of Representative Portions of the M.O.R.L.
Reactor without 4-Pi Shielding, (-3.0° Initial Flight
Angle Case)

ATOMICS INTERNATIONAL

A Division of North American Aviation, Inc.

NO. NAA-SR-TDR-12623

DATE 12/14/67

PAGE 34 OF 44

Again at time and altitude of peak heating (230 sec, 88,500 feet) the reactor core components remain at low temperatures. The reactor vessel wall and fuel are heated to approximately 10°F . The exterior of the beryllium reflector attains a temperature of $\sim 220^{\circ}\text{F}$ at the reactor mid-plane. The center of the beryllium reflector reaches $\sim 800^{\circ}\text{F}$ at time of peak heating.

B. MORL Reactor with 4-Pi Shielding Cases

1) 0.0° Initial Flight Angle Case

From the results of the calculation simulating this case it was found that the only components of the system to ablate were portions of the outer stainless steel-lithium hydride containment vessel and the outer surface of the lithium hydride neutron shielding material. The thermal distribution throughout the reactor system at time and altitude of peak heating (3370 seconds, 125,000 feet) is shown in Figure 18. Those portions of the system which ablated during reentry are designated by an "A", located at the corresponding nodal position. From Figure 18 it can be seen that the various 4-Pi shielding materials serve as an insulating barrier keeping the reactor core components from receiving aerodynamic heat. The reactor components, external BeO reflectors, and tungsten gamma shield remain at approximately 0°F during reentry. Temperatures in the Min-K insulation material vary from 0°F to 7°F while those in the inner SS-LiH containment wall are in the 1 to 12°F range at time and altitude of peak heating.

The high heat capacitance of the lithium hydride neutron shielding material absorbs most of the aerodynamic heat which produces a large thermal gradient between the inner and outer surfaces of the lithium hydride.

Temperatures of representative portions of the reactor system which ablate during reentry are shown as functions of time in Figure 19. The number designation and approximate location of the nodal temperatures shown in Figure 19 are as follows:

Node	Location
34	Central portion of outer SS-LiH containment wall in system's front face
107	Center of first LiH analytical segment located below node 34
44	Peripheral portion of outer SS-LiH containment wall on system's front face
125	Center of first LiH analytical segment located below node 44
49	First vertical segment of outer SS-LiH containment wall below system's front face

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**Temperature Distribution Throughout M.O.R.L. 4-Pi
Shielded System at Time and Altitude of Peak Heating
(0.0° Initial Flight Angle Case)**

"A" Indicates portion has ablated

Numbers = temperature °F

ATOMICS INTERNATIONAL

A Division of North American Aviation, Inc.

NO. NAA-SR-TDR-12623

DATE 12/14/67

PAGE 36 OF 44

Node	Location
134	Center of first LiH analytical segment located inward from node 49
59	Third vertical segment of outer SS-LiH containment wall below system's front face

The exact location of these nodes and their relationship to the other analytical divisions may be seen in Figure 12 Section IV.

As with the MORL system without 4-Pi shielding the temperature leveling or decrease of the exterior surface nodes (34, 44, 49 and 59) between 1600 and 2200 seconds may be attributed to the corresponding decrease in aerodynamic heat loading to the system caused by the ablate earth. Node 59, located on the vertical portion of the stainless steel-lithium hydride containment wall receives far less aerodynamic heating than nodes 34, 44 or 49 and therefore attains its ablation temperature at a later time.

Initial ablation of the system occurs at the periphery of the outer SS-LiH containment wall at ~ 2960 sec; 265,000 feet altitude. The various positions on the outer SS wall designated by an "A" in Figure 18 are completely ablated by 3360 sec; an altitude of 134,000 feet. Initial ablation of the lithium hydride neutron shield takes place at node 125 at 3235 seconds; $\sim 200,000$ feet altitude. Those portions of the lithium hydride neutron shield with an "A" in Figure 18 have ablated by 3320 seconds on altitude of 163,000 feet.

2) -3.0° Initial Flight Angle Case

From the results of this case it was found that only portions of the outer SS-LiH containment wall attained ablation temperature during reentry. The LiH neutron shield remained intact and at temperatures well below that of ablation at time and altitude of peak heating. The temperature distribution throughout the MORL, 4-Pi shielded reactor (-3.0° initial flight angle case) at time and altitude of peak aerodynamic heating (210 sec; 115,000 feet) is shown in Figure 20.

The temperature vs time traces of those portions of the outer SS-LiH containment wall which attain ablation temperature during reentry are shown in Figure 21. The number designation and locations of the nodal temperatures shown in Figure 21 are the same as those plotted for the 0.0° initial flight angle case.

Figure- 19
Temperatures of Representative Portions of the M.O.R.I. Reactor
System with 4-Pi Shielding (0.0° Initial Flight Angle Case)

Numbers = Nodes

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Temperature Distribution Throughout M.O.R.L. 4-Pi
Shielded System at Time and Altitude of Peak Heating
(-3.0 Initial Flight Angle Case)

Numbers = temperature °F

12/14/67

Page 39 of 44

Figure- 21

Temperatures of these Portions of the M.O.B.L. Reactor
System with 4-Pi Shielding which Ablate During Reentry
(-3.0° Initial Flight Angle Case)

ATOMICS INTERNATIONAL

A Division of North American Aviation, Inc.

NO. NAA-SR-TDR-12623
DATE 12/14/67
PAGE 40 OF 44

C. Lunar Base Reactor System

1) 0.0° Initial Flight Angle Case

The thermal distribution throughout the simplified lunar base reactor analog at time and altitude of peak heating is shown in Figure 22. Peak aerodynamic heat loading occurs at 3330 seconds and an altitude of 120,000 feet for the 0.0° initial flight angle case. As in the MORL 4-Pi shielded case the thick lithium hydride neutron shielding absorbed the aerodynamic heat input and prevented the interior reactor components from increasing in temperatures above the initial 0.0°F.

As seen in Figure 22 the only portion of the lunar base reactor system to ablate during reentry is the outer SS-LiH containment wall. The outer containment wall reaches its melting temperature at 3230 seconds, an altitude of approximately 204,000 feet.

2) -3.0° Initial Flight Angle Case

The results of the lunar base reactor, -3.0° initial flight angle case, closely follows the results of the 0.0° initial flight angle case. Again the only portion of the reactor system to ablate during reentry was the outer stainless steel-lithium hydride containment wall at 170 seconds, 169,000 feet altitude. The temperature distribution throughout the reactor system for this case at time and altitude of peak aerodynamic heating is given in Figure 23. Peak aerodynamic heat loading occurs at 2.0 seconds and an altitude of ~ 115,000 feet for the -3.0° initial flight angle case.

VII. Conclusions

From the results of this analysis, it is concluded that the MORL reactor without 4-Pi shielding is the only system investigated whose reactor core components partially ablate during reentry to the earth's atmosphere. During both the 0.0° and -3.0° initial flight angle cases the reactor's top head and upper grid plate ablated prior to peak heating. The upper portion of the reactor's external beryllium reflectors ablated during both initial flight angle cases. The system's stainless steel core vessel and fuel elements did not ablate during either case and remained at temperatures well below that of ablation. From this it may be concluded that the configuration of the MORL reactor without 4-Pi shielding at impact will be as follows:

ATOMICS INTERNATIONAL

A Division of North American Aviation, Inc.

NO. NAA-SR-TDR-12623

DATE 12/14/67

PAGE 41 OF 44

SS-304	• A
	• 815
	• 148
	• 31
LiH	• 9
	• 1
	• 0+
	• 0+
SS-304	• 0+
Min-K	• 0+
Tungsten	• 0+
SS-316	• 0+
	• 0+
Fuel Heat Sink	

Figure- 22
Temperature Distribution Throughout the Lunar
Base Reactor Analog at Time and Altitude of
Peak Heating (0.0° Initial Flight Angle Case)

ATOMICS INTERNATIONAL

A Division of North American Aviation, Inc.

NO. NAA-SR-TDR-12623

DATE 12/14/67

PAGE 42 OF 44

SS-304 • A	• 190	• 4	• 0+	LiH • 0+	• 0+	• 0+	• 0+	SS-304 • 0+	Min-K • 0+	Tungsten • 0+	SS-316 • 0+	• 0+	Fuel Heat Sink
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Figure- 23

Temperature Distribution Throughout the Lunar
Base Reactor Analog at Time and Altitude of
Peak Heating (-3.0° Initial Flight Angle Case)

ATOMICS INTERNATIONAL

A Division of North American Aviation, Inc.

NO. NAA-SR-TDR-12623

DATE 12/14/67

PAGE 43 OF 44

- 1) The top head and upper grid plate will have ablated.
- 2) The external reflector will be detached from the upper portion of the core vessel and may be dispersed due to aerodynamic forces.
- 3) The core vessel and fuel elements will not totally ablate during reentry and may remain intact upon impact if the molten grid. plate and top head material flows back into the reactor core and "solidifies" the core components into one aggregate mass.
- 4) The fuel elements may be ejected prior to impact due to aerodynamic forces or may be scattered upon impact.

Thus the MORL reactor system without 4-Pi shielding may present a radiation safety hazard upon impact due to the presence of unblated fuel material.

This analysis shows that both the 4-Pi shielded MORL reactor and the lunar base reactor systems will not ablate to an appreciable extent upon reentry. From this it is concluded that both systems will remain essentially intact during reentry.

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ATOMICS INTERNATIONAL

A Division of North American Aviation, Inc.

NO. NAA-SR-TDR-12623

DATE 12/14/67

PAGE 44 OF 44

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