DISINTEGRATION AND DISPERSION
OF THE SNAP 10A REACTOR UPON
RETURN FROM SATELLITE ORBIT

AEC Research and Development Report

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RETURN FROM SATELLITE ORBIT

By
R. D. ELLIOTT

ATOMICS INTERNATIONAL
A DIVISION OF NORTH AMERICAN AVIATION, INC.

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CONTENTS

	Page
Abstract	5
I. Introduction	7
II. Description of Reactor and Vehicle	9
A. In-orbit Configuration of the SNAP 10A/ Agena	9
B. Description of the SNAP 10A System	9
III. Reentry and Abort Conditions	13
A. Flight Dynamics	13
B. Reentry Trajectories	16
C. Aerodynamic Heating	17
IV. Mode of Disintegration	20
A. Preliminary Remarks	20
B. Structural Failure of Vehicle and Radiator-Converter	20
C. Effects of Coolant in the Flow System	21
D. Release of Reflectors	22
E. Separation of Reactor from System	23
F. Disintegration of the Reactor Vessel	27
G. Release of Fuel Elements	29
V. Summary and Conclusions	30
VI. References	30
Appendices	
A. Inertial and Aerodynamic Characteristics of the Vehicle	31
B. Computation of Aerodynamic Heating Rates	35
C. Thermophysical Properties of Materials	39
D. Description of Coolant System Analog	43

TABLES

D-1. Local Heating Factors on Coolant Pipe	45
D-2. Results of Analog Study of Coolant Pipe Failure	46

FIGURES

1. Typical Orbiting Vehicle Carrying a SNAP 10A	10
2. SNAP 10A System	11
3. Components of the SNAP 10A Reactor	12
4. Pictorial Representation of Angular Body Motion During Reentry	14
5. Total Angle-of-Attack Envelope - Type I Reentry	15
6. Total Angle-of-Attack Envelope - Type II and Type III Reentry	15

FIGURES

	Page
7. Reference Trajectory Used for Reentry Disintegration Analysis	16
8. Lockheed Six-Degree-of-Freedom Trajectory for Expected Reentry	17
9. Aerodynamic Heating Rates for SNAP 10A/Agena Reentry Trajectories	18
10. Aerodynamic Heating Rates for SNAP 10A/Agena Reentry Trajectories Compared on Basis of Altitude	18
11. Heating Coefficients Measured on 1/50-Scale Model of SNAP 10A/Agena	20
12. Aerodynamic Heating Rates on Reflector Retaining Band Obtained During RFD-1 Flight Test	22
13. Sectional Views of Reactor Support Leg	24
14. Thermal Network for Analysis of Reactor Support Leg	24
15. Local Heating Factors on Reactor Support Leg	24
16. Temperatures of Reactor Support Leg ($\alpha = 0^\circ$, no NaK).	25
17. Temperatures of Reactor Support Leg ($\alpha = 30^\circ$, with NaK, Vehicle Spinning)	25
18. Thermal Model of Section Through SNAP 10A Reactor Core	26
19. Local Heating Factors on Reactor Vessel.	26
20. Reactor Vessel Wall Temperature Histories.	27
21. Influence of Various Factors on Altitude of Vessel Wall Failure.	28
A-1. Axial Force Coefficients for Free-Molecule Flow	32
A-2. Normal Force Coefficients for Free-Molecule Flow.	32
A-3. Pitching Moment Coefficients for Free-Molecule Flow	32
A-4. Axial Force Coefficients for Continuum Flow	33
A-5. Normal Force Coefficients for Continuum Flow.	33
A-6. Pitching Moment Coefficients for Continuum Flow	34
A-7. Pitching Moment Coefficients for Various Amounts of Residual Rocket Fuel	34
B-1. Correction Factor for Effect of Body Surface Temperature on Aerodynamic Heating Rate.	36
B-2. Comparison of Theoretically Predicted Stagnation Point Heat Transfer Rates	37
B-3. Stagnation Heating Rates to a 1-ft Radius Sphere	37
B-4. Stagnation Heating Rates to a 0.1-ft Radius Sphere.	37
C-1. Thermal Emissivity of Type 321 Stainless Steel	39
D-1. SNAP 10A Coolant Pipe, Showing Node Divisions Used in Thermal Analog.	42
D-2. SNAP 10A Thermoelectric Pump, Showing Node Divisions Used in Thermal Analog.	43
D-3. Local Heating Coefficients on Coolant Pipe Forward of Reactor	45
D-4. NaK Flow Rate and Coolant Pipe Temperatures During Reentry.	45

ABSTRACT

A study of the disintegration and dispersion of the SNAP (Systems for Nuclear Auxiliary Power) 10A reactor upon atmospheric reentry from a satellite orbit is described. The flight configuration is that of the SNAP 10A reactor containing NaK coolant and mated to the forward end of the Agena-D vehicle. It is shown that the SNAP 10A/Agena system will be oscillating in an approximately nose-first attitude at the time of reentry. It is concluded that the reactor components will have disintegrated and dispersed at an altitude of not less than 237,000 ft.

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I. INTRODUCTION

When a vehicle carrying an atomic reactor is launched into a satellite orbit around the earth, it is essential to consider the possible hazards that may be created when the vehicle eventually spirals down into the lower atmosphere and disintegrates as a result of aerodynamic heating. If the initial altitude of the orbit is high enough, reentry to the lower regions of the atmosphere will not occur for several centuries. The lower the initial altitude, the sooner reentry will occur.

The SNAP 10A (Systems for Nuclear Auxiliary Power) reactor, installed on the Lockheed Agena vehicle, will remain subcritical until it has been established that a satisfactory orbit has been achieved. This eliminates the radioactive hazard that might otherwise occur in case of a launch abort or of a very low orbit. A reactor that has not been run at power has no significant inventory of fission products, and the unused fuel may be safely handled. The primary objective in this case would be to insure that the reactor core would be in such a condition that it could not possibly go critical after impact.

An analytical and experimental program to investigate the disintegration and dispersion of the SNAP 10A reactor upon reentry has been pursued at Atomics International since 1960. This work was conducted as a portion of the overall Aerospace Nuclear Safety Program. Preliminary studies ^{(1)*} led to the conclusions that the reactor vessel would melt open and the fuel elements would be separated from each other before the reactor impacted with the earth. These conclusions were based on aerodynamic force and heating coefficients that were calculated by use of aerodynamic theory.

An interim report on the expected mode of disintegration of the SNAP 10A/Agena during reentry was published in 1963.⁽¹⁾ Since the time of that report, a considerable amount of experimental data has been obtained on the aerodynamic force and heating characteristics of the system. A flight test of a full-scale mockup of the SNAP 10A reactor was conducted in a reentry environment.⁽²⁾ Wind tunnel tests were run to determine local heating coefficients at various angles of attack and at various simulated altitudes.^(3,4) Other wind tunnel tests were conducted under a subcontract to Ling-Temco-Vought (LTV) to obtain data on the aerodynamic force and moment coefficients of the SNAP 10A/Agena vehicle. In addition to these experimental data, the analysis was improved through the use of more refined methods for calculating aerodynamic heating rates and their effects on structural components of the reactor and vehicle.

Based on the new data and on the improved analysis, the following conclusions can now be made:

1) The Agena vehicle, during reentry, will be oscillating about an approximately nose-first attitude, with the amplitude of the oscillations tending toward smaller values as the vehicle descends. Tail-first reentry is impossible, because the vehicle is aerodynamically unstable in a tail-first attitude.

2) The external components of the SNAP 10A system will begin to disintegrate by melting at altitudes above 300,000 ft. Portions of the vehicle will fail at altitudes above 280,000 ft, and the reactor will separate from the vehicle at an altitude above 260,000 ft.

*Superscripts refer to the like-numbered references in Section VI of this report.

3) The reactor vessel walls will melt away, releasing the partially melted remains of the top and bottom heads and allowing the core assembly to fall free at an altitude of not less than 237,000 ft.

4) The foregoing statements are based on the analysis of a system that is filled with NaK-78 (sodium-potassium eutectic alloy) at the time of reentry. Circulation of the NaK due to aerodynamic heating of the thermoelectric elements in the pump will cause the core temperature to be approximately 940°F at the time of reactor

vessel opening. If the NaK escapes from the system prior to reentry, the coolant pipes will melt sooner than if they were filled with NaK, but the altitude of fuel-element release will not be affected appreciably. Without NaK, the temperature of the core will be approximately the same as it was during the final hours of its orbital lifetime.

The mode of burnup and disintegration of the fuel elements after their release and exposure to the reentry environment has been thoroughly analyzed in another study.⁽⁵⁾

II DESCRIPTION OF REACTOR AND VEHICLE

A. IN-ORBIT CONFIGURATION OF THE SNAP 10A/AGENA

This report deals with the reentry from orbit of the SNAP 10A reactor and power-conversion system (manufactured by Atomic International) mounted on the front of the Agena-D vehicle (manufactured by Lockheed Missiles and Space Company) as shown in Figure 1. The SNAP 10A will remain attached to the vehicle during the orbital mission, thus, the analysis of the early phases of reentry must be based on the dynamic characteristics of the entire system. Currently estimated and measured values of the mass, center-of-mass location, moments of inertia, and aerodynamic coefficients of the vehicle in the orbital configuration are presented in Appendix A.

B. DESCRIPTION OF THE SNAP 10A SYSTEM

The major components of the SNAP 10A system are the reactor, the shield, and the radiator-converter. A cutaway view of the radiator-converter is shown in Figure 2. It consists of a hollow conical structure of titanium, the outer surface of which is covered with an array of separate aluminum fins. Each fin dissipates the heat from a thermoelectric element. Sodium-potassium alloy (NaK) cools the reactor and is the working fluid of the power conversion system. The fluid passes through 40 vertical tubes along the hot ends of the thermoelectric elements.

The reactor and the shield are each supported from the upper end of the converter cone. There is no direct connection between the reactor and the shield, thus, failure of the reactor support legs and the NaK pipes within

them will allow the reactor to separate from the system.

The major components of the reactor are shown in Figure 3. The core consists of a hexagonal array of 37 fuel elements and 6 beryllium reflector pieces, loosely held between two grid plates. The fuel is an alloy of uranium and zirconium, hydrided nearly to the saturation level. Each fuel element comprises a rod of fuel alloy, 1.212 in. in diameter by 12.25 in. long, and a jacket of 0.015-in. -thick Hastelloy-N (nickel alloy). The inside of the cladding is coated with a vitreous material which blocks the escape of the hydrogen from the fuel element at reactor operating temperatures. Each fuel element, as clad, is 1.250 in. in diameter and 12.450 in. long. There is a small pin on each end which is used to hold the fuel element in place between the grid plates.

The reactor containment vessel is made of stainless steel (type 321) and is 0.032 in. thick and 9.5 in. in diameter in its central region. The base of the vessel has an annular box-like ring welded to it, as shown in detail B of Figure 3. This ring serves as a structural member to which the reactor support legs and the reflector hinges are attached.

The upper end of the vessel is thickened and machined to receive the top head. There are 12 springs inside the top head which bear against the upper grid plate and keep the core assembly from shifting during launch and while the reactor is in operation. The bottom grid plate rests on a support ring inside the vessel. After the core assembly has been placed inside the vessel, the top head is held in place by a fusion weld around the rim of the vessel.

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Figure 1. Typical Orbiting Vehicle Carrying a SNAP 10A

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Figure 2. SNAP 10A System

The coolant inlet pipes are enclosed within two of the support legs and enter the vessel at its lower end. The coolant outlet pipe is at the center of the top head. The coolant pump surrounds this outlet pipe and is self-powered by heat loss from the coolant passing through thermoelectric elements and out through fins. Above the pump, the outlet pipe branches into two directions, passing horizontally across the front of the system and down on either side of the reactor vessel. The downcomer pipes are enclosed within the support legs at and below the base of the vessel.

During the operational lifetime of the reactor, the core vessel is surrounded by a beryllium

reflector assembly, as shown in detail C of Figure 3. The reflector assembly is separable into two halves, each of which is hinged to the base ring of the reactor. The two halves of the reflector are held together at the top by a thin (0.016-in.) steel band. A tension of nominally 165 lb is maintained in this band by two springs in the band and by the springs below the reflector which tend to force the two halves apart. When the retaining band ruptures, either by an end-of-operation signal from the system or by the heat of reentry, the halves of the reflector are forced outward, pivoting about its hinges. The hinges are designed so that they release the reflector after a few degrees of rotation, allowing it to fall away.

A. FUEL ELEMENT

B. REACTOR VESSEL AND CORE

C. REACTOR WITH REFLECTOR

D. ASSEMBLED REACTOR

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Figure 3. Components of the SNAP 10A Reactor

III. REENTRY AND ABORT CONDITIONS

A. FLIGHT DYNAMICS

A comprehensive study of the dynamics of the SNAP 10A/Agena during reentry was subcontracted to the Lockheed Missiles and Space Company. Their study included an analysis of the various failures that could occur during establishment of the initial orbit. The normal mode of operation is for the first burning period of the Agena rocket motor to carry the vehicle to an altitude of 90 n. mi, with the flight path horizontal at that altitude. The vehicle would then coast out to an altitude of 700 n. mi, and a second burning period at that altitude would circularize the orbit. The lifetime of such an orbit would be several thousand years.

Failures in the various control and propulsion systems could result in shorter-lived orbits, even down to as low as the time for one pass around the earth. Lockheed's analysis, based first on theoretical aerodynamic coefficients and later on wind tunnel measurements,⁽⁴⁾ shows that in every case of descent from high altitude, the vehicle will oscillate with a conical motion of its axis, while rocking or spinning about that axis, in a nose-first orientation.

Lockheed categorized the possible modes of reentry into three types, as shown in Figure 4. Type I corresponds to reentry from a long-life orbit with negligible initial roll, pitch, and yaw rates. The envelope of the oscillations which would occur is shown in Figure 5. The frequency of the oscillations increases and the amplitude decreases as the vehicle descends to lower altitudes, because of the increasing aerodynamic pressures. The amplitude of the motion is confined to a maximum of 40 degrees from nose-first at an altitude of 300,000 ft, and tends toward coning at the trim angle of 22 degrees at lower altitudes. (The trim angle

was first estimated to be 22 degrees, and the results of wind tunnel tests later established it as 32 degrees, as described in Appendix A.)

The vehicle is not perfectly symmetrical about its major axis, and its center of mass lies slightly off the axis. Therefore, the coning motion will always induce a rolling moment, which will result in a spin, or a rocking motion of large amplitude. Thus, the surfaces on all sides of the vehicle will be exposed to the aerodynamic heating in a cyclic manner.

Motion of Type II corresponds to reentry from an abortive approach to orbit in which the engine or attitude control system has malfunctioned and a large initial pitch rate has been induced. Motion of Type III corresponds to a hypothetical case in which the vehicle has a high initial roll rate and a large angle of attack. Envelopes of the oscillations which would occur in these cases are shown in Figure 6. With neither of these latter two types of reentry would the conditions in orbit have been such that the reactor could have been started.

The conclusions of the Lockheed study were stated as follows:

"A practical limit on reentry body angular rates can be set at 2 rad/sec about any axis as a result of probable SNAP 10A/Agena system malfunctions. The probability-per-launch of the vehicle reentering with rates in excess of 0.1 rad/sec is small (2×10^{-3}). Unsymmetrical effects in shape and CG (center of gravity) location are present during reentry and insure that a roll rate, if not present at reentry, will be induced. A rate about one axis also induces a rate about the other two axes. A stable tail-first reentry is not possible."

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Figure 4. Pictorial Representation of Angular Body Motion During Reentry
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Figure 5. Total Angle-of-Attack Envelope - Type I Reentry

Figure 6. Total Angle-of-Attack Envelope - Type II and Type III Reentry

"Reentry heating is more significant than structural loads in causing the first major configuration change in the reentering SNAP 10A/Agena. It is estimated that initial breakup will occur in the altitude range of 275,000 to 290,000 ft."

B. REENTRY TRAJECTORIES

Prior to the availability of wind tunnel data on the aerodynamic coefficients of the SNAP 10A/Agena vehicle, it was estimated that the aerodynamic drag coefficient in free-molecule flow was 2.0 at an angle of attack of 0 degrees. In continuum flow at an angle of attack equal to the predicted trim angle of 34 degrees, the drag coefficient was estimated to be also equal to

2.0. Thus, the ballistic parameter, $W/C_D A$, was estimated to be the same for free-molecule and for continuum flow, and a value of 132 lb/ft^2 was used. A representative trajectory based on this value was calculated and used as a standard for the analysis reported in Reference 1. Figure 7 shows the variations of altitude, velocity, and flight angle with time for this trajectory.

The recent wind tunnel test data⁽³⁾ and other data supplied by Lockheed are summarized in Appendix A. The experimentally determined trim angle is 32 degrees, and the drag coefficient in continuum flow at this angle is 2.08. In free-molecule flow, the trim angle is 0 degrees, and the drag coefficient at this angle

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Figure 7. Reference Trajectory Used for Reentry Disintegration Analysis

is estimated by Lockheed to be 2.7. Thus, the changes in the aerodynamic coefficients have been relatively small, and the previous analysis has not been invalidated.

Altitude, velocity, and flight angle variations with time, calculated with a six-degree-of-freedom trajectory code for the case depicted in Figure 5, are presented in Figure 8. This trajectory was calculated for a polar orbit, with an altitude of 400,000 ft as the vehicle passes over the North Pole. The initial flight angle was taken to be -0.12 degrees and the initial angle of attack was 90 degrees.

C. AERODYNAMIC HEATING

Reference values of the aerodynamic heating rates for the trajectories of Figures 7 and 8 are

shown as functions of time in Figure 9. These reference values are for the heating at the stagnation point of a 1.0-ft-radius sphere moving along the given trajectories. Methods used for calculating these heating rates are given in Appendix B.

Figure 10 shows the reference heating rates for the same two trajectories plotted as functions of the atmospheric density, which is a function of the altitude. It may be noted that the two trajectories are more nearly alike on an altitude basis than on a time basis. For this reason, it has been found preferable to report events during reentry as occurring at certain altitudes rather than at certain times. This is especially true for melting of those components which have a relatively low heat

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Figure 8. Lockheed Six-Degree-of-Freedom Trajectory for Expected Reentry

Figure 9. Aerodynamic Heating Rates for SNAP 10A/Agena Reentry Trajectories

Figure 10. Aerodynamic Heating Rates for SNAP 10A/Agena Reentry Trajectories Compared on Basis of Altitude

storage capacity. For these, the magnitude of the instantaneous heating rate is more important than the integrated heat input.

It has been found that the local heating rates on most of the important forward-facing surfaces of a vehicle can be related to the reference heating rate by the use of a heating factor, F_q , which does not vary appreciably with altitude or velocity. Thus, values of F_q can be calculated or measured in wind tunnels for various locations on the surface of a vehicle at each of several angles of attack; these values can be multiplied by the reference heating rates for any desired trajectory. Where shock wave interference effects occur, or where one component of the vehicle is in the wake of another, special modifications are necessary.

The aerodynamic heating in the two principal flow regimes, free-molecule and continuum, follows different scaling laws. In free-molecule flow, the heating rate per unit surface area is independent of the body size. In continuum flow, the rate varies inversely as the square

root of the body size. Therefore, different values of the heating factor apply for the two regimes.

In addition to the aerodynamic heating, there may be a small amount of nuclear-decay heating at the time of reentry. The magnitude of this heating will be a function of the time between reactor shutdown and reentry.⁽⁶⁾ If the reactor has been operating for a year or more with a thermal power output of 39 kw, the decay heating will be as tabulated below:

Time After Shutdown	Thermal Output (watts)
1 sec	2300
1 min	1600
1 hr	600
1 day	300
1 yr	30

For comparison, the rate of aerodynamic heating of the reactor vessel at an altitude of 240,000 ft will be 114,000 watts. Thus, it is evident that the decay heating will have a negligible effect on reentry disintegration.

IV. MODE OF DISINTEGRATION

A. PRELIMINARY REMARKS

As discussed previously in this report, the vehicle during reentry will be oscillating and rolling, with its major axis precessing about the flight path with a cone angle of 32 degrees or greater. The aerodynamic heating on the lateral surfaces of the system will be greater than if the vehicle were stabilized at 0 degrees angle of attack. The intensity of the heating will vary periodically at each location on the structure. In this analysis of the mode of disintegration, the heating rate coefficients for those components which have an appreciable thermal storage capacity have been smoothed by averaging them over a cycle time. Components that have a low thermal capacity, such as thin sheet metal parts, will fail at one of the peaks in their heating curves.

B. STRUCTURAL FAILURE OF VEHICLE AND RADIATOR-CONVERTER

The aluminum fins on the SNAP radiator-converter and some regions on the outside skin of the Agena vehicle will be heated to melting temperatures and will disintegrate early in the reentry period. Figure 11 shows aerodynamic heating coefficients measured on a

1/50-scale model of the vehicle at 0 degrees angle of attack. These measurements were taken in a hotshot-type wind tunnel, as described in Reference 3. The heating on the Agena at this angle of attack was lower than could be measured with the heat-sensitive paint used in the tests, but good data were obtained on the converter cone. Heating coefficients on the NaK pipe are not shown in Figure 11, because more detailed measurements on these components were available from full-scale and 1/4-scale tests (see Appendix D).

The outside of the radiator-converter is covered with aluminum fins 0.030 in. thick. Each fin is bonded to the end of a thermoelectric element, and the exposed side of the fin is coated with a material that has a high thermal emissivity, of the order of 0.9. The altitude at which these fins will melt during reentry was calculated by setting up an equation involving the aerodynamic heating input, the heat stored in the fin, and the heat lost by thermal radiation to space from the outside and to the inner structure. The thermophysical properties of aluminum given in Appendix C were used to evaluate the equation. It was found that the fins will melt when the heat input rate reaches $4.3 \text{ Btu/ft}^2\text{-sec}$. Since the heating coefficient, F_q , at the forward part of the converter cone is 0.24, the fins in that area will melt when the reference heating rate becomes $18.0 \text{ Btu/ft}^2\text{-sec}$. Figure 10 shows that this will occur at an altitude of 305,000 ft. The fins on the aft part of the converter will melt at an altitude above 290,000 ft.

A similar analysis was made for the internal structure of the converter cone, which is made of 0.018-in. -thick titanium alloy. Because the melting temperature of titanium

Figure 11. Heating Coefficients Measured on 1/50-Scale Model of SNAP 10A/Agena

is so high (3510°R), this structure will not fail until the reference heating rate reaches 94 Btu/ft²-sec. This will occur at an altitude of 245,000 ft if the vehicle is at 0-degree angle of attack. No allowances have been made in these calculations for the increased heating due to roughness of the finned and corrugated surfaces. Air flow at the low densities corresponding to the altitudes discussed here will be laminar on smooth surfaces, but local turbulence and shock-induced flow separations and reattachments will increase the local heating. Thus, the foregoing calculations are conservative, and failure may occur at higher altitudes than stated here. Furthermore, the oscillations of the vehicle will increase the lateral heating rates over the values used here.

Lockheed has made an analysis of the mode of failure of the Agena vehicle. They estimated that the average heating coefficient in the region of the oxidizer tank will be 0.13 when the vehicle is oscillating or coming at angles less than 60 degrees. The wall of the tank is aluminum alloy, 0.056 in. thick, and Lockheed predicts that it will fail by melting at an altitude of 287,000 ft. Failure of portions of the vehicle skin will change the aerodynamic coefficients somewhat, but the general mode of oscillating and rolling will not be altered appreciably.

C. EFFECTS OF COOLANT IN THE FLOW SYSTEM

As the vehicle descends into the atmosphere below an altitude of 400,000 ft, the aluminum fins on the coolant pump will become heated. The heat will flow inward through the thermoelectric elements and into the coolant pipe. If the NaK coolant has not escaped prior to reentry of the system, it will be forced by the pump to circulate in a direction opposite to that which it normally takes during reactor operation. An analog computer model of the

coolant flow system was devised and used to study the NaK flow and its effects on the heating of the system during reentry. A description of this analog model and a summary of the results obtained from it are presented in Appendix D.

The analog studies showed that the NaK flow rate will reach a maximum value of about 0.76 lb/sec soon after the start of reentry. As the NaK warms up, the flow rate will decrease to about 0.52 lb/sec. When the aluminum fins melt, the flow will stop. This will occur at an altitude of 310,000 ft. When the flow stops, the temperature of the NaK will be approximately 940°F, and this will be the temperature of the reactor core at that time. (If the NaK escapes in orbit, the temperature of the core at reentry will be much cooler — about 100°F if the fission-product-decay heat is negligible.)

After the NaK flow has ceased, the coolant pipe will melt in one or more places, and the hot NaK will begin to boil because of the reduced pressure. This will occur at an altitude not lower than 275,000 ft. The voids formed by vaporization of the NaK will allow other sections of the pipe to melt. The deceleration of the system at this altitude will be about 2 ft/sec², which will create a small static head in the liquid NaK. The rate at which the NaK will escape from the several openings as it vaporizes cannot be reliably predicted on a purely theoretical basis. There are about 26 lb of NaK in the system, and if this entire amount had to be vaporized, a large amount of heat would be required. It is expected that the greater portion of the NaK in the external pipes and in the core vessel will spray out as a mixture of liquid and vapor. An experimental investigation of this problem is planned for the near future.

D. RELEASE OF REFLECTORS

The reflectors which surround the reactor vessel and make it possible for a chain reaction to be sustained are normally expected to be jettisoned in orbit when the system power drops below a predetermined level. If the reflectors are still in place at the time of reentry, the aerodynamic heating of the reflector-retaining band will cause the band to fail. The reflectors will then be forced away from the vessel by the springs and caused to fall away from the system. The band is held away from the reflectors by standoff posts so that it will be exposed to the heating with a minimum of interference.

Analysis of the heating of the band shows that it will melt and release the reflectors at an altitude of not less than 280,000 ft. If the tensile stress (20,000 psi) due to the spring loading is considered, the band will fail at a temperature of about 1700°F. This is calculated to occur at an altitude of 300,000 ft.

These conclusions are based on actual measurements of the heating rates to the band taken during the RFD-1 (Reentry Flight Demonstration No. 1) flight test.⁽²⁾ The values obtained in flight are shown in Figure 12 as a function of the density of the ambient air. The flight velocity for RFD-1 was only 20,100 ft/sec, whereas satellite reentry velocity is 25,700 ft/sec at altitudes above approximately 275,000 ft. Since aerodynamic heating varies as the 3.0 power of the flight velocity in free-molecule flow and as the 3.15 power of the velocity in continuum flow, the data from RFD-1 can be conservatively scaled up to satellite reentry conditions using the cube of the velocity ratio. The curve thus obtained is shown in Figure 12.

The RFD-1 vehicle was rolling with a period of about 0.5 sec/cycle and coning with an average angle of 15 degrees at the time of

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Figure 12. Aerodynamic Heating Rates on Reflector Retaining Band Obtained During RFD-1 Flight Test

band release. The SNAP 10A/Agena reentry mode, shown in Figures 5 and 8, has the vehicle rolling with a period of about 50 sec/cycle and oscillating with a period of about 150 sec. The range of angles of attack at 300,000 ft is 0 to 40 degrees. Thus, the thermal effects will not be averaged out over a cycle as they were for RFD-1.

The band is made of stainless steel, 0.016 in. thick and 0.5 in. wide. The thermal properties used in the analysis of band heating are given in Appendix D. Considering a segment of the band of length, L , width, w , and thickness, b , the equation for heating this segment is as follows:

$$\begin{aligned} (2wLq_{aero}) - \left[(\epsilon \sigma T^4) \cdot (2w + 2b)L \right] \\ = \rho c_p w b L \frac{dT}{dt} \quad \dots (1) \end{aligned}$$

In this equation, it should be noted that the aerodynamic heating rate, q_{aero} , as obtained from Figure 12 was derived from the flight

test data in such a way that it must be multiplied by the surface area of both sides of the segment of the band to give the proper heat input rate.

The heating rate required to maintain the band in thermal equilibrium at its melting temperature can be found from Equation 1 by setting the right-hand side to zero and using the melting temperature of steel (3060°R) for the temperature, T . With an emissivity, $\epsilon = 0.8$, it is found that the value of $q_{aero} = 34.6 \text{ Btu/ft}^2\text{-sec}$. Figure 12 shows that this heating will occur with an atmospheric density of $4.4 \times 10^{-7} \text{ lb/ft}^3$, which corresponds to an altitude of 281,000 ft.

Although Equation 1 is nonlinear, it has been found to be useful in analysis to define a thermal lag time based on a linearized radiation admittance thus:

$$\tau = \frac{\rho c_p w b}{2 (w + b) \epsilon \sigma T^3} \quad \dots (2)$$

Evaluating this expression at the melting temperature of steel gives a lag time of 4.9 sec. The lag time is greater at lower temperatures; but digital computer calculations of this problem in detail have demonstrated that, regardless of initial conditions, the band temperature rapidly approaches the curve of equilibrium temperature vs time and follows it very closely at the higher temperatures. Since the vertical component of the velocity of the vehicle is -120 ft/sec at an altitude of 281,000 ft, the altitude will decrease about 600 ft during the lag time of 4.9 sec, and melting above 280,000 ft will occur.

The foregoing figures are based on the assumption that the variations in angle of

attack will be the same as for RFD-1. Figures 5 and 6 show that angles at least as high as 40 degrees will occur during SNAP 10A/Agena re-entry. It can be shown that, in this case, the band will melt at an altitude of 290,000 ft. It will be shown later in this report that it is not essential to determine the exact altitude of reflector ejection, since the influence on the altitude of vessel melting is small down to ejection altitudes of approximately 260,000 ft, provided that the NaK is also released at or above about 260,000 ft.

E. SEPARATION OF REACTOR FROM SYSTEM

A detailed thermal model was devised to represent a cross section through one of the four reactor support legs and the coolant tube inside it, as shown in Figures 13 and 14. A digital thermal analyzer code was used to compute transient temperatures in this system for cases of 0- and 30- degree angles of attack. Local heating rates on the outside of the support legs were based on the projected area in the free-molecule regime and were based on the results of the wind tunnel tests⁽³⁾ in the continuum flow regime. The local heating factors in continuum flow are shown in Figure 15, where the numbers shown are values of F_q , as discussed in Section III-C.

Figure 16 shows the temperature histories of the upper and lower surfaces of the support leg, as well as the temperature of the pipe inside the leg, for the case of the vehicle at 0 degrees angle of attack. After the upper surface of the leg melts, the other surfaces are exposed to intense heating, and the legs fail completely at 1500 sec, corresponding to an altitude of 262,000 ft.

Figure 17 shows temperature histories for the upper surface of the leg for the case of the vehicle spinning at 30 degrees angle of attack.

Figure 13. Sectional Views of Reactor Support Leg

Figure 14. Thermal Network for Analysis of Reactor Support Leg

Figure 15. Local Heating Factors on Reactor Support Leg

Figure 16. Temperatures of Reactor Support Leg ($\alpha = 0^\circ$, no NaK)

Figure 17. Temperatures of Reactor Support Leg ($\alpha = 30^\circ$, with NaK, Vehicle Spinning)

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Figure 18. Thermal Model of Section Through SNAP 10A Reactor Core

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Figure 19. Local Heating Factors on Reactor Vessel

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In this case, each leg is subjected to a cyclic variation in heating, and it is predicted that failure of each leg will occur as it passes the forward, or stagnation-heating region. This will occur over the altitude range from 300,000 to 285,000 ft.

If the aerodynamic heating rates are averaged over a spin cycle, the calculated temperatures follow the mean line shown in Figure 17, and it would be thought that the legs would fail at an altitude of 225,000 ft or lower. However, the titanium shell that forms the leg is only 0.032 in. thick, and its thermal lag time, as calculated by Equation 2, is only 14 sec. Since the spin rate is slow relative to this lag time, the metal temperature will follow the oscillatory curve shown in Figure 17, and failure will occur at one of the peaks in the curve.

F. DISINTEGRATION OF THE REACTOR VESSEL

A thermal model of a sector of the reactor core was devised for use with a digital thermal analyzer program. This model is shown in Figure 18. Thermal properties of the materials used in the reactor are given in Appendix C. Local heating factors, as measured in the wind tunnel,⁽³⁾ are shown in Figure 19 for angles of attack of 30 and 90 degrees. These values apply to the midheight of the vessel, but variations along the length of the vessel were found to be small, and analysis of a midplane is valid. A mean value of $F_q = 0.37$, averaged around the circumference of the vessel, was used in the thermal analysis at an angle of attack of 30 degrees. (For comparison, it may be noted that the mean value of F_q was 0.3 for the vessel wall during the RFD-1 flight, with the average angle of attack being about 15 degrees.)

Vessel wall temperatures, plotted vs time and altitude during the reentry period, are shown in Figure 20 for several assumed cases, all at 30- degrees average angle of attack. In one case, the external reflectors and the NaK are assumed to have been released in orbit. The other cases are for various combinations of reflector and NaK release, either in orbit or at altitudes of 290,000 and 250,000 ft. The variations in altitude of vessel melting are less than 10,000 ft for all of these cases. This is due to the low thermal storage capacity of the walls in comparison with the rate of heat input and rate of heat loss by radiation at the melting temperature of steel. The thermal lag time, found by the use of Equation 2, is 10.5 sec. Therefore, the use of a mean value of F_q averaged over a spin cycle is very conservative; and if the roll rate is low, initial failure of the vessel wall will occur about 11 sec after release of the NaK, or at an altitude as high as 270,000 ft.

Figure 20. Reactor Vessel Wall Temperature Histories

A survey was made of the effects of various parameters on the altitude of vessel wall melting, with the results shown in Figure 21. The thermal emissivity of the outer surface of the vessel was found to be an important factor; therefore, an experimental program was conducted to determine the thermal emissivities of stainless steel at high temperatures with surfaces oxidized as expected during reentry. The results of these experiments are summa-

rized in Appendix C. A thermal emissivity of 0.8 at temperatures near the melting point of steel was adopted as a conservatively high value.

Figure 21 shows that the vessel walls would melt at altitudes of about 280,000 ft if the angle of attack were 60 degrees or higher, such as may occur in cases of early abort with a large amount of residual fuel in the Agena tanks.

Figure 21. Influence of Various Factors on Altitude of Vessel Wall Failure

G. RELEASE OF FUEL ELEMENTS

Analysis of the heating of the top head of the reactor vessel indicates that portions of the lip will melt at altitudes above 250,000 ft, but the interference from the coolant pipes and pump will block the aerodynamic heating in such a way that a clean separation of the lip cannot be expected. Instead, the vessel will fail by melting of its side walls. After the walls have melted, the core assembly will be free to separate from the remains of the base

of the vessel. The angular momentum which it attained in the oscillating, spinning vehicle will assist in the separation of any remaining portions of the top head.

The top and bottom grid plates will melt soon after they have been exposed to the aerodynamic heating, and the fuel elements will no longer be held together. Variations in the aerodynamic pressure over the cluster of fuel elements will promote separation of the elements from each other.

V. SUMMARY AND CONCLUSIONS

The minimum altitudes for each of the important events in the reentry disintegration of a SNAP 10A/Agena are listed as follows:

<u>Event</u>	<u>Altitude (kiloft)</u>
Pump fins melt off	310
NaK flow stops	310
Converter fins melt off	290
Reflectors eject	280
Agena oxidizer tank fails	287
Coolant system ruptures	275
Reactor support legs fail	262
Reactor vessel melts open	237

An important result of this study has been the determination that the vehicle will be oscillating in an approximately nose-first attitude during reentry. This tends to increase the heating on the sides of the reactor and other components. Tail-first reentry, with the reactor behind the shield, has been found to be impossible.

It has been found that the presence of NaK in the system at the time of reentry does not appreciably delay opening of the vessel. If the NaK circulates, it has a beneficial effect in that the fuel elements will be warmer at the time of release than if the core were dry.

VI. REFERENCES

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5. A. W. Barsell and L. D. Montgomery, "Thermal Behavior of SNAP Reactor Fuel Elements During Atmospheric Reentry," NAA-SR-11502 (to be published)
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APPENDIX A INERTIAL AND AERODYNAMIC CHARACTERISTICS OF THE VEHICLE

Nominal values for the inertial characteristics of the SNAP 10A/Agena vehicle, as given by Lockheed, are tabulated below:

Mass	= 144.35 slugs (4650 lb)
Center-of-Mass Location (ft)	
x	= 6.23 aft of SNAP 10A/Agena interface
y	= 0.1067 to the right of central axis
z	= 0.036 below central axis
Moments of Inertia (slug-ft ²)	
I _x	= 383.9
I _y	= 13,662
I _z	= 13,651
I _{xy}	= 91.5
I _{xz}	= 112.5
I _{yz}	= 0

These values pertain to the in-orbit configuration at the end of reactor operation and were used in calculating the six-degree-of-freedom trajectory shown in Figure 8.

1. Aerodynamic Coefficients in Free-Molecule Flow

Force and moment coefficients in the free-molecule flow regime, as calculated by Lockheed, are given in Figures A-1 through A-3. The parameter, S, is the ratio of the velocity of the vehicle to the mean velocity of the gas molecules in the atmosphere. S is a function of altitude as shown below:

<u>Altitude (n. mi)</u>	<u>Molecular Speed Ratio, S</u>
700	3.5
300	7.1
90 and below	12.0

The aerodynamic coefficients corresponding to S = 12 should be used for reentry calculations. The other values should be used for calculating orbital lifetimes.

The axial force coefficient, C_A, and the normal force coefficient, C_N, are used to compute the aerodynamic forces in the direction of the longitudinal axis of the vehicle and normal to that axis, respectively. The direction of the normal force always lies in the plane defined by the body axis and the vector of the relative wind. The magnitudes of the forces are obtained from the following equations:

$$F_A = \frac{1}{2} \rho V^2 A C_A$$

$$F_N = \frac{1}{2} \rho V^2 A C_N ,$$

where

- ρ = density of the atmosphere (slug/ft³)
- V = velocity of vehicle relative to atmosphere (ft/sec)
- A = cross sectional area of vehicle, 19.62 ft².

Figure A-1. Axial Force Coefficients for Free-Molecule Flow

Figure A-2. Normal Force Coefficients for Free-Molecule Flow

Figure A-3. Pitching Moment Coefficients for Free-Molecule Flow

The pitching-moment coefficient, C_M , is defined such that a moment which tends to increase the angle of attack of the vehicle is considered to be positive. The coefficients shown in Figure A-3 are all negative, which indicates that the vehicle in free-molecule flow will tend to oscillate about a mean angle of attack of 0 degrees. The magnitude of the pitching moment is obtained from the following equation:

$$M = \frac{1}{2} \rho V^2 A L C_M ,$$

where

L = the diameter of the vehicle (5.0 ft) and the other terms are as previously defined.

Yawing and rolling moment coefficients in free-molecule flow were not estimated because the vehicle is essentially symmetrical about its central axis, and the center of pressure for the force coefficients is assumed to lie on the axis. Small moments will actually exist because of the displacement of the center of mass away from the axis. These moments were calculated in the six-degree-of-freedom trajectory program, based on the given values of C_A , C_N , and the coordinates of the center of mass.

2. Aerodynamic Coefficients in Continuum Flow

Force and moment coefficients in hypersonic, continuum flow are given in Figures A-4 through A-6. The solid lines show the preliminary values estimated by Lockheed, based on Newtonian theory and on some data from previous tests. The data points show values recently obtained from tests in the Ling-Temco-Vought, hypervelocity wind tunnel. The trajectories calculated for this report were based on the Lockheed values. The principal difference between the estimates and the recent data is that the trim angle, estimated to be 22 degrees, has now been found to be 32 degrees. This increase in trim angle tends to cause increased heating on the sides of the reactor and vehicle, and thus promotes earlier disintegration of the system.

Figure A-4. Axial Force Coefficients for Continuum Flow

Figure A-5. Normal Force Coefficients for Continuum Flow

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Figure A-6. Pitching Moment Coefficients for Continuum Flow

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Figure A-7. Pitching Moment Coefficients for Various Amounts of Residual Rocket Fuel

The trim angle is the angle of attack at which the vehicle tends to become stabilized under the influence of the pitching moment. Figure A-7 shows pitching-moment curves for three postulated cases of residual rocket fuel. The trim angle for each case is the angle at which the moment curve crosses the zero axis with a negative slope. In the normal case of no residual fuel, the trim angle is 32 degrees. If the second burn of the engine in the Agena is completed but the tanks are not purged, the trim angle is 49 degrees. If the second burn does not occur, the trim angle is 70 degrees. These higher trim angles could occur only in abortive situations, and the higher lateral heating associated with them would tend to cause earlier disintegration.

The moment curves also change sign at $\alpha = 0^\circ$ and $\alpha = 180^\circ$, but in such a manner that an unstable situation exists. It is, therefore, impossible for the vehicle to assume a stable attitude at either of these angles.

APPENDIX B

COMPUTATION OF AERODYNAMIC HEATING RATES

Aerodynamic heating results from collisions between a moving body and the molecules of gas in the surrounding atmosphere. With each collision, some of the energy possessed by the moving body is converted into heat, and a fraction of this heat remains with the body.

The phenomena of aerodynamic heating may be broadly divided into two categories: (1) free-molecule heating and (2) continuum heating. A body reentering the atmosphere first encounters heating of the free-molecule type. As the body descends into the more dense regions of the atmosphere, collisions between the gas molecules become more frequent, shock waves form ahead of the body, and viscous effects in the gas cause a boundary layer to form around the body. This is the regime of continuum flow. The transition from purely free-molecule flow to fully developed continuum flow is a gradual one, and most of the important events in the disintegration sequence of the SNAP 10A/Agena will occur during the transition period. Therefore, a detailed study of heating in the transition regime has been made during the course of the analysis leading to this report.

Free-molecule flow is defined as flow in which there is a negligible probability that a molecule of gas that has been scattered after collision with a body will subsequently collide with another gas molecule in the path of the body. Thus, each collision may be treated as a separate event. If the surface of the body is cold with respect to the energy level of the colliding molecules, and if each molecule is assumed to be brought to thermal equilibrium with the surface temperature by collisions with the submicroscopic surface irregularities and then randomly scattered, the heating rate per unit-projected area of the body is given by the following equation:

$$q_{fm} = \frac{1}{2} \rho V^3, \quad \dots (B-1)$$

where

q_{fm} = the rate of heat input to the body (ft-lb/ft²-sec)

ρ = the density of the surrounding air (slug/ft³)

V = the velocity of the body (ft/sec).

The heating rates given by Equation B-1 are used as reference values for free-molecule heating. In the application of these rates, they must be multiplied by the thermal accommodation coefficient, which has a value of approximately 0.9 for most metallic surfaces in air.^(B-1) If the surface is at a high temperature or if the flight velocity is low, a further correction must be made for the enthalpy of the gas at the surface temperature. The magnitude of this correction is indicated in Figure B-1. It is generally negligible at the high velocities of satellite reentry.

If the density of the atmosphere is high enough that multiple collisions between gas molecules forward of the body occur, the body is said to be in the continuum-flow regime. A boundary layer in which viscous effects predominate becomes established around the body. If the flight velocity is supersonic, a shock wave forms ahead of the body. An abrupt compression of the gas occurs through this wave.

Figure B-1. Correction Factor for Effect of Body Surface Temperature on Aerodynamic Heating Rate

At the higher supersonic (hypersonic) velocities, some of the gas molecules dissociate after they pass through the shock. If the density of the gas is high enough, the dissociated species may recombine in the boundary layer at a rate high enough to keep the gas in thermochemical equilibrium. An empirical formula which is widely accepted for calculating aerodynamic heating in the equilibrium, laminar-flow regime has been derived by Detra and Hidalgo.^(B-2) This formula is based on the work of Fay and Riddell^(B-3) and is as follows:

$$q_{\text{stag}} = \frac{865}{\sqrt{R}} \left(\frac{\rho}{0.00238} \right)^{0.5} \left(\frac{V}{10,000} \right)^{3.15} \left(\frac{H_s - H_w}{H_s - H_{300}} \right), \quad \dots (B-2)$$

where

q_{stag} = the heating rate at the stagnation point of a spherical body (Btu/ft²-sec)

R = the radius of curvature of the body surface at the stagnation point (ft)

ρ = the density of the undisturbed ambient air (slug/ft³)

V = the velocity of the body (ft/sec)

H_s = the enthalpy level of the air in the stagnation region (Btu/lb)

H_w = the enthalpy level of air at the temperature of the body surface (Btu/lb)

H_{300} = the enthalpy level of air at 300°K (80°F) (Btu/lb).

If the radius, R , is taken to be 1.0 ft and the wall temperature is taken to be 300°K, Equation B-2 may be used to define a reference heating rate for continuum flow:

$$q_{\text{ref}} = 865 \left(\frac{\rho}{0.00238} \right)^{0.5} \left(\frac{V}{10,000} \right)^{3.15}. \quad \dots (B-3)$$

Aerodynamic heating in the transition regimes between free-molecule and fully developed continuum flow has been studied by several investigators.^(B-4 through B-8) Values of heating rates

for the stagnation point of a 1.0-ft-radius sphere as calculated by the methods of these investigators are compared in Figure B-2. It may be noted that all of the results lie within a fairly narrow range, and that the Fay and Riddell theory may be used almost to the place where its line intersects the free-molecule heating line.

Figure B-2. Comparison of Theoretically Predicted Stagnation Point Heat Transfer Rates

Figure B-3. Stagnation Heating Rates to a 1-ft Radius Sphere

Figure B-4. Stagnation Heating Rates to a 0.1-ft Radius Sphere

When the gases in the boundary layer are highly dissociated, the aerodynamic heating rates depend on the effectiveness of the body surface in catalyzing the recombination of those atoms which collide with the surface. This is shown in Figures B-3 and B-4, which are based on calculations for spheres of 1.0- and 0.1-ft radius respectively, moving along the trajectory of Figure 7. Metallic surfaces are known to be highly catalytic to atom recombination; therefore, the heating rates for fully catalytic surfaces have been used in the analysis in this report.

Heating rates in the continuum-flow regime are dependent on the gradient of the velocity along the surface, which in turn depends on the radius of curvature of the surface. The heating rates in free-molecule flow are independent of surface curvature and also represent the greatest possible conversion of aerodynamic resistance into heat. Therefore, the procedure has been adopted in this analysis of calculating both free-molecule and continuum heating rates for each location on the body at each trajectory point and taking the lesser of the two values found. Transition does not occur at the same altitude for all components of a complex body, and some smaller components may still be in free-molecule flow while the larger ones are in continuum flow.

References (for Appendix B)

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APPENDIX C

THERMOPHYSICAL PROPERTIES OF MATERIALS

Values of thermal and physical properties of the materials used in the SNAP 10A system are tabulated in this appendix. These values were taken from several standard reference books, principally from the compilation of Goldsmith et al.* Thermal emittance values of the stainless-steel core vessel material were obtained by testing samples of the metal that had been oxidized in a manner approximating that which is expected to occur in the actual reentry from orbit.

1) Stainless Steel (Types 316 and 321)

Density at 70°F	— 495 lb/ft ³
Melting temperature	— 2550°F
Heat of fusion	— 127 Btu/lb
Specific heat capacity	— 0.11 Btu/lb-°F at 0°F 0.18 Btu/lb-°F at 2550°F (Linear Variation)
Thermal conductivity	— 7.4 Btu/ft-hr-°F at 0°F 18.6 Btu/ft-hr-°F at 2550°F (Linear Variation)
Thermal emissivity	— (See Figure C-1)

Note: The material used for the core vessel of the flight system is Type 321, and the thermal emissivity values were measured for this material.

Figure C-1. Thermal Emissivity of Type 321 Stainless Steel

*A. Goldsmith, T. E. Waterman, and H. J. Hirschhorn, Handbook of Thermophysical Properties of Solid Materials, Vol II, Alloys (The Macmillan Company, New York, 1961)

2) Titanium Alloy (Type 6AL-4V)

Density at 70°F - 282 lb/ft³
Melting temperature - 3053°F
Heat of fusion - 187 Btu/lb
Specific heat capacity - 0.122 Btu/lb-°F at 0°F
0.275 Btu/lb-°F at 3053°F
(Linear Variation)
Thermal conductivity - 3.4 Btu/ft-hr-°F at 0°F
17.6 Btu/ft-hr-°F at 3053°F
(Linear Variation)
Thermal emissivity - 0.7 (assumed constant)

3) Aluminum (Type 1100, Commercially Pure)

Density at 70°F - 170 lb/ft³
Melting temperature - 1218°F
Heat of fusion - 167 Btu/lb
Specific heat capacity - 0.20 Btu/lb-°F at 0°F
0.30 Btu/lb-°F at 1218°F
(Linear Variation)
Thermal conductivity - 130 Btu/ft-hr-°F
(assumed constant)
Thermal emissivity - 0.3 (bare surface)
0.9 (with emissive coating)

4) Pump Magnet Material (Alnico 5)

Density at 70°F - 456 lb/ft³
Melting temperature - > 2300°F
Specific heat capacity - 0.15 Btu/lb-°F
Thermal emissivity - 1.0 (assumed)

5) Pump Thermoelectric Material (Pb-Sn-Telluride)

Density at 70°F - 480 lb/ft³
Melting temperature - 1692°F
Specific heat capacity - 0.04 Btu/lb-°F
Thermal conductivity - 1.30 Btu/ft-hr-°F at 0°F
0.58 Btu/ft-hr-°F at 800°F
0.72 Btu/ft-hr-°F at 1000°F

6) Copper

Density at 70°F - 557 lb/ft³
Melting temperature - 1981°F
Heat of fusion - 75.6 Btu/lb
Specific heat capacity - 0.092 Btu/lb-°F at 0°F
0.125 Btu/lb-°F at 1980°F
Thermal conductivity - 223 Btu/ft-hr-°F at 0°F
186 Btu/ft-hr-°F at 1980°F

7) Coolant (Na-78% K)

Density - 48 lb/ft³
Specific heat capacity - 0.21 Btu/lb-°F
Thermal conductivity - 15 Btu/ft-hr-°F
Heat of vaporization - 775 Btu/lb
Vapor pressure - 108 lb/ft² at 1000°F
2740 lb/ft² at 1500°F
17500 lb/ft² at 2000°F

8) Beryllium

Density - 115 lb/ft³
Melting temperature - 2336°F
Heat of fusion - 470 Btu/lb
Specific heat capacity - 0.44 Btu/lb-°F
Thermal conductivity - 70 Btu/ft-hr-°F
Thermal emissivity - 0.6

9) Reactor Fuel Material (U-Zr-H)

Density - 374 lb/ft³
Melting temperature - 3365°F
Heat of fusion - 90 Btu/lb
Heat of dehydrogenation - 610 Btu/lb
Specific heat capacity - 0.15 Btu/lb-°F
Thermal conductivity - 15 Btu/ft-hr-°F

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Figure D-1. SNAP 10A Coolant Pipe, Showing Node Divisions
Used in Thermal Analog

NAA-SR-11103

APPENDIX D

DESCRIPTION OF COOLANT SYSTEM ANALOG

The coolant flow system of the SNAP 10A was modeled on an analog computer, and studies were made of the NaK flow rates and the temperatures of the coolant pipes during reentry. The system represented on the analog computer is shown schematically in Figures D-1 and D-2. The coolant pipe running across the top of the reactor and down each side was considered to be divided into six nodes, as shown in Figure D-1. Each node was further considered in three parts: (1) the outer or exposed half of the pipe, (2) the half of the pipe facing the reactor, and (3) the NaK inside the pipe. Pipe nodes 5 and 6 were surrounded by the titanium support leg, which was considered to be divided into two nodes, 5S and 6S. Each of these support leg nodes was considered in two parts, the exposed sides and the inner sides, respectively.

Figure D-2. SNAP 10A Thermoelectric Pump, Showing Node Divisions Used in Thermal Analog

The thermoelectric pump and the pump fins were modeled in detail, with the thermal capacities of the fin nodes, the thermoelectric elements, the copper electrodes, the pump magnet, and the NaK inside the pump calculated from their volumes and the thermal properties of the materials. Thermal conductances for all the heat-flow paths were calculated, and the film conductance coefficients from the pipe wall to the NaK were calculated by use of the following equation:*

$$\frac{h D}{k} = 5.8 + 0.02 (Pe)^{0.8}$$

where

h = film coefficient from wall to NaK

D = effective diameter of the pipe

k = thermal conductivity of the NaK

Pe = Péclet number, involving the velocity of the flow.

The characteristic equations for the pump flow were programmed into the analog computer so that the NaK flow rate would be caused to vary as a function of the temperature drop across the thermoelectric elements. During normal operation of the reactor, the heat flow is from the NaK, through the thermoelectric elements, and out through the fins. It is known, however, that a reverse flow of heat will cause the pump to drive the NaK in the reverse of the normal direction. The effect of the temperature of the magnet on the strength of the magnetic flux across the channel was considered in the analog, but the magnet did not become hot enough for this effect to be important.

The reactor and the radiator-converter were not modeled in detail because the number of nodes required would have exceeded the capacity of the available analog equipment. Instead, the core and converter were considered to be a single heat-exchanger assembly, with its total effective mass and heat input rate fed into the analog.

Aerodynamic heating rates to the components of the system were input for two assumed flight attitudes: (1) the vehicle at 30 degrees angle of attack with one coolant pipe along the stagnation line and (2) the vehicle at 30 degrees angle of attack with a rapid rate of spin about its major axis. Heating rates in the free-molecule flow regime were calculated by considering the exposed projected area of each of the components. In the continuum-flow regime, heating rates as shown in Figure D-3 were obtained from the results of the wind tunnel tests.[†] For the case of the vehicle with a high rate of spin, the heating rates on the support legs and on pipe nodes 2 through 4 were taken as 0.4 of the heating rates without spin. The values used are shown in Table D-1.

Transition between free-molecule and continuum flow was handled by calculating the heating rates for each node for both types of flow, and then selecting the lower of the two values at each time along the trajectory. The trajectory shown in Figure 1 was used in these studies.

Three cases were studied for each of the flight attitudes: (1) the system without NaK, assuming that the NaK may be lost in orbit; (2) the system with NaK but with the pump assumed to be inoperative; and (3) the system with NaK flowing as driven by the pump. Curves of NaK flow rate and

*G. F. Burdi, "SNAP Technology Handbook, Volume I Liquid Metals," NAA-SR-8617, Vol I (Rev July 9, 1964) p 2.14

†L. E. Shpiner and H. Hidalgo, "SNAP Aerospace Safety Program, Phase I Wind Tunnel Tests," NAA-SR-9781 (February 1, 1965)

6-1-65

7611-0873

Figure D-3. Local Heating Coefficients on Coolant Pipe Forward of Reactor

TABLE D-1
LOCAL HEATING FACTORS ON COOLANT PIPE

Node No.	Heating Factor	
	No Spin	With Spin
1	1.9	1.9
2	1.27	0.51
3	1.3	0.52
4	1.3	0.52
5S	1.4	0.56
6S	1.3	0.52

6-1-65

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Figure D-4. NaK Flow Rate and Coolant Pipe Temperatures During Reentry

temperatures of pipe nodes 1 and 5 vs time are shown in Figure D-4. The flow was found to stop when the aluminum pump fins melted at an altitude of 310,000 ft (1040 sec after start of reentry). The results of these studies are summarized in Table D-2.

The location of the first failure of the coolant pipe was found to be either in Node 1 or Node 5 for all cases. Node 1, being on the front of the system, is not greatly influenced by the spin rate. Node 5 is inside the titanium support leg, where it is not directly exposed to the air stream. However, it receives heat by radiation from the titanium, and it is of thinner gage metal than the other portions of the pipe. The failure of Node 5 prior to failure of the support leg was substantiated by the results of a detailed study of a section through the pipe and leg.

There was found to be practically no difference in the altitude of failure with stagnant NaK and flowing NaK in the system. The altitudes shown for failure of nodes after the first failure are not realistic, since the NaK will boil and form vapor bubbles after the first opening in the system has occurred.

TABLE D-2
RESULTS OF ANALOG STUDY OF COOLANT PIPE FAILURE

Calculation	$\alpha = 30$ degrees No Spin			$\alpha = 30$ degrees With Spin		
	No NaK	NaK not flowing	NaK flowing	No NaK	NaK not flowing	NaK flowing
NaK flow rate (max) (lb/sec)	-	0	0.76	-	0	0.76
Altitude of flow stopping (kiloft)	-	-	310	-	-	310
NaK temperature at stopping ($^{\circ}$ F)	-	-	940	-	-	940
Altitudes of pipe node failure (kiloft)						
Node 1	293*	280	280	294*	279*	278*
Node 2	288	279	279	266	236	234
Node 3	285	273	272	255	211	206
Node 4	284	272	272	261	208	208
Node 5	293*	289*	294*	257	253	253
Node 6	286	286	285	245	245	245
Fill tube	263	264	263	264	263	263
Altitudes of support leg failure (kiloft)						
Node 5S	263	266	265	201	201	195
Node 6S	263	263	264	195	195	206

*Nodes so marked fail first. Other failure altitudes are not exact since geometry of system changes after initial failure.

The altitude of failure of the support legs is not influenced by the presence or absence of NaK. For the nonspinning case, the legs are predicted to fail at an altitude of 263,000 ft. For the spinning case, failure is calculated to occur at 195,000 ft. Since the legs are of thin-gage metal, they will fail as they pass the stagnation region, and averaging the heating over a complete cycle is overly conservative. This effect was discussed in the section on heating of the reflector-retaining band.