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RFD-2 FLIGHT TEST PROGRAM

FINAL SUMMARY REPORT

MND-3283-2

June 1965

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FOREWORD

This report is the final summary report for the RFD-2 program. It was prepared in compliance with U. S. Atomic Energy Commission Contract AT(30-1)-3283 and Statement of Work MN-SW-1175, Revision 2, "Support of a Flight Test Program on Radioisotope-Fueled Space Power Systems (Re-entry Flight Demonstration)" dated November 3, 1964.

SC-RR-65-43 final report on Re-entry Flight Demonstration Number Two, published by the Sandia Corporation, contains a summary of the re-entry vehicle, equipment used for data acquisition, method of data reduction and conclusions resulting from their independent analyses.

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ACKNOWLEDGMENT

Acknowledgment is made to the Sandia Corporation for information used in this report regarding trajectory data, re-entry vehicle data, and information pertaining to the design and procedures for acquisition of flight test data.

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SUMMARY

Re-entry Flight Demonstration 2 (RFD-2) was a flight test program conducted jointly by Sandia Corporation and Martin Company to investigate the re-entry behavior of a SNAP 19-type nuclear thermoelectric generator.

The program was conducted from NASA's Wallops Island launch complex aboard a Scout vehicle. Re-entry of the payload occurred in the near vicinity of Bermuda Island. The generator was instrumented with thermocouples, movement switches, and flare material so that the experiment could be monitored by both optical and telemetering equipment. Downrange stations were located at Bermuda Island, on aircraft and on ships.

The objectives of the program were: (1) to investigate the heating rate and disassembly of the generator; (2) to measure the manner of heat distribution and its mode of transfer throughout the system; and (3) to investigate the effect of tantalum liner thickness on fuel capsule ablation.

Results of the program showed that the generator disassembled at an altitude between 157,000 to 159,000 feet. Calculations showed that the system should disassemble at an altitude of 158,300 feet. Hence, the primary objective of the program was met, and it was shown that current methods of predicting the fate of re-entering SNAP generators are valid.

The analyses concerning the four externally mounted, scaled, operational fuel capsules were conducted for two modes of re-entry: tumbling end-over-end and nontumbling, longitudinal axis normal to the air stream. Both methods considered the aerodynamic heating to be distributed by a surface average method. Internal liners of three of the capsules were of various wall thicknesses for the purpose of determining the rate and mode of failure of the tantalum material when exposed to re-entry oxidation mechanisms. One capsule containing a thallium flare had no liner, to provide an analytical base point. To date, only the capsule with the thallium flare has been positively identified. The flare was exposed at an altitude of 187,000 feet. It was predicted that exposure should have been at an altitude of 166,500 feet for the tumbling mode and at an altitude of 204,000 feet for the nontumbling mode. The experimental value is approximately the average of the two analytical results. Therefore, it may be concluded that the motion of the capsule was more complex during the actual re-entry than the modes assumed. The analyses of the other external capsules are not finished, in that all optical and radar tracking information have not been fully evaluated.

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Sandia Corporation had prime responsibility for conducting the flight test, designing and fabricating the telemetry equipment and its housing, and acquiring and reducing all data.

NASA and its contractors launched the Scout vehicle and provided downrange data acquisition. The Air Force Special Weapons Center and Eastern Test Range also provided aircraft for data acquisition. Their participation in this program is fully described in Sandia Corporation's report, SC-RR-65-43.

Martin Company had the responsibility for designing, fabricating, and instrumenting the payload, conducting ground tests pertinent to the payload, and performing independent postflight data evaluations.

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GLOSSARY OF SYMBOLS

C_p	= specific heat
H_e	= total enthalpy external to the boundary layer $h + U_e/2$
h	= enthalpy
h_o	= average atomic dissociation energy times atom mass fraction
K	= coefficient of thermal conductivity
L	= length of notch
Le	= Lewis number
M	= Mach number
N	= 0 for two-dimensional flow and 1 for axisymmetric flow
Pr	= Prandtl number $= \frac{C_p \mu}{K}$
p	= static pressure
p_s	= stagnation pressure behind a normal shock
$\dot{q}$	= heat flux per unit area
R	= nose radius of body in meridional plane
$Re_{(x)}$	= Reynolds number $\rho_e u_e X/\mu_e$
r	= radius of cross section of body of revolution
T	= temperature
T_{aw}	= adiabatic wall recovery temperature
t	= time
u	= X-component of velocity

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GLOSSARY OF SYMBOLS (continued)

- u_c = circular velocity taken as 26,000 ft/sec in numerical calculations
- (du/dx) = velocity gradient
- x = distance along a wetted surface
- Y = coordinate normal to free stream (origin at notch wall)
- β = defined as $2 \left[d \ln u_e / d \ln \left(\int_0^x \rho_w \mu_w u_e r^2 dx \right) \right]$
- γ = ratio of specific heats
- δ_s = thickness of the free shear layer at reattachment
- θ = stream deflection angle
- λ = angle between flight direction and radius vector from center of curvature of nose
- μ = viscosity
- ρ = mass density
- ψ = exponent in Lewis number correction factor

SUBSCRIPTS

- bl = boundary layer conditions on comparable body without cavity
- e = conditions at outer edge of boundary layer
- o = sea level conditions
- s = stagnation point conditions
- w = wall conditions
- 300° = value at 300° Kelvin
- ∞ = free-stream conditions

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GLOSSARY OF SYMBOLS (continued)

SUPERSCRIPTS

- * = indicates values are to be determined using the reference enthalpy
- (⁻) = indicates average value

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I. INTRODUCTION

Re-entry Flight Demonstration 2 (RFD-2) was the second in a series of operational safety flight tests conducted by Sandia Corporation. This one was in conjunction with the Martin Company to evaluate the flight characteristics of a SNAP 19-type thermoelectric generator. This generator system was developed to disassemble and release fuel to the atmosphere during re-entry from orbit. The program was designed to demonstrate the behavior of the space power system when exposed to a re-entry environment. Results and conclusions of the program will be used to strengthen analytical arguments when evaluating the safety aspects of future space power systems.

The program included experiments which monitored heat distribution and disassembly of the outer generator housing, the separation of generator inner components, and the exposure and release of the simulated generator fuel. Also, four simulated fuel capsules with constant wall thickness and varying liner thicknesses were released from the payload package prior to generator disassembly to determine the effects of re-entry heating on tumbling capsules.

Extensive ground tests were conducted by both the Sandia Corporation and the Martin Company as a means of establishing techniques to predict the re-entry behavior of the specimens. These ground tests included mechanical, thermal, shock, drop, and aerodynamic wind tunnel programs.

This report summarizes the effort expended by the Martin Company for the RFD-2 program.

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II. PROGRAM OBJECTIVES

No matter what the disposition philosophy of fuel may be, space nuclear generators must be evaluated in terms of aerothermodynamic effects. Since the design geometries of such systems are such that little experimental aerodynamic data are available, good flight tests supported by necessary ground tests are essential to provide the safety analyst with the tools to strengthen his evaluation. The RFD-2 program was designed to provide such a tool for a system which must disassemble and release fuel upon re-entry from orbit. Specifically, the objectives of the RFD-2 program were:

- (1) To investigate analytically the disassembly and burnup characteristics of an inert isotopic generator of the SNAP 19 type re-entering along a ballistic trajectory.
- (2) To determine experimentally flight characteristics of such a generator configuration in terms of generation and distribution of aerodynamic heating, destruction of the generator housing, separation of the generator inner components, and the exposure and release of the simulated generator fuel.
- (3) To establish a degree of confidence in existing aerothermodynamic analyses for orbital re-entry conditions.
- (4) To determine the aerothermodynamics of re-entering fuel capsules with various liner configurations.
- (5) To obtain flight information on such fuel capsules by optically recording the spectral lines of tracer materials released when capsule casing fails due to burnup.
- (6) To correlate flight data with analytical predictions based on heating rates obtained theoretically and experimentally, using existing heat transfer codes.

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III. DESCRIPTION OF TEST PROGRAM

The RFD-2 experiment was launched by a three-stage Scout vehicle from the NASA Wallops Station at 04:04:56 Zulu time on October 9, 1964. It was launched on an azimuth of 126 degrees and programmed to an apogee of 480,000 feet into a re-entry trajectory leading to impact about 150 nautical miles southeast of Bermuda. Details of the test program, including a description of the launch facility, launch vehicle, re-entry vehicle, and experimental payload, along with methods of data acquisition are summarized below.

A. LAUNCH FACILITY

NASA Wallops Station is located off of the Delmarva Peninsula in Virginia near the Maryland state line. The base is owned and operated by the government for experimental free-flight re-entry tests, vertical tests, or orbital missions involving small research payloads.

The facility is divided into three areas: the Main Base, Wallops Island Proper, and the Mainland. The Main Base is operational headquarters. It is the former Chincoteague Naval Air Station at the western edge of the causeway leading to Chincoteague Island. Wallops Island Proper is about 10 miles southeast of the Main Base. The island, about five miles long and one-half mile wide, is separated from the mainland by two miles of marsh and inland waterway. The third part of the complex, Wallops Mainland, straddles the western approach of the causeway leading to the island. It houses the facility's long range radar, acoustical, meteorological, and telescopic tracking equipment. Figure III-1 shows the general layout of the complex.

A Scout launch tower provides the facility for erecting, servicing, and launching. The space vehicle in its retracted position is shrouded by an aluminum building (Fig. III-2) which acts as an assembly and shelter area, with provisions for controlling temperature and humidity. The atmosphere within the building is controlled to prevent degradation of the Scout's solid fuel. The building is rolled away on a track when the rocket is ready for firing. The entire launcher is rotated for control of launching azimuth and adjusted for elevations from 75 to 90 degrees. Elevation angle and unbilical ejection systems are hydraulically controlled from the blockhouse. Individual hydraulic controls are installed in the erector tower for all other operating units. Figure III-3 shows the Scout 130 in the launcher ready for firing.

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Fig. III-1. Wallops Station Launch Complex

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Fig. III-2. MK-2 Shelter, Scout Shed

Fig. III-3. Scout 130 Ready for Firing

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B. LAUNCH VEHICLE

The Scout vehicle used in this experiment was developed and built for NASA by Ling-Temco-Vought of Dallas, Texas. It is capable of performing re-entry and high altitude probe missions with payload weights up to 500 pounds and orbital flights with payloads up to 150 pounds. Scout has launched five satellites as part of the U. S. space exploration program and has performed re-entry flights similar to the RFD-2.

For the RFD-2 program, three rocket engines were used. The fourth stage housing was simulated to provide mechanical transition for interfacing with the third stage and payload package. The general arrangement and major assemblies of the Scout are shown in Fig. III-4. Available vehicle system data is given in Table III-1 and nominal trajectory events for the RFD-2 experiment are given in Table III-2.

In the liftoff configuration, the Scout vehicle is aerodynamically stable. A proportional control system, featuring a combination of jet vanes and aerodynamic tip control surfaces operated by hydraulic servoactuators, is used to control the vehicle throughout the entire first-stage burning period. These controls operate in pairs for pitch and yaw motion. The jet vanes provide the greater control force during the thrusting phase, and the aerodynamic tip controls provide all the control force during the coasting phase following the burnout of the first stage.

TABLE III-1
Scout Vehicle Data

	<u>First Stage</u> <u>(Algol)</u>	<u>Second Stage</u> <u>(Castor)</u>	<u>Third Stage</u> <u>(Antares)</u>
Vehicle weight (lb)	24,671	9,760	3,383
Structure weight (lb)	3,389	2,227	780
Fuel weight (lb)	21,282	7,533	2,603
Propellant designations*	ANP-2639AF	TP-H8038A	BUU
Propellant type*	Ammonium perchlorate polyurethane A1	Ammonium perchlorate PBAA/A1	Double bass/A1
Burning time (sec)	71.3	42.5	36.3
Maximum thrust (lb)	117,000	79,000	19,000

Total liftoff weight = 38,309 pounds

*Scout E data.

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Fig. III-4. General Arrangement and Major Assemblies of Scout S-130R Rocket

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TABLE III-2
Nominal Trajectory Events for Scout Vehicle

<u>Event</u>	<u>Time from Launch (sec)</u>	<u>Altitude (feet)</u>	<u>Range (nautical miles)</u>
First stage burnout	71.30	106,288	17.04
Second stage ignition	87.70	138,713	25.28
Second stage burnout	130.19	252,869	70.83
Third stage ignition	229.10	443,476	218.67
Apogee	241.00	447,667	238.49
Third stage burnout	265.36	425,072	299.00
Separation	278.00	400,412	337.60

After separation of the first stage, all succeeding stages are aerodynamically unstable. For this reason, the spent first stage is not separated from the vehicle until an altitude of 120,000 feet is attained. At this altitude, the effect of destabilizing aerodynamic air loads is reduced. Control during second and third stage burning is provided by hydrogen peroxide reaction jets which are operated as an on-off system within a small deadband. Guidance is confined to the pitch plane only, with the yaw and roll orientation maintained during flight at essentially the reference attitudes established at the time of launch.

The Scout command-destruct system consists of shaped charges in the first and second stages which, on command, rupture the rocket motor and terminate thrust.

C. EXPERIMENTAL PAYLOAD

Principal elements of the RFD-2 payload consisted of an inert SNAP 19-type thermoelectric generator and four external fuel capsules with simulated fuel loadings of tracer materials attached to the generator. Details of this hardware are given below. A summary of ground test programs designed to demonstrate the characteristic behavior of the system materials and components when exposed to a re-entry environment is given in Appendix A.

1. Simulated Thermoelectric Generator

The inert thermoelectric generator tested in the RFD-2 experiment was of the SNAP 9A/SNAP 19 type, which is designed for aerodynamic

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burnup. It was of a size which would produce 20 watts of electrical power from four fuel capsules. Instrumentation was provided to determine thermal data with respect to time and breakup characteristics of the system during re-entry. Also the internal fuel capsules were designed to separate the flare material from the capsule immediately upon release from the generator. This provided means for positive and immediate determination of time of destruction of the generator housing during re-entry. For this experimental program, four generators were built--two for ground test and two for the flight test, one of which was used as a backup.

a. Generator structure

The generator consists of four major subassemblies: the housing assembly, consisting of an outer housing with top and bottom cover plates; module assembly, consisting of four module blocks; the insulation assembly; and the heat accumulator assembly. Details of the assembly procedures for the system, along with a list of production drawings, are given in Appendix B. Figure III-5 shows a cross section of the assembled generator, and Table III-3 presents a detailed weight breakdown of the system.

Magnesium was used in the construction of the outer housing and top cover plate because it is light and strong and has a relatively low melting point, approximately 1100° F. The latter is of primary consideration when designing a system for re-entry burnup. Although the bottom cover plate would generally be constructed of magnesium in operational systems, a substitute material was used for the RFD-2 experiment, so that a part of the generator might survive re-entry heating and be recovered. For this reason, the bottom cover plate was made of stainless steel.

Four module bars, each containing 30 thermoelectric elements, made up the module assembly. Each bar was constructed of aluminum and was identical with that in the SNAP 19 system; however, a material substitution was made for the lead tin telluride thermoelectric to facilitate manufacturing. This substitute was a stainless steel element with comparable thermal properties. Each element was assembled in the bar under spring compression equal to approximately 10 pounds.

The insulation assembly consists of four strips of Min-K around the periphery of the generator housing between the four module bars, two disks of Min-K under the top cover plate, each segmented into two pieces, and a Dynatherm E300 potting compound filler between the heat accumulator block and bottom cover plate. This assembly was dissected as required to accommodate generator instrumentation. Disks under the top plate were segmented to facilitate removal by aerodynamic forces during re-entry.

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Fig. III-5. Vertical Cross Section of RFD-2 Generator

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Fig. III-5. (continued) Horizontal Cross Section of RFD-2 Generator

TABLE III-3
Weight Breakdown--RFD-2

Part Number	Volume (in. ³)	Material	Density (lb-in. ³)	Weight (lb)	Quantity per Generator	Total Weight per Generator
439B0210005-001 Bottom cover	17.94	321 SS	0.29	5.203	1	5.203
439B0210006-001 Housing	26.366	HM-31A-F Mag	0.065	1.714	1	1.714
439B0210007-001 Top cover	11.837	HM-21AT8 Mag	0.064	0.757	1	0.757
439B0210008-001 Bracket slide	0.041	6061-T6 Al	0.098	0.004	4	0.016
439B0210008-003 Bracket	0.024	6061-0 Al	0.098	0.0023	4	0.009
439B0210008-005 Guide	0.009	6061-0 Al	0.098	0.0009	4	0.003
439B0210008-007 Cover	0.022	Al foil	0.100	0.0022	1	0.0022
439B0210009-001 & 003 Insulating disks	15.148	Min-K (28 lb/ft ³)	0.0162	0.245	1	0.245
439B0210009-005 & 007 Insulating disks	12.732	Min-K (28 lb/ft ³)	0.0162	0.206	1	0.206
439B0210012-009 Fuel block assembly	14.459	Graphite-ATJ	0.065	0.940	1	0.940
439B0210013-001 Module bar	5.174	6063-T5 Al	0.098	0.507	3	1.521
439B0210013-003 Module bar	5.058	6063-T5 Al	0.098	0.496	1	0.496

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TABLE III-3 (continued)

Part Number	Volume (in. ³)	Material	Density (lb-in. ³)	Weight (lb)	Quantity per Generator	Total Weight per Generator
439B0210014-001 Insulating module strip	5.111	Min-K (20 lb/ft ³)	0.0115	0.059	4	0.235
439B0210015-001 Piston	0.076	304 SS	0.29	0.022	120	2.645
439B0210016-001 Clamp plate	1.353	2024-T4 Al	0.100	0.135	4	0.541
439B0210011-001 Capsule end. int	0.523	Haynes-25	0.33	0.173	8	1.381
439B0210011-003 Capsule half int	0.381	304 SS	0.29	0.110	8	0.884
439B0210011-005 Capsule cap int	0.028	Haynes-25	0.33	0.009	8	0.074
Potting agent E-300	30.929	E-300	0.043	1.330	1	1.330
Bolts 1/4 in. x 1-1/4 in.	0.090	SS	0.29	0.0261	24	0.636
Springs WB2756		SS		0.0022	120	0.264
439B0210004-009 Potting ring	1.321	6061-T6 Al	0.098	0.131	1	0.131
Total (excluding flare material and instrumentation)						19.464

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A five-piece graphite heat accumulator block and four simulated fuel capsules containing flare materials made up the heat accumulator assembly. The graphite block, shown in Fig. III-6, was designed to disassemble as soon as it was exposed to aerodynamic forces. The purpose of the four tracer-loaded fuel capsules inside the generator heat accumulator block was to establish the time when the generator assembly disassembled during flight. This was accomplished by recording on spectral motion picture and plate film, radiations from the burning tracers contained in each capsule. The capsule was designed to release the tracer-filled container immediately upon release from the generator (Fig. III-7). All internal capsules were identical in size and configuration; however, each contained a different flare material supplied by Sandia Corporation--sodium, lithium, barium, and gallium. Figure III-8 shows the configuration of a typical tracer assembly. The cylinder was 0.625 inch in diameter by 2.43 inches long. Each tracer material was surrounded by 0.080 inch of Fiberfrax insulation segmented longitudinally into three segments. Insulation was used to prevent heating and possible melting before disassembly of the generator. It was segmented to facilitate tracer exposure once the thin, 10-mil stainless steel liner was burned away. This liner was used to prevent oxidation of the flare material. Material used to make up the internal capsule was Haynes-25 alloy, the same as that used in the SNAP 19 capsule. Both ends of each capsule were coated with aluminum oxide material to prevent premature melting of the Haynes-25 material before the capsule was released to the air stream.

The entire generator structure was attached to the re-entry vehicle (RV) by means of three bolts through an adapter section of phenolic Refrasil and fiber glass. A detailed structures analysis of the generator and its attachment is given in Appendix C.

b. Generator instrumentation

The RFD-2 experimental generator was instrumented to measure temperatures relative to time throughout the structure and to record motion within the unit so that a time history of generator disassembly could be made during re-entry. There were 29 thermocouples within the generator structure, located as shown in Fig. III-5. Each internal capsule was positioned on a contact switch which gave indication when the capsule moved within the generator, thereby indicating the beginning of failure of the generator housing. Details of instrumentation used in the generator are given below.

Thermocouples

Two types of thermocouples were used in the generator: chromel-alumel for lower temperature ranges, below 1500° F; and platinum-13% rhodium-platinum for high temperature ranges, above 1500° F.

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Fig. III-6. Disassembly of Heat Accumulator Block--RFD-2 Generator

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Assembled Capsule

Disassembled Capsule

Fig. III-7. Internal Fuel Capsules--RFD-2 Generator

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Partially Assembled Capsule

Component Parts

Fig. III-8. Typical Internal Flare Capsule--RFD-2

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Chromel-alumel was selected because the expected temperature range in materials on which it was to be used corresponded with the best working range of the thermocouple. Also, the millivolt output range per degree of temperature measurement is higher for chromel-alumel than comparable base-type metals. Platinum-rhodium couples were selected over other noble metals because of their higher output per degree in the higher temperature range.

All thermocouples were constructed of standard grade, 30-gage wire, using a mercury arc pool as a fusing device. This process yielded beads 30 mils in diameter with a tolerance of $\pm 15\%$. Voltage output tests on each thermocouple were made by a comparison technique, using a thermocouple which was calibrated with one from the National Bureau of Standards. Once installed, each couple was tested for continuity between positive and negative leads and between each lead and some reference point in the generator housing. Results of these checks for the two flight generators are given in Appendix D. Temperature responses of the couples were checked by heating the junction with an outside source.

Five different methods were used to install the thermocouples into the generators. Table III-4 summarizes the various thermocouple configurations, and Fig. III-9 shows the method of assembly of each.

Contact Switches

Four contact switches were used in the generator system to indicate when the internal fuel capsules were released during re-entry. The switches were wired so that a continuous signal was received from an independent voltage source when the switch was closed. Switches were selected on the basis of high temperature capability and compactness.

A typical switch installation is shown in Fig. III-10. Care was taken to prevent the E-300 potting compound from restricting the movement of the switch plungers. Switch specifications and ratings were:

- (1) Maximum: 4 amperes, 18 to 30 volts, dc, resistive
- (2) Nominal: 2.5 amperes, 18 volts, dc, inductive
- (3) Minimum: 0.1 ampere, 18 volts, dc
- (4) -65°F to $+650^{\circ}\text{F}$ continuous operation
- (5) Life

Maximum: 100,000 operations

Minimum: 25,000 operations

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TABLE III-4
Generator Thermocouple Data

Thermocouple Designation	Thermocouple Location	Thermocouple Materials	Installation Style
T1	Top cover	Chromel alumel	Type A
T2	Top cover	Chromel alumel	Type B
T3	Top cover	Chromel alumel	Type A
T4	Top cover	Chromel alumel	Type B
T5	Top cover	Chromel alumel	Type B
T6	Top cover	Chromel alumel	Type B
T7	Housing--top flange	Chromel alumel	Type A
T8	Housing--top flange	Chromel alumel	Type A
T9	Housing--inside wall--top	Chromel alumel	Type B
T10	Housing--inside wall--top	Chromel alumel	Type B
T11	Housing--center band	Chromel alumel	Type A
T12	Housing--inside wall--center	Chromel alumel	Type B
T13	Housing--center band	Chromel alumel	Type A
T14	Housing--inside wall--center	Chromel alumel	Type B
T15	Housing--inside wall--bottom	Chromel alumel	Type B
T16	Housing--inside wall--bottom	Chromel alumel	Type B
T17	Container--top side	Platinum rhodium	Type B
T18	Container--top side	Platinum rhodium	Type B
T19	Module plate--inside top	Chromel alumel	Type B
T20	Module plate--inside center	Chromel alumel	Type B
T21	Graphite block--outside center	Platinum rhodium	Type C
T22	Graphite block--outside center	Platinum rhodium	Type C
T23	Container--bottom side	Platinum rhodium	Type D
T24	Container--bottom side	Platinum rhodium	Type D
T25	Graphite block--top	Platinum rhodium	Type C
T26	Graphite block--bottom	Platinum rhodium	Type C
T27	E-300 potting--center	Platinum rhodium	Type E
T28	Bottom cover	Platinum rhodium	Type B
T29	Bottom cover	Platinum rhodium	Type B

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Installation--Type A

Installation--Type B

Installation--Type C

Installation--Type D

Installation--Type E

Fig. III-9. Types of Instrumentation Installations

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Fig. III-10. Typical Switch Installation

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- (6) Switch travel (normal open to normal closed): 0.019 in.
- (7) Vibration: 10 g from 500 to 2000 cps.
- (8) Shock: Complies with MIL-STD-202A (509).

2. External Capsule Experiment

In the planning stages of the RFD-2 program, it was realized that operational SNAP 9A/19 capsules (100-mil wall thickness of Haynes-25 and 20-mil wall thickness of tantalum liner) would not ablate completely if released from the RFD-2 generator along the suborbital trajectory flown. Therefore, an external capsule experiment was planned primarily to study the effect of aerodynamic heating and oxidation of tantalum liners during re-entry. This problem has been under study for some time because tantalum, with its high melt temperature, was considered to be the only material compatible with the fuel utilized in some nuclear devices. Since it is essential to burn up the liner and release the fuel in operational systems, one must depend on the oxidation characteristics of the tantalum at high temperatures.

Four capsules were attached to the outside of the RFD-2 generator--one without a liner and the other three with tantalum liners of wall thicknesses of 6 mils, 12 mils, and 20 mils, each containing a different flare material. Each capsule was designed with a wall thickness of 50 mils of Haynes-25. Although this is only half as thick as an operational capsule, the primary objective of the experiment could better be met. These capsules were mounted in two groups of two each, 180 degrees apart on the outside of the generator housing. Mounting cradles were designed to release all four capsules simultaneously at a predetermined altitude by detonating explosive bolts which secured a retaining band around the capsules. Each was released from the cradle with the aid of a spring on one end to ensure an initial tumbling mode of re-entry. Tracer materials were selected for each capsule so that the weight and ballistic coefficients would be somewhat equal, resulting in capsule trajectories as similar as possible to one another to facilitate optical coverage of the test. Details of the various capsule configurations and flare materials are given in Table III-5, and a cross section of a typical capsule is shown in Fig. III-11.

Tracer materials were supplied by Sandia Corporation. They were selected on the basis of strong and identifiable spectral lines. Fiberfrax insulation was used between the flare material and capsule housing to delay melting of the flare before the capsule material ablated off. Also, the insulation controlled the vapor pressure of flare during the re-entry heating.

D. RE-ENTRY VEHICLE

Specific details of the re-entry vehicle were obtained from the Sandia Corporation, which was responsible for its design and fabrication. A cursory description of the vehicle is presented on the following pages.

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TABLE III-5
Details for External Capsules--RFD-2

Capsule			Liner			Tracer			Total Weight (lb)*
Capsule No.	Weight (lb)	Volume (in. ³)	Weight (lb)	Thickness (in.)	Volume (in. ³)	Material	Weight (lb)	Volume (in. ³)	
50H	0.302	0.979	--	--	--	Thallium	0.447	1.054	0.828
50H6T	0.322	0.979	0.048	0.006	0.072	Silver	0.388	1.026	0.812
50H12T	0.322	0.979	0.087	0.012	0.131	Indium	0.273	1.054	0.731
50H20T	0.329	1.033	0.141	0.020	0.239	Strontium	0.099	1.036	0.635

*Total weight includes tracer container and split insulation.

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Fig. III-11(a). Cross Sectional View of Typical Fuel Capsule

Fig. III-11(b). External Fuel Capsules

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Principal functions of the RV were to provide an aerodynamically stable support for the isotopic generator and external fuel capsule experiment and to house and thermally protect telemetry equipment needed in the experiment. The RV was designed to survive water impact and to float so as to facilitate recovery by search craft. The RV (Fig. III-12) contained the experimental payload, a structurally simulated dummy fourth stage rocket engine, a recovery aid system, and all equipment necessary to perform timed functions and data transmission.

1. Stability

Axial stability of the RV was initially accomplished on re-entry by spinning the RV to maintain the major axis in the direction of the velocity vector. Following ejection of the external capsules and simulated fourth stage, the RV was despun by ejecting weights attached to cables.

2. Structure and Ablation Material

The RV structure, ablation material, and insulation were combined into one assembly to simplify manufacture and minimize weight. An aluminum substructure provided rigidity, internal support, and strength for the threaded joint in the center section of the RV, which was incorporated to facilitate assembly.

The inner 0.125 inch of the RV shell was made by a flat concentric layup of phenolic-impregnated fiber glass, which was used both for structural strength and thermal insulation. Phenolic-impregnated refrasil ablation material was wound over the inner fiber glass layer, and the entire assembly was then cured as a unit and machined to final size.

The after body and cavity of the RV that were to be exposed to re-entry heating after separation of the load adapter were covered with Dynatherm 47-55-2 polyurethane-cork ablation material and Armstrong 2755 phenolic cork.

3. Telemetry System

a. Commutation

The outputs of both the thermocouples and the displacement indicating devices were commutated to condition them for pulse amplitude modulation (PAM) and, finally, for PAM/FM/FM transmission. The commutation of the slowly varying measurements allowed the use of one subcarrier (14.5 kc) oscillator to carry all the temperature data and another (22.0 kc) to carry the displacement data.

Figure III-13 shows the schematic diagram for the high level commutation process which sampled five times per second. This rate permitted the departure time of the fuel capsules to be determined within 200 milliseconds.

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Fig. III-12. Re-entry Vehicle with Isotopic Generator and Protective Cage

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Schematic Diagram Showing Method Used to Acquire Position Data for PAM (pulse amplitude modulation) Transmission

Fig. III-13. High Level Commutation--2.5 Rev/Sec

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b. Conversion and transmission

The data were transmitted from the re-entry vehicle to ground and airborne receivers by means of a PAM/FM/FM telemetry system. In this process, the data frequency modulates a subcarrier by means of pulse amplitude modulation. The amount of modulation of the subcarrier is related to the commutated data amplitudes. The FM subcarrier, in turn, frequency modulates the main carrier.

FM/FM telemetering was chosen as a communication link because of its relative insensitivity to atmospheric disturbances in amplitude modulation. In addition, frequency response is improved with this type of system.

Figure III-14 shows the on-board telemetry block diagram for acquisition and reduction of the data. The commutated data frequency modulate subcarriers, the temperature data being on one subcarrier and the displacement data on another. The multiplexed subcarriers modulate the real time (Package B) carrier to produce a PAM/FM/FM signal for transmission to receiving stations. Package A operates in a similar fashion, but is delayed 83 seconds through a continuous magnetic tape loop.

The main carrier is removed on reception of the signal and the subcarriers are separated by band pass filters. The intelligence is removed from the carriers and is decommutated to reproduce the recorded data. The raw data is placed on magnetic tape for storage and is also presented on chart paper by servo indicating devices.

c. Beacons

Included aboard the RV were four tracking and recovery-aid beacons. In the TM compartment a C-band beacon (5750 mc) provided a radar-tracking aid for the downrange station at Bermuda. A 1/2-watt CW beacon (225.7 mc) continuously transmitted an RF signal for search craft. Attached to the flotation bag on the main chute, a SARAH beacon provided further post-impact recovery aid. Two flashing lights were included among the beacons, one attached to the aft end of the RV and the other attached to the flotation bag.

d. Antennas

Three antennas were aboard the RV. The forward portion of the aluminum substructure of the RV constituted one half of the ring-dipole antenna. The driven half of the ring-dipole was a thin aluminum shell within the RV. A 10-inch, high-temperature, tungsten stub antenna protruded aft of the RV, providing transmission during re-entry heating.

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Fig. III-14. Telemetry Block Diagram RFD-2

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For the C-band beacon, the antenna system consisted of six cavity antennas and a six-way RF power divider. Three of these were tilted 15 degrees forward to aid in early radar acquisition. The other three radiated at right angles to the longitudinal axis of the RV to permit tracking into the re-entry phase of the trajectory.

e. Programming system

A dual-channel system in the TM compartment handled firing and monitoring of the pyrotechnic devices in the RV and programmed certain TM functions. Each channel consisted of one Logitek Model A690 time-code generator, an RFD-2 inflight programmer, control relays, and squib-monitoring circuits. The pyrotechnic events, programmed through either channel of the dual-channel system, were:

- (1) Inflight arming.
- (2) Ejection of the externally mounted fuel rods effected by the initiation of either of two Horex 2503 10-32 explosive bolts.
- (3) Separation of the cylindrical load adapter through the ignition of a hot-gas generator.
- (4) Despin which required the initiation of a Horex 2801 guillotine to release the despin weights.
- (5) Separation of the despin band effected by the firing of either of two Horex 2503 10-32 bolts.
- (6) Parachute deployment initiated by firing the drogue gun.
- (7) Inflation of the flotation bags effected by the opening of explosively actuated valves on CO₂ reservoirs.

The programmed TM functions and their purpose were:

- (1) The record and erase electronics in the tape recorder were turned off at the predicted end of blackout. This prevented destruction of the blackout recorded data by subsequent post-blackout recording. This increased the probability of recovering these data by continuous retransmission or possible recovery of the TM package.
- (2) The tape recorder output was fed to Package B 473 seconds after launch. This was done to increase the probability of recovering the blackout recorded data. No real-time data of significance were expected after this time.

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- (3) All electrical systems were turned off except for the tape recorder, Package A, and the CW beacon at the expected impact time. This was done to save battery power for the systems left on, which were expected to continue operating after impact.

f. Data reduction

Figure III-15 shows the schematic diagram and final form of the output data for the temperature measuring system. The thermocouples which were expected to vary most rapidly (T1 through T16) were sampled twice per second, while the remaining couples (T17 through T29) were sampled once per second. A reference mark was printed out to establish a standard value to which the data could be compared. The presence of constant reference marks in the reconstructed data is a good indication that the modulation-transmission-demodulation process did not affect the data.

The reconstructed data were channeled into a digital computer which examines the data to determine the minimum and maximum values. The former is assigned a value of 0.0; the latter, 999.0; and intermediate values are assigned to the data in proportion to their respective magnitudes. A subroutine relates the count number to the corresponding temperature, and the final digital output is the time-temperature history of each thermocouple.

The displacement data through the demodulation process were reconstructed in a manner similar to that described above for the temperature data. This data represents a go, no-go situation, the transition time of which was resolved to within 200 milliseconds by the presence or absence of the voltage.

4. Recovery System

A recovery system was provided for retardation, flotation, and acquisition of the RV. It was included primarily so that the vehicle and the remaining sections of the experimental payload could be examined after exposure to the re-entry environment. In addition, retrieval of an on-board tape recorder in the TM system would have provided a redundant method of obtaining data on events occurring during the period of RF blackout.

The recovery system consisted of a parachute, flotation aids, a dye marker, RF beacons, and flashing lights (Fig. III-16).

At an altitude of 23,000 feet, a 7.5-foot diameter parachute was deployed to decelerate the RV to an acceptable water-entry velocity. The main chute was opened by a smaller pilot chute actuated by the firing of a TM programmed drogue gun.

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Amplitude-Time Relation for Sampled Temperature Data (T1-T16)

Amplitude-Time Relation for Sampled Temperature Data (T17-T29)

Fig. III-15. Low Level Commutation--1.0 Rev/Sec

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Fig. III-16. RFD-2 Recovery System Deployed

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To increase RV buoyancy, all unused volume in the RV was filled with low-density polyurethane foam, the TM package was sealed to form a flotation tank, and two CO₂ gas-inflatable bags were included. One bag was attached to the apex of the main parachute and was filled at the time of parachute deployment. The second bag, inside the RV, was inflated about the same time by a sequence of TM programmed events.

The dye marker included 1.5 pounds of aluminum powder packaged in a water-soluble bag. In average sea conditions, the marker should provide a green slick about 100 by 200 feet in area, visible for about 15 miles.

E. METHODS OF DATA ACQUISITION

Sandia was responsible for all RFD-2 data acquisition. Instrumentation at the launch site and downrange included radar coverage for trajectory data, TM receiving equipment, and photo-optical instrumentation. The latter was divided into ground-based and airborne stations, with both tracking and fixed-axis instrumentation employed. Details of these instrumentations are summarized below. Figure III-17 shows the ground plan of all downrange support elements.

1. Launch Site

Two beacon tracking radars (FPS-16, FPQ-6) and four skin tracking radars (FPQ-6, MPS-19, MOD-11, SPANDAR-MIT) were used to obtain trajectory data. Wallops station provided range control, TM coverage, communications, and meteorological support.

2. Bermuda

The NASA Mercury Station on Bermuda provided downrange radar and TM coverage, position data for the optical aircraft, downrange timing, and communications.

Optical instrumentation at High Point is summarized in Table III-6 and is shown in Fig. III-18.

3. Downrange Instrumentation and Recovery

Five aircraft and two ships were stationed downrange, instrumented with optical, TM receiving, SARAH homing and receiving, and CW homing and receiving equipment. Details of the optical instrumentation onboard the aircraft are given in Tables III-7 and III-8.

The ships, besides collecting TM data, were stationed in the impact zone to effect the recovery operation.

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Fig. III-17. Ground Plan of Predicted RFD-2 Trajectory Events and Location of Downrange Support Elements

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TABLE III-6
Optical Instrumentation, High Point

Instrument	Purpose	Sampling Rate	Number Used	Lens			Grating	Film		Instrument Mount
				Type or Maker	Aperture	Focal Length (in.)		Type	Camera Capacity	
Sandia time-resolved spectrograph 3/4 x 9 in.	Time-resolved spectrographs	Continuous, 1/8 - 1 in. / sec	2	24-in. dia mirror	f/5.0	117	600 lines/mm	Tri-X Aerecon	180 ft	LA-24 No. 1, LA-24 No. 2
Photometer	Time-resolved photometry	240 samples/sec	2	8-in. dia Cassegrain	f/10.0	80	Filter wheel	None	Not used	LA-24 No. 1, LA-24 No. 2
Mitchell 35mm motion picture camera	Time correlation and event coverage	24 frames/sec	1	Kempian	f/5.6	40	None	MS-Ektachrome	1000 ft	LA-24 No. 1
Mitchell 35mm motion picture camera	Time correlation and event coverage	24 frames/sec	1	LW 12 reflector	f/5.0	60	None	MS-Ektachrome	1000 ft	LA-24 No. 2
Mitchell 35mm motion picture camera	Time correlation and event coverage	10 frames/sec	2	Aeroektar	f/2.5	12	None	MS-Ektachrome	1000 ft	LA-24 No. 1, LA-24 No. 2
Beatie Coleman 35mm streak camera	Time correlation and event coverage	Continuous, in. / sec	2	Aeroektar	f/2.5	12	None	MS-Ektachrome	100 ft	LA-24 No. 1, LA-24 No. 2
Photosonics 10A 70mm motion picture camera	Event coverage	10-80 frames/sec	1	16-in. dia mirror	f/7.3	117	None	MS-Ektachrome	1000 ft	ME-16
Mitchell 35mm motion picture camera	Event coverage	48 frames/sec	1	Paxar	f/3.5	24	None	MS-Ektachrome	1000 ft	ME-16
Mitchell 35mm motion picture camera	Event coverage	16 frames/sec	1	Paxar	f/3.0	18	None	MS-Ektachrome	1000 ft	ME-16
Mitchell 35mm motion picture camera	Event coverage	8 frames/sec	1	Aeroektar	f/2.5	12	None	MS-Ektachrome	1000 ft	ME-16
Beatie Coleman 35mm streak camera	Time correlation and event coverage	Continuous, 2 in. / sec	1	Aeroektar	f/2.5	12	None	MS-Ektachrome	100 ft	ME-16
Photosonics 10A 70mm motion picture camera	Cinespectrographs	5 frames/sec	1	Aeroektar	f/2.5	12	200 lines/mm	Anso Super Hypan	1000 ft	Tripod No. 3 hand tracked
Sandia time-resolved spectrographs	Time-resolved streak spectrographs	Continuous, 3/16 in. / sec	4	Aeroektar	f/2.5	12	600 lines/mm	Tri-X Aerecon	180 ft	(2) Tripod No. 1, (2) Tripod No. 2; hand tracked
Millikan 16mm motion picture camera	Time correlation and event coverage	16-24 frames/sec	2	Aeroektar	f/2.5	7	None	MS-Ektachrome	1200 ft	(1) Tripod No. 1, (1) Tripod No. 2; hand tracked
Sandia spectrographic plate cameras 10 x 12 in.	Spectrographs	Once/flight	8	Carl Meyer	f/2.5	12	600 lines/mm	103F plates	One plate	Fixed tripods
Sandia plate cameras 10 x 12 in.	Event streak	Once/flight	4	Carl Meyer	f/2.5	12	None	103F plates	One plate	Fixed tripods
K-37 cameras modified to 9 x 10 in. plate	Chopped trajectory photographs	Coded chopping rates	5	Aeroektar	f/2.5	12	None	103F plates	One plate	Fixed tripods
K-37 cameras modified to 10-in. film pull	Time correlation to trajectory cameras	Once/2 sec	5	Aeroektar	f/2.5	12	None	Tri-X Aerecon	150 ft	Fixed tripods
K-37 cameras (unmodified)	Experimental use of color event streak	Once/flight	3	Aeroektar	f/2.5	12	None	8 x 10 in. cut	One plate	Fixed tripods
K-36 cameras modified to 10 x 19 in. plate	Event streak	Once/flight	4	Perkin-Elmer	f/3.5	24	None	103F plates	One plate	Fixed tripods
Plate camera, 36 in., 10 x 19 in. plate	Event streak	Once/flight	3	Perkin-Elmer	f/4.0	36	None	103F plates	One plate	Fixed tripods

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Fig. III-18. Optical Instrumentation at High Point, Bermuda

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TABLE III-7

Optical Instrumentation, Sandia Aircraft 04B

Instrument	Purpose	Sampling Rate	Number Used	Lens			Grating	Film			Instrument Mount
				Type	Aperture	Focal Length (in.)		Type	ASA Speed	Camera Capacity	
Sandia-designed UV spectrographs	Spectrographs	Once per flight	3	Sandia design	f/4	12	300 lines/mm	103-0 cut film 5 x 7 in.	200	One plate	Fixed
Modified K-37 framing cameras	Time correlation to trajectory cameras and event coverage for framing spectrographs	Once per 2 sec	6	Aeroektar	f/2.5	12	None	Tri-X Aerecon 9 x 9-in. format	200	400 ft	Fixed
Modified K-37 framing spectrographs	Time-resolved spectrographs	Once per 2 sec	6	Aeroektar	f/2.5	12	600 lines/mm	Tri-X Aerecon 9 x 9-in. format	200	400 ft	Fixed
Modified K-37 chopped trajectory cameras	Event and time correlation to plate spectrographs	Coded chopping	4	Aeroektar	f/2.5	12	None	103-F glass plates 10 x 12 in. 9 x 9-in. format	200	One plate	Fixed
Modified K-37 plate spectrographs	Spectrographs	Once per flight	4	Aeroektar	f/2.5	12	600 lines/mm	103-F glass plates 10 x 12 in. 9 x 9-in. format	200	One plate	Fixed
Mitchell 35mm motion picture cameras	Event coverage	16/32 frames/sec	2	Aeroektar	f/2.5	12	None	MS-Ektachrome	1000	400 ft	Hand tracked

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TABLE III-8
Optical Instrumentation, NASA Aircraft 232 and 238

Instrument	Purpose	Sampling Rate	Number Used	Lens			Grating	Film		Aircraft
				Type or Maker	Aperture	Focal Length (in.)		Type	ASA Speed	
K-24 aero-recon cameras	Spectrographs	DNA	12	Aeroektar	f/2.5	7	75-600 lines/mm	Royal-X Pan	1600	232 (6), 238 (6)
RC5 motion picture camera	Ballistics	Chopped 2 times/sec	1	Wild Aviogon	f/5.6	6	None	Royal-X Pan	1600	238
Flight research 35mm motion picture camera	Spectrographs	10 frames/sec	1	NA	NA	2	300 lines/mm	Royal-X Pan	DNA	238
Flight research 35mm motion picture camera	Event coverage	10 frames/sec	1	Wollensak	f/4.5	10	None	Royal-X Pan	DNA	238
Kodak cine special 16mm motion picture camera	Event coverage	16 frames/sec	1	Kodak	f/2.5	2	None	Ektachrome	DNA	238
K-37 streaking cameras	Event coverage and streak for star background	Continuous	3	Aeroektar	f/2.5	12	None	8 x 10 in. plate	1600	232 (2), 238 (1)
K-24 streaking cameras	Event coverage and streak for star background	DNA	4	Aeroektar	f/2.5	7	None	Royal-X Pan	1600+	232 (2), 238 (2)
RC7 motion picture cameras	Ballistics	Chopped 2 times/sec	2	Wild Aviogon	f/5.6	4	None	Royal-X Pan	DNA	232 (1), 238 (1)
Flight research 35mm motion picture camera	Event coverage	10 frames/sec	1	Bausch and Lomb	f/2.5	6	None	Ektachrome	DNA	238
Barnes 70mm cinespectrograph	Spectrographs	10 frames/sec	1	NA	f/4.0	NA	210 lines/mm	Royal-X Pan	DNA	232
Millikan 16mm motion picture camera	Event coverage	16 frames/sec	1	Apochromat Kinoptik	f/2.5	6	None	Royal-X Pan	DNA	232

NA--Not applicable
DNA--Data not available

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IV. METHODS OF ANALYSIS

One of the most critical problems in establishing a safe evaluation for space systems equipped with nuclear generators is to determine the re-entry burnup characteristics of the generator. In some cases, it is desirable to ensure burnup at sufficient altitude to permit safe dispersal of the nuclear fuel, while in others it is imperative that the fuel containment structure impact the earth intact without fuel release. To this end, it is essential that a detailed trajectory, aerothermodynamic, and heat transfer analysis of the system be made. Methods for accomplishing these are discussed below.

A. TRAJECTORY ANALYSIS

During the preflight study, external capsule trajectories were developed using Martin Company Program UB024; and a re-entry trajectory for the generators was developed with the Martin Company Program UB003. During the postflight study, trajectory information was taken directly from the test flight data. The Martin Company trajectory codes are described below. These trajectory and heating data, as well as information concerning the analytical model and its materials, are then used in the three-dimensional heat transfer, one-dimensional ablation program, FB090. This code will be described under methods of heat transfer analysis, Section C.

1. Code UB003

UB003 is an N-phase, two-dimensional, two-degree-of-freedom program which will continuously compute a vehicle trajectory which has been broken into any number (N) of parts or phases. This procedure is accomplished automatically by starting each successive phase with the conditions which existed at the conclusion of the previous phase. One of two types of solution may be selected as desired in any given phase--integration or free-flight. The integration solution integrates the equations of motion as a function of time, using prescribed aerodynamic, thrust, and control data inputs, while assuming a rotating earth and the 1959 ARDC standard atmosphere. The free-flight computations give the solution of elliptic equations based on an inverse-square gravity force field.

The program, in this analysis, used the integration solution to yield trajectory and aerodynamic heating data. This data includes velocity, altitude, flight path angle, dynamic pressure, Mach number, altitude pressure, heat fluxes for both convection and convection plus radiation, and total integrated heat for both convection and convection plus radiation, all as functions of time.

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Figure IV-1 depicts the forces acting on a body as used in this program. Using this figure, the equations of motion in two dimensions with two degrees-of-freedom can be evolved. These are:

$$\ddot{\bar{X}} = \frac{1}{M} \left[T \cos (\bar{\gamma} + \alpha + \delta_p) - L \sin \bar{\gamma} - D \cos \bar{\gamma} \right] - g \sin \phi_p, \text{ and}$$

$$\ddot{\bar{Y}} = \frac{1}{M} \left[T \sin (\bar{\gamma} + \alpha + \delta_p) + L \cos \bar{\gamma} - D \sin \bar{\gamma} \right] - g \cos \phi_p$$

where

$\ddot{\bar{X}}$ = acceleration in $\bar{X}$ direction (ft/sec²),

$\ddot{\bar{Y}}$ = acceleration in $\bar{Y}$ direction (ft/sec²),

M = mass (slugs),

T = thrust (lb),

L = lift (lb),

D = drag (lb),

g = local gravitational acceleration (ft/sec²), and the angles are defined in Fig. IV-1.

The heat flux and total integrated heat are obtained from the relationships:

$$\dot{q}_c = \frac{17,600}{\sqrt{R_N}} \left(\frac{\rho}{\rho_0} \right)^{1/2} \left(\frac{V}{\sqrt{u/R}} \right)^{3.15}$$

$$\dot{q}_R = 26.8 R_N \left(\frac{E}{2} \right) \left(\frac{\delta}{R_N} \right)$$

$$\dot{q}_c + R = \dot{q}_c + \dot{q}_R, \text{ and}$$

$$q_c + R = \int \dot{q}_c + R \, dt$$

where

$\dot{q}_c$ = convective heating rate (Btu/ft²-sec)

$\dot{q}_R$ = radiative heating rate (Btu/ft²-sec)

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Fig. IV-1. Two-Dimensional Force Diagram for UB003

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- $\dot{q}_c + R$ = total heating rate (Btu/ft²-sec)
 $q_c + R$ = integrated total heat (Btu/ft²)
 R_N = body nose radius (ft)
 ρ = air density at altitude (slugs/ft³)
 ρ_0 = air density at sea level (slugs/ft³)
 V = velocity (ft/sec)
 u = earth's gravitational constant (1.4076×10^{16} ft³/sec²)
 R = earth's mean radius (20.9256×10^6 ft)
 δ = shock standoff distance (ft)
 $E/2$ = one half of the emitted radiation energy per unit volume from the stagnation region (watts/cm³)

2. Code UB024

UB024 is an N-phase, three-dimensional, three-degree-of-freedom trajectory program which assumes a rotating oblate earth in an inertial reference frame. Input data for UB024 is basically the same as for UB003, with the exception of more complex control constants and initial position data (latitude and longitude). The equations used in the solutions are similar to those in UB003, differing, in the case of the equations of motion, by the addition of a third dimension and a third degree of freedom. In conjunction with the 1959 ARDC standard atmosphere the equations of motion are integrated and the heating equations are solved to yield trajectory and aerodynamic heating data.

B. AEROTHERMODYNAMIC ANALYSIS

Aerodynamic heating arises from the conversion of kinetic energy to heat by the action of particle impact (in free molecular flow) and by viscous forces in the shock wave and boundary layer (in continuum flow). Obtaining exact theoretical solutions for the heat transfer to the body due to this energy conversion is a formidable problem, and has proven impossible to date. However, several solutions based on theory have been established which are acceptable for engineering practice.

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Each of these solutions assumes some simplifications of the basic equation, the most common being the concepts of local similarity, constant Prandtl number, isothermal body surface, concept of "highly cooled surface," power law velocity distributions of the boundary layer, and viscosity varying as the first power of the temperature. These analytical solutions can be grouped into three categories: stagnation point heating, local heating for laminar flow, and local heating for turbulent flow.

Configurations which have ramps, cavities, protuberances, or steps encounter separated flow in these areas, often with drastic effects on performance. Nearly all of the early work in flow separation was limited to the low speed turbulent regime pertaining to aircraft, although some attention was given to the buffet problem in building and bridge construction. More recently, with the advent of supersonic and hypersonic flight speeds, separated flow has come to the forefront and, with it, the problems of aerodynamic heating. However, the complexity of the problem has defined detailed solution for the general case. Only the overall heat transfer for laminar flow conditions has lent itself to theoretical treatment. A summary of the various theories, together with a brief account of the problem of separated flow, is given below.

1. Continuum Region Theory

All equations for aerodynamic heat transfer can be reduced to the general form

$$\dot{q} = \text{Const } R_e^E \left(\frac{\mu}{x} \right)^{1-E} (h_r - h_w) F \left(\frac{\rho_e}{\rho_w}, \frac{\mu_e}{\mu_w}, \frac{u_e}{u_\infty}, \text{Pr}, \text{Le} \right) \quad (\text{IV-1})$$

by relating the shearing stress to the Reynolds number and accounting for dissociation (Ref. IV-1). The type of boundary layer establishes the value of the exponent, E. It is 0.5 for laminar flow and approximately 0.8 for turbulent flow. The function F accounts for real gas effects and compressibility. Since the relationships have the same form for stagnation points, stagnation lines, flat plates and cones in laminar flow, there is strong evidence that this general form is independent of geometry.

2. Stagnation Point Heating

The Fay and Riddell equation for stagnation point heating (Ref. IV-2) takes the form

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$$\dot{q} = 0.94 \left(1 - \frac{h_{sw}}{h_{se}}\right) (\rho_{ws} \mu_{ws})^{0.1} (\rho_{se} \mu_{se})^{0.4} h_{se} \sqrt{\left(\frac{du_e}{dx}\right)_s} \left[1 + 0.45 (Le - 1) \frac{h_{De}}{h_{se}}\right] \quad (IV-2)$$

This equation was obtained by means of a numerical solution of the stagnation point boundary layer differential equations, using air properties at high temperatures for dissociated equilibrium conditions. The Prandtl number was assumed equal to 0.71. For Pr not equal to 0.71, the constant is replaced by the factor $(0.76(Pr)^{-0.6})$. In the equation, it is assumed that the Lewis number is constant across the boundary layer. It was found that, if the surface subjected to heating is catalytic, good accuracy can also be expected for the nonequilibrium case.

The formulation of the problem is exact within the limitations imposed by the theory of similarity. Inaccuracies are largely due to the limitations of the knowledge of the transport properties of high temperature air. In this regard, the state of the boundary layer is dependent upon the recombination of the dissociated atoms as they diffuse through the boundary layer.

Kemp and Riddell (Ref. IV-3) developed an approximate formula for computing stagnation point heating by correlating numerical results in Equation (IV-2). The resulting simplified equation states that

$$\dot{q}_s = \frac{20,800}{\sqrt{R}} \left(\frac{\rho_\infty}{\rho_o}\right)^{1/2} \left(\frac{u_\infty}{u_c}\right)^{3.25} \left(1 - \frac{h_{sw}}{h_{se}}\right) \quad (IV-3)$$

Further refinements correlated with shock tube test results of model tests under simulated hypersonic flight conditions resulted in a modification to Equation (IV-3).

$$\dot{q}_s = \frac{17,600}{\sqrt{R}} \left(\frac{\rho_\infty}{\rho_o}\right)^{1/2} \left(\frac{u_\infty}{u_c}\right)^{3.15} \left[\frac{h_{se} - h_{sw}}{h_{se} - (h_{sw})_{300}} \right] \quad (IV-4)$$

This equation was derived by Detra, Kemp, and Riddell (Ref. IV-4). It is considered accurate to within $\pm 10\%$ of the calculated heat transfer rates in the range of altitudes from sea level to 250,000 feet and velocities from 7000 to 25,000 feet per second. Figure IV-2 shows a comparison of Equations (IV-3) and (IV-4), together with the shock tube test results. If the satellite velocity, $u_c = 26,000$ ft/sec, is substituted in Equation (IV-4), it becomes

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Fig. IV-2. Stagnation Point Heat Transfer Rate Versus Flight Velocity

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$$\dot{q}_s = \frac{865}{\sqrt{R}} \left(\frac{u_\infty}{10^4} \right)^{3.15} \left(\frac{\rho_\infty}{\rho_o} \right)^{1/2} \left[\frac{h_{se} - h_{sw}}{h_{se} - (h_{sw})_{300}} \right] \quad (\text{IV-5})$$

3. Local Heat Transfer--Laminar Flow, No Separation

Several formulations have been established to determine the local heat-transfer rates on blunt bodies. Among the early methods are those of Stine and Wonlass, Cohen and Reshotko, and Lees (Refs. IV-5, IV-6, and IV-7). Tewfik (Ref. IV-8) compared these three theories with experimental data obtained in the low pressure wind tunnel at the University of California. He found that heat transfer rates computed with Lees' equation showed the best correlation of the three methods.

Lees used the assumption of local similarity in dealing with heat transfer to highly cooled bodies. The boundary layer, for discrete points on the body, is described by ordinary differential equations involving an independent similarity variable. The parameters and boundary conditions are assumed to depend only on the wall conditions and those at the outside edge of the boundary layer. Additional approximations were made by assuming that the pressure gradient would have a negligible effect and that the mass flow, ρu , was constant across the boundary layer at the external value. Lees then used a nondimensional wall enthalpy gradient for a flat plate according to Cohen and Reshotko (Ref. IV-6) for the condition $\rho u = \text{constant}$ and no dissipation. This method results in a constant, nondimensional wall enthalpy over the entire body. The resulting equation for the ratio of the local heat transfer rate to the heat transfer rate at the forward stagnation point for an axisymmetric body is

$$\frac{\dot{q}}{\dot{q}_s} = \frac{\frac{1}{2} \frac{p}{p_s} \frac{u_e}{u_\infty} r}{\left(\int_0^x \frac{p}{p_s} \frac{u_e}{u_\infty} r^2 dx \right)^{1/2}} \left(\frac{\frac{u_\infty R}{\left(\frac{du_e}{dx} \right)_s}}{\left(\frac{du_e}{dx} \right)_s} \right)^{1/2} \quad (\text{IV-6})$$

For a hemisphere, this equation reduces to

$$\frac{\dot{q}}{\dot{q}_s} = \cos^{1.2} \lambda \quad (\text{IV-6a})$$

Kemp, Rose, and Detra (Ref. IV-9) extended the stagnation point theory of Fay and Riddell to regions away from the stagnation point. In contrast to Lees, the local similarity differential equations were solved

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exactly using variable external pressure gradients and variable mass flow (ρu). Further, a term for dissipation was included.

$$\frac{\dot{q}}{\dot{q}_s} = \frac{\frac{1}{2} \rho_w \mu_w u_e r}{\left(\int_0^x \rho_w \mu_w u_e r^2 dx \right)^{1/2}} \frac{1 + 0.096 \sqrt{\beta}}{1.068} \left[\frac{h_e - h_{ws}}{h_e - h_w} \right] \cdot \frac{1}{\left[\rho_{ws} \mu_{ws} \left(\frac{du_e}{dx} \right)_s \right]^{1/2}} \quad (\text{IV-7})$$

which may also be written

$$\frac{\dot{q}}{\dot{q}_s} = \frac{\frac{1}{2} \left(\frac{\rho_w}{\rho_{ws}} \right) \left(\frac{\mu_w}{\mu_{ws}} \right) \left(\frac{u_e}{u_\infty} \right) r}{\left[\int_0^x \left(\frac{\rho_w}{\rho_{ws}} \right) \left(\frac{\mu_w}{\mu_{ws}} \right) \left(\frac{u_e}{u_\infty} \right) r^2 dx \right]^{1/2}} \left[\frac{u_\infty}{\left(\frac{du_e}{dx} \right)_s} \right]^{1/2} \cdot \left[\frac{1 + 0.096 \sqrt{\beta}}{1.068} \right] \left[\frac{h_e - h_w}{h_e - h_{ws}} \right] \quad (\text{IV-7a})$$

The last term in brackets in Equation (IV-7a) is the cold wall correction factor. The next-to-last term reflects the effect of the velocity gradient parameter, β . For the range of conditions covered, Lees assumed both to have a value approaching unity. Likewise, in deriving Equation (IV-6), Lees assumed that the quantity $\mu_w/R_w T_w$ varied slowly with enthalpy at high enthalpy levels; hence,

$$\frac{\rho_w \mu_w}{(\rho_w \mu_w)_s} = \frac{p_w}{p_{ws}} \cdot \frac{\mu_w}{\mu_{ws}} \frac{R_{ws} T_{ws}}{R_w T_w} \approx \frac{p_w}{p_{ws}}$$

It can be seen that these assumptions, applied to Equation (IV-7a), will result in Lees' equation (IV-6).

Eckert and Tewfik (Ref. IV-10) approached the problem of local heat transfer rates by applying the reference enthalpy method to these

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equations, thereby accounting for variations of specific heat and ρu across the boundary layer. By this procedure, the equations become more realistic at very high free-stream stagnation temperatures.

$$\frac{\dot{q}}{\dot{q}_s} = \left[\frac{k^*}{k_s} \right] \left[\frac{H^*}{H_s} \right] \left[\frac{h_{rec} - h_w}{h_{se} - h_w} \right] \quad (IV-8)$$

In this equation, for the axisymmetric case,

$$H^* = \frac{\left(\frac{\rho^*}{\rho_s} \right) \left(\frac{u_e}{u_\infty} \right) r}{\left[\int_0^x \left(\frac{\rho^*}{\rho_s} \right) \left(\frac{\mu^*}{\mu_s} \right) \left(\frac{u_e}{u_\infty} \right) r^2 dx \right]^{1/2}} \quad (IV-8a)$$

At the stagnation point, $u_e = \left(\frac{du_e}{dx} \right)_s x$ and $r = x$.

Hence,

$$H_s^* = \frac{\left(\frac{\rho_s^*}{\rho_s} \right) \left(\frac{du_e}{dx} \right)_s \left(\frac{1}{u_\infty} \right) x^2}{\left[\left(\frac{\rho_s^*}{\rho_s} \right) \left(\frac{\mu_s^*}{\mu_s} \right) \left(\frac{du_e}{dx} \right)_s \left(\frac{1}{u_\infty} \right) \int_0^x x^3 dx \right]^{1/2}} =$$

$$2 \sqrt{\frac{\left(\frac{\rho_s^*}{\rho_s} \right) \left(\frac{du_e}{dx} \right)_s}{u_\infty \left(\frac{\mu_s^*}{\mu_s} \right)}} \quad (IV-8b)$$

Combining Equations (IV-8), (IV-8a) and (IV-8b),

$$\frac{\dot{q}}{\dot{q}_s} = \frac{\frac{1}{2} \left(\frac{\rho^*}{\rho_s} \right) \left(\frac{u_e}{u_\infty} \right) r}{\left[\int_0^x \left(\frac{\rho^*}{\rho_s} \right) \left(\frac{\mu^*}{\mu_s} \right) \left(\frac{u_e}{u_\infty} \right) r^2 dx \right]^{1/2}} \sqrt{\frac{u_\infty}{\left(\frac{\rho_s^*}{\rho_s} \right) \left(\frac{\mu_s^*}{\mu_s} \right) \left(\frac{du_e}{dx} \right)_s}} \left(\frac{k^*}{k_s} \right) x$$

$$\left[\frac{h_{rec} - h_w}{h_{se} - h_w} \right] \quad (IV-9)$$

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The starred quantities are evaluated at the local pressure and the reference enthalpy. The reference enthalpy is obtained from the relationship:

$$h^* = \frac{h_e + h_w}{2} + 0.22 \sqrt{\text{Pr}} (h_{se} - h_e) \quad (\text{IV-9a})$$

The recovery enthalpy for laminar flow is equal to

$$h_{\text{rec}} = h_e (1 - \sqrt{\text{Pr}}) + h_{se} \sqrt{\text{Pr}} \quad (\text{IV-9b})$$

where

$$h_{se} = h_\infty + \frac{u_\infty^2}{2gJ}$$

There are two assumptions used in deriving Equation (IV-9): constant Prandtl number and specific heat across the boundary layer. If these parameters are included as variables and are treated in accordance with the reference enthalpy concept, then

$$\frac{\dot{q}}{q_s} = \left[\frac{k^*}{k_s^*} \right] \left[\frac{H^*}{H_s^*} \right] \left[\frac{h_{\text{rec}} - h_w}{h_{se} - h_w} \right] \left[\frac{C_{p_o}}{C_{p_w}} \right] \quad (\text{IV-10})$$

and

$$h_{\text{rec}} = h_e (1 - \sqrt{\text{Pr}^*}) + h_{se} \sqrt{\text{Pr}^*} \quad (\text{IV-10a})$$

Figures IV-3 and IV-4 compare the equations of Lees, Kemp et al., and Eckert and Tewfik. It will be noted that Lees gives the best correlation across the flat face (Fig. IV-4), while Kemp et al., and Eckert and Tewfik show better results along the sides.

4. Local Heat Transfer--Turbulent Flow, No Separation

For the most part, the Reynolds number for small configurations re-entering the earth's atmosphere is sufficiently low (less than 300,000) to ensure laminar flow. There may be cases, however, which become turbulent before burnup. Rose, Probstein, and Adams (Ref. IV-11) showed that the turbulent heat transfer through a highly cooled, partially dissociated boundary layer could be expressed in terms of Nusselt number as follows:

$$\text{Nu} = 0.029 \text{Pr}^{1/3} \text{Re}_{(x)}^{0.8} \left\{ 1.037 [\text{G}(x)]^{1/5} \right\} \left[1 + (\text{Le}^\psi - 1) \frac{h_{\text{De}}}{H_e} \right] \quad (\text{IV-11})$$

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Fig. IV-3. Comparison of Heat Transfer Distribution by the Reference-Enthalpy Method with Other Methods and Experiments for a Hemisphere-Cylinder Body

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where both Nusselt number and Reynolds number are based on external conditions. The term $G(x)$ is a form factor dependent on body shape and pressure gradient and is defined by

$$[G(x)]^{-1} = \frac{1}{u_e^{5/2} r^{5/4} \rho_e^{5/4}} \left(\frac{u_e}{\gamma_e} \right)^{1/4} \frac{1}{x} \int_0^x \left(\frac{\gamma_e}{\mu_e} \right)^{1/4} u_e^{5/2} r^{5/4} \rho_e^{5/4} dx \quad (IV-11a)$$

The term in the last bracket reflects the energy of dissociation outside the boundary layer and is dependent on both local pressure and entropy external to the boundary layer.

This approximate equation, based on theory, is limited to the cases of blunted axisymmetric bodies with highly cooled boundary layers. It was correlated with experimental results obtained from shock tube tests for conditions simulating flight speeds to 21,350 ft/sec. Up to 30% of the molecules were dissociated in these tests. Reynolds numbers of 2.5×10^6 were obtained which were based on the properties external to the boundary layer. The correlation showed that the Lewis number term, Le^ψ , was equal to 1.4. It was not possible to separate the effect of Lewis number and ψ .

Detra and Hidalgo (Ref. IV-12) simplified Equation (IV-11) by numerical correlation as a function of altitude and flight velocity. Using Feldman's hypersonic gas dynamic charts for equilibrium air, Sutherland's law of viscosity, $Pr = 0.71$, $Le^\psi = 1.58$, a wall temperature of 300° Kelvin, and a constant ratio of specific heats ($\gamma = 1.2$) for isentropic flow around the body, the equation can be reduced to the form:

$$\dot{q}(x)^{0.2} = 1.346 \times 10^4 \left(\frac{\rho_\infty}{\rho_0} \right) \left(\frac{u_\infty}{10^4} \right)^{3.18} \phi \quad (IV-12)$$

where

$$\phi = \left(\frac{p}{p_s} \right)^{4.1/6} \left[1 - \left(\frac{p}{p_s} \right)^{1/6} \right]^{0.4} \quad (IV-12a)$$

This heat transfer equation reproduces the values obtained by Rose, Probstein, and Adams with a maximum error of 5% for altitudes from 40,000 to 200,000 feet and velocities from 6000 to 26,000 ft/sec. At sea level the deviation is 15% high.

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The ratio of local heat transfer rate to the stagnation point heat transfer rate can be obtained from the ratio of Equations (IV-12) and (IV-5).

$$\frac{\dot{q}}{q_s} = 15.56 \left(\frac{\rho_\infty}{\rho_o} \right)^{0.3} \left(\frac{u_\infty}{10^4} \right)^{0.03} \frac{(R)^{0.5}}{(x)^{0.2}} \left[\frac{h_s - (h_{sw})_{300}}{h_s - h_{sw}} \right] \quad (\text{IV-13})$$

Libby and Cresci (Ref. IV-23) have evaluated an empirical equation for turbulent flow which is given in terms of Nusselt number.

$$\frac{Nu}{Re^{4/5}} = 0.0296 \frac{Pr_s}{Pr^*} \left[\frac{\hat{\rho} \hat{u} \hat{s}}{\hat{\mu}^*} \right]^{0.8} \left(\frac{\hat{\mu}^*}{s} \right) \quad (\text{IV-14})$$

where

$$\hat{\rho} = \rho^* / \rho_{se}$$

$$\hat{u} = u^* / u_{se}$$

$$\hat{\mu} = \mu^* / \mu_{se}$$

$$\hat{s} = x/R$$

This equation can be rewritten in terms of heat flux for either two-dimensional or conical flow as follows:

$$\dot{q}_T = \frac{0.0296 g^{1/3} (1+N)^{0.2} (K^*) (\rho^* u_e)^{0.8} \left[(1 - \sqrt[3]{Pr_e}) h + \sqrt[3]{Pr_e} h_s - h_w \right]}{(\mu^*)^{7/15} (C_{ps})^{2/3} x^{0.2}} \quad (\text{IV-14a})$$

5. Separated Flow

As stated earlier, separated flow is usually encountered on the body in areas where ramps, cavities, protuberances, or steps are placed. This phenomenon is present in both laminar and turbulent boundary layer conditions. The problem of separated flow is sufficiently complex that only the simplest configurations have lent themselves to mathematical treatment. Further, these analyses are based on rather broad assumptions with regard to the so-called dead air region between the boundary layer streamlines and the body. This is not to say, however, that knowledge pertaining to this region is not available. Charwat, Dewy, et al. (Refs. IV-13 and IV-14) conducted experiments wherein the pressure, temperature, heat transfer, and flow were studied in cavities in a flat plate. A brief summary of their findings follows.

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For flow visualization during these experiments, an oil film was painted on the floor of the cavity or a suspension of lamp black in kerosene injected into it. It was discovered that all but the shortest notches, where the cavity length was less than one and one-half times the depth, contain a vortex at the separation corner which opposes the mean circulation in the cavity. A well-defined stagnation line on the cavity floor separated this vorticity from the rest of the flow. The diameter of the vortex was found to be equal to the cavity depth regardless of cavity length. Another vortex, with a diameter equal to the cavity depth, was found at the downstream recompression corner. Its circulation is opposite to that at the separation end. In this case, no stagnation line was established because the vortex flow direction at the floor was the same as that at the floor in the midsection upstream. The flow in this central zone was found to have low, unsteady velocity. The flow structure observed is illustrated in Fig. IV-5.

Mass exchange was proven by injecting a detectable gas (ammonia, smoke) into the flow upstream of the cavity or in the cavity itself. In the first case, gas penetrated into the cavity almost instantaneously. In the latter case, it was detected immediately in the boundary layer downstream of the cavity. Hence, there is an exchange of mass between the cavity and the external flow.

A mass exchange model was proposed in which the mass is assumed injected into the cavity at one-half pulse, at which time this excess mass is first heated and then ejected from the cavity. During the remaining half of the pulse, it carries heat away. The heated fluid is recirculated in the recompression vortex before being picked up in the shear layer and discharged downstream. The momentum impulse associated with this injected mass must be proportional to the centrifugal impulse of the mass circulated by the recompression vortex. If the profile near the mean streamline is known, the magnitude of the pulsation is fixed by this proportionality. This mechanism leads to the formulation for the mean heat transfer to the separated cavity in terms of the Stanton number.

$$St = \frac{\dot{q}}{C_p u_\infty (T_{aw} - T_w)} \sim \frac{1}{B} \frac{\delta}{L} \quad (IV-15)$$

where

$$B = \left[\frac{d \left(\frac{u}{u_\infty} \right)}{d \left(\frac{Y}{\delta} \right)} \right]_{Y=0} \quad (IV-15a)$$

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Fig. IV-4. Comparison of Heat Transfer Distribution by the Reference-Enthalpy Method with Other Methods and Experiment for a Flat-Nosed Plate

Fig. IV-5. Structure of the Internal Flow for the Mass-Exchange Heat Transfer Model

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This model is limited by the fact that it depends upon pulsation to the exclusion of other mechanisms. Although the reported tests indicate pulsation is likely to occur, there is also evidence that some cavities do not have unsteady flow. Apparently the geometry of the cavity comes into play, particularly at the recompression corner.

Chapman (Ref. IV-15) presented a theoretical analysis of heat transfer in regions of separated flow. This analysis was compared with test results by Larson (Ref. IV-16) and found to predict the average total heat rate to the cavity, provided the flow was laminar. It is not acceptable for turbulent flow.

The flow field analyzed is assumed to be a thin, constant-pressure, viscous mixing layer separated from a solid surface by an enclosed region of low velocity air, referred to as dead air. The rate of heat transfer at the solid surface was related to the calculated conditions in the mixing layer by the laws of conservation of energy. It was assumed, for the calculations, that the boundary layer thickness was zero at the point of separation. Chapman solved the differential equations for viscous flow at arbitrary Mach numbers for the enthalpy and velocity profiles within the thin boundary layer where mixing with the low velocity air in the cavity takes place. Results were presented in tabular form for Prandtl numbers between 0.1 and 10.0; calculations for the boundary layer-flow (no cavity) for the same Prandtl numbers were made based on an appropriate small Prandtl number expansion formula developed by Logerstrom and Liepmann (unpublished research). It was assumed that p_e , u_e , R_e , and h_w/h_e are the same for both separated and unseparated flow.

For air ($Pr \approx 0.72$), the calculated average total heat transfer in a separated mixing layer is 0.56 of that for a corresponding attached boundary layer. A curve fit of Chapman data, $\frac{\bar{q}_w}{(\bar{q}_w)_{bl}}$ vs Pr , shows that

$$\frac{(\bar{q}_w)}{(\bar{q}_w)_{bl}} = 0.6 Pr^{0.222} \quad (IV-16)$$

for $0.5 \leq Pr \leq 2.0$.

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It should be noted that the use of the integral form of the energy conservation law permits only the average or overall heat transfer rate, $\bar{q}_w$, to be computed and not the local rates. In this respect, Chapman's analysis differs from that of an attached laminar boundary layer theory wherein both local rates and the average rate can be calculated.

At the present time, neither the Chapman-Larson conduction model nor the Charwatt, et al., mass exchange model is sufficiently complete so as to be applicable to the general case. A further limitation is the fact that both theories provide no local distribution along the cavity, but only the mean heat transfer to it.

6. Free Molecular Region

When a flow takes place in a medium sufficiently rarefied that the mean free path of the molecules is much larger than the body characteristic length, it is said to be free molecular. In essence, this rarefied condition permits the molecules to be scattered and re-emitted from the surface by the passage of the body through the medium without disturbing the equilibrium free stream velocity distribution near the body. An underlying hypothesis of free molecular flow is that the Maxwellian distribution of molecular velocities may be superimposed on the uniform velocity of the free stream. Because of this assumption, aerodynamic characteristics and heat transfer rates can be easily calculated by using Newtonian theory directly or with some modification.

The familiar equation for Newtonian pressure is:

$$p = \rho_{\infty} u_{\infty}^2 \sin^2 \theta$$

or (IV-17)

$$\frac{\Delta p}{q} = 2 \sin^2 \theta$$

This theory does not account for either variations in Mach number or differences in the ratio of specific heats. As stated, it applies for the case where $\gamma = 1$ and $M \rightarrow \infty$. In general, it is acceptable for use with pointed bodies with attached shocks. However, when used with blunt bodies, it should be multiplied by the following ratio (Ref. IV-17).

$$A = \frac{\gamma + 3}{2(\gamma + 1)} \left[1 - \frac{2}{(\gamma + 3) M^2} \right] \quad (IV-17a)$$

for

$$M \geq 5 \text{ and } \gamma = 1.4$$

$$A \approx 0.92$$

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The heat transfer equation for the conditions upon which the Newtonian pressure is based is given in Ref. IV-18.

$$\dot{q} = \frac{1}{2} \rho_{\infty} u_{\infty}^3 \sin \theta \quad (\text{IV-18})$$

which is considered applicable unless the surface temperature is very much larger than the free-stream temperature (at least of the order $T_{\infty} \frac{\gamma}{2} M^2 \sin^2 \theta$). In this case, the random velocities of the molecules at the surface are no longer small, when compared with the free-stream velocity, and molecular reflection cannot be neglected.

7. Approach Used in RFD-2 Analysis

Design requirements associated with nuclear-fueled generators usually dictate external shapes with complicated geometries. Since the theoretical equations are only applicable for simple shapes, such as flat plates, ogives, hemispheres, cones, etc., it is necessary to obtain experimental data on the more complex shapes, such as the generator used on the RFD-2 experiment.

Past experience in the field of fluid dynamics has shown that neither theory nor experiment will necessarily provide exact answers for each specific case. Care must be exercised in applying the results obtained by these methods because of the assumptions and experimental limitations. Likewise, there is danger in deriving an empirical equation based on theory and experiment of a specific complex model for use in the general case. Because of these factors, it was decided that the analysis of the RFD-2 re-entry burnup should use the type of data which would be available prior to flight, i. e., theory and experiment. By comparing the results obtained with these inputs and the actual flight test data, it is possible to ascertain the engineering accuracy which might be expected.

Aerodynamic heating tests were run at the Rhodes and Blossom applied physics research facility on 1/2- and 1/25-scale models of the RFD-2 generator mounted on the re-entry vehicle cone. The results are published in Refs. IV-19 and IV-20. The 1/2-scale model was tested with a duplicated fluted top cover, including attachment bolts. The 1/25-scale models were fitted with flat, smooth face covers. The smaller models were required to ensure heating rates, along the sides, of sufficient magnitude to provide a color spectrum on the heat sensitive paint.

Some of the results of the tests at zero angle of attack, Ref. IV-20, are shown in Figs. IV-6 through IV-10. The data on the fluted cover

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Fig. IV-6. Heat Transfer Based on Rhodes and Bloxson Tests of RFD-2 Generator (forward face only)--Between Ribs

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Fig. IV-7. Heat Transfer Based on Rhodes and Bloxson Tests of RFD-2 Generator (forward face only)--Along a Rib

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Fig. IV-8. RFD-2 Heat Transfer for the Forward Face Cover Bolts

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Fig. IV-9. Heat Transfer Comparison for Flat-Faced Cylinder--Theory and Experiment

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Fig. IV-10. Heat Transfer Based on Rhodes and Bloxsom Tests of RFD-2 Generator--Generator Sides

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plate are plotted as a function of the stagnation point value and show typical radial distributions along a rib or between ribs. The heat distribution on a typical bolt is shown separately in Fig. IV-8. Superimposed on the cover plate data is a curve showing Lees' theoretical distribution calculated in accordance with Equation (IV-6). Lees' theory was selected for RFD-2 analysis because of its simplicity and the close agreement with experiment (Fig. IV-9). The heating rate on the sides of the generator is given in Fig. IV-10. It is shown as a function of the heat transfer rate at the point of separation which occurs at the edge of the forward face.

Because of the inadequacy of the present theories pertinent to the problem of separated flow, it was found necessary to correlate existing test data on axisymmetric bodies. Such data are contained in Refs. IV-16, IV-21, and IV-22. The data presented by Larson (Ref. IV-16) cannot be properly used because the geometry of the model is not defined. However, it appears that the local heating rate at the floor of the cavity can be qualitatively established as being 15 to 20% of the heating rate at the point of separation. Centolanzi's results are likewise limited in their application since the point of separation on the rounded blunt noses is difficult to determine accurately. However, one of the shapes has a sharp nose cone angle of 55 degrees, with a well-defined separation point which permits its use in the correlation. The data obtained by Nicoll (Ref. IV-22) on a series of 20-degree cone models incorporating annular cavities provides the major portion of the correlation.

Figure IV-11 shows a plot of the ratio of local heating rate to the heating rate at the point of separation as a function of cavity length defined in terms of cavity depth. The data shown apply to the region of the cavity from the forward lip to just past midlength. It does not include the heating rates due to the recompression vortex at the downstream end of the cavity. Fortunately, the RFD-2 generator can be considered as being located in the region ahead of compression, as shown in the following sketch

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Fig. IV-11. Heat Transfer Comparison for Separated Flow on Generator Sides at $\alpha = 0^\circ$

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Rhodes and Bloxsom data are included in Fig. IV-11 for comparison. The agreement is noteworthy.

Past experience with analyses of magnesium casings has shown that the time from first ablation to burnup is extremely short. Because of this fact, the heat flux distribution, i. e., the ratio of local-to-stagnation point values as a function of x , was assumed constant throughout the burnup phase. Further, the change in heating rate with ablation is an estimate, at best, on complex shapes such as the RFD-2, when taken together with possible creep of molten metal and an unsteady air flow field.

C. HEAT TRANSFER ANALYSIS

Heat transfer calculations for the generator were performed, using the Martin Company Code FB090 described below. Analytical models for use in the code are set up and then broken into elements which accurately delineate the material boundaries and heat paths. Input data to the code include material thermodynamic properties, element geometrical properties, and trajectory parameters. Output consists of time histories of enthalpy and temperature for each element, as well as a chronological history of element ablation.

FB090 is a structural heating program which analyzes heat transfer in three dimensions and ablation in one dimension. The method of solution requires dividing the structure into elements that form a space network. A heat balance is set up for each element of the network, and the simultaneous set of equations which results is solved for temperature for small, successive increments of time, when boundary and initial conditions are specified.

The three-dimensional heat transfer equation is:

$$\frac{\partial T}{\partial t} = \frac{1}{\rho C_p} \left[\frac{\partial}{\partial X} \left(k \frac{\partial T}{\partial X} \right) + \frac{\partial}{\partial Y} \left(k \frac{\partial T}{\partial Y} \right) + \frac{\partial}{\partial Z} \left(k \frac{\partial T}{\partial Z} \right) \right]$$

where:

- T = temperature ($^{\circ}R$)
- ρ = density (lb/in.³)
- C_p = specific heat (Btu/lb- $^{\circ}R$)
- t = time (sec)

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X, Y, Z = distance (inches)

k = thermal conductivity (Btu/in. -sec-°R)

This equation is solved numerically by the midpoint finite difference technique and, in this finite difference form, the heat balance equation is:

$$\begin{aligned} \frac{\rho E_f V_e}{\Delta t} J_{E_f} &= \frac{\rho E_i V_E}{t} J_{E_i} + 1/2 \left[-F_{R_E} \sigma \epsilon_{E_i} A_T T_{E_i}^4 \right. \\ &+ F_{ab} F_q A_T q_{K_i} + A_L U_{L_i} (T_{L_i} - T_{E_i}) + A_R U_{R_i} (T_{R_i} - T_{E_i}) \\ &+ A_T U_{T_i} (T_{T_i} - T_{E_i}) + A_u U_{u_i} (T_{u_i} - T_{E_i}) \\ &+ A_F U_{F_i} (T_{F_i} - T_{E_i}) + A_B U_{B_i} (T_{B_i} - T_{E_i}) \left. \right] \\ &+ 1/2 \left[-F_{R_E} \sigma \epsilon_{E_i} A_T T_{E_f}^4 + F_{ab} F_q A_T q_{K_f} \right. \\ &+ A_L U_{L_i} (T_{L_f} - T_{E_f}) + A_R U_{R_i} (T_{R_f} - T_{E_f}) \\ &+ A_T U_{T_i} (T_{T_f} - T_{E_f}) + A_u U_{u_i} (T_{u_f} - T_{E_f}) \\ &+ A_F U_{F_i} (T_{F_f} - T_{E_f}) + A_B U_{B_i} (T_{B_f} - T_{E_f}) \left. \right] \end{aligned}$$

where:

ρ = density (lb/in. ³)

V = volume (in. ³)

t = time increment (sec)

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- J = enthalpy (Btu/lb)
- F_{ab} = ablation blocking factor
- F_R = radiation loss factor
- F_q = external heating factor to correct for shape, orientation, etc.
- U_{ji} = conductance between two adjacent elements (Btu/in.²-sec-°R)
- A = area (in.²)
- ϵ = emissivity
- σ = Stefan-Boltzmann constant (0.333×10^{-14} Btu/in.²-sec-°R⁴)
- T = temperature (°R)
- $\dot{q}_K$ = hot wall external heating (Btu/in.²-sec), i. e. ,

$$\dot{q}_K = \dot{q}_{C+R} \frac{J_S - J_W}{J_S - (J_W)_{300^\circ K}}$$

where:

- $\dot{q}_{C+R}$ = total heating rate obtained from trajectory data (Btu/in.²-sec)
- J_S = $h_o + V^2/2 g_c$ stagnation enthalpy of air (Btu/lb)
- h_o = ambient enthalpy of air (Btu/lb)
- V = velocity
- g_c = gravitational acceleration (32.2 ft/sec²)
- J = mechanical equivalent of heat (778 ft lb/in.)
- h_W = enthalpy of air at the wall temperature (Btu/lb)
- $(h_W)_{300^\circ K} = (130 \text{ Btu/lb})$

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Subscripts

E = element in question
i = initial time of calculating interval
f = final time of calculating interval
T = top of element
u = underside of element
L = left side of element
R = right side of element
F = front of element
B = back of element.

Writing the heat balance equation for each element of the network results in a series of equations which must be solved simultaneously for the final enthalpy of each element from which the final temperatures can be obtained.

The elements are defined by temperature-dependent material properties. Tables of values of enthalpy versus temperature were utilized in handling variable specific heat and phase changes, such as melting.

The method employed to solve the equations is an iteration procedure where the first iteration is made by evaluating the unknown terms on the right side of the equation. The results of the first iteration are then used to obtain a second iteration. This procedure can be repeated to obtain successive iterations leading to a solution, provided the procedure is converging. A technique is used after the second iteration which accelerates convergence and forces convergence for cases which are normally divergent.

Ablation of an element is considered to occur when the melting temperature is reached and the heat of transformation is added to the melting enthalpy during this constant-temperature process. In the studies conducted for RFD-2, no blocking was considered during ablation, and all radiating elements were considered to radiate to infinity.

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V. PREFLIGHT ANALYSIS

Procedures followed for the preflight analysis of the simulated RFD-2 isotope-powered generator are those currently being used on all nuclear systems under study by the Martin Company. Of particular interest in the studies being conducted during this program is the determination of the reliability of the assumptions which must be used for evaluating the effects of aerodynamic heating of odd-shaped nuclear generator systems. Therefore, attention has been placed on these re-entry assumptions. First, the system must be evaluated in terms of its trajectory parameters; then, an analytical model of the system must be developed; and finally, the re-entry environment must be established. The latter includes an investigation of the aerodynamic heating of and heat transfer through the re-entering body. The following is a description of these factors and a summary of the analysis.

A. NOMINAL TRAJECTORY AND HEATING CURVES

1. Generator Assembly

Analysis of the generator re-entry trajectory proceeded on the assumption that attachment between the generator and the re-entry vehicle (RV) would be maintained throughout the entire flight, as prescribed by the Sandia Corporation. Therefore, with the RV influencing the generator as a stabilizing device, the angle of attack of the system was assumed to be zero degrees.

Because the four-stage Scout launch vehicle could not be made available for the flight test, a trajectory based upon a three-stage Scout vehicle and the generator/RV drag coefficients (Ref. V-1) were used with the Martin Code UB003 to provide aerodynamic heating data. The initial trajectory conditions for altitude, velocity, and flight path angle were 399,872 feet, 19,055 ft/sec, and -6.187 degrees, respectively. Trajectory and heating data are shown in Fig. V-1. System weight for this trajectory was 465 pounds.

2. External Capsules

Re-entry altitude and velocity decay curves and stagnation heating rates used in the heating analysis for the external capsule experiment are shown in Fig. V-2. The initial conditions for the capsule trajectories were obtained from the three-stage Scout data. Drag curves as a function of Mach number were obtained from information based on experiment and Newtonian impact theories (Ref. V-2). These are shown in Fig. V-3. For the tumbling re-entry mode, the capsule drag coefficient was determined by averaging the coefficients for cases where

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Fig. V-1. RFD-2 Generator--RV Re-entry; 3-Stage Scout = 0°; Based on LVVC 27; 1.0-ft Radius Hemisphere, 4.4-ft Reference Area

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Fig. V-2. RFD-2 External Fuel Capsule Trajectories for Tumbling, Spinning Re-entry Based on Trajectory LVVC 27

Fig. V-3. External Fuel Capsule Drag Curves

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the capsule would enter with its longitudinal axis perpendicular or parallel to the flight path. Altitude and velocity curves were used directly in the heating program.

B. MODEL DESCRIPTION

1. Generator Assembly

Analysis of the heat transfer and ablation characteristics of the generator required the development of analytical models which represented the configuration of the actual generator. Since the generator is not homogeneous, two distinct models were set up to consider all of the materials and their arrangements. The sections taken to define these models are shown in Fig. V-4. These models were broken up into elements which represented specific regions in the generator. Due to the limitation placed on the number of elements allowed by the heat transfer and ablation computer program, FB090, each model was separated into two sections. Elemental representation, material distribution, and thermocouple locations for each model section are shown in Figs. V-5, V-6, V-7, and V-8, and details of each elemental section are given in Appendix E. Model 1 is a cross section through one of the main ribs of the top cover plate and one of the thermoelectric module assemblies. Model 2 is a cross section through the web in the upper cover plate and through a Min-K insulation section in the generator housing.

2. External Capsules

The four external fuel capsules analyzed during this program were cylindrically shaped bodies 6.106 inches long with diameters of 0.840 and 0.880 inches. Table V-1 describes the various elements, and Fig. V-9 graphically represents the analytical heat transfer models of each capsule. All capsule configurations consisted of an outer layer of Haynes-25 and an inner layer of Fiberfrax containing a flare material. Three of the models (50H6T, 50H12T, 50H20T) contained a liner material (tantalum) between the Haynes and Fiberfrax. The Haynes outer capsule and tantalum liner are integral containers and must be removed by aerodynamic heating. The Fiberfrax, however, consists of loosely held sections which will be removed by the action of dynamic pressure when aerodynamic heating has destroyed the outer layers of material.

The analytical treatment of the capsules required that they be divided into elements forming a space network to describe the heat transfer problem. This elemental array depended on the type of heat transfer involved, i. e., whether one-, two-, or three-dimensional, and the type of heat transfer was, in turn, dependent on the re-entry

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Fig. V-4. Generator Cross-Section

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Magnesium		Min-K
Steel		Haynes-25
Graphite		Al ₂ O ₃
Aluminum		

Fig. V-5. Model 1 Section 1 Material Distribution (Section A-A, Fig. V-4)

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Fig. V-6. Model 1 Section 2 Material Distribution (Section A-A, Fig. V-4)

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Fig. V-7. Model 2 Section 1 Material Distribution (Section B-B, Fig. V-4)

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Fig. V-8. Model 2 Section 2 Material Distribution (Section B-B, Fig. V-4)

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TABLE V-1

Nominal Sizes of Capsules

<u>Capsule Designation</u>	<u>Element No.</u>	<u>Material</u>	<u>Outside Radius (in.)</u>	<u>Inside Radius (in.)</u>	<u>Flare Material</u>
50H	1	Haynes-25	0.420	0.370	Thallium
	2	Fiberfrax	0.370	0.320	
	3	Fiberfrax	0.320	0.270	
50H6T	1	Haynes-25	0.420	0.370	Silver
	2	Tantalum	0.370	0.364	
	3	Fiberfrax	0.364	0.314	
	4	Fiberfrax	0.314	0.264	
50H12T	1	Haynes-25	0.420	0.370	Indium
	2	Tantalum	0.370	0.358	
	3	Fiberfrax	0.358	0.308	
	4	Fiberfrax	0.308	0.258	
50H20T	1	Haynes-25	0.440	0.390	Strontium
	2	Tantalum	0.390	0.370	
	3	Fiberfrax	0.370	0.320	
	4	Fiberfrax	0.320	0.270	

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50 H

50 H6T

50 H12T

50 H20T

Fig. V-9. Analytical Heat Transfer Models

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mode of the capsules. It was assumed that the capsules would make an atmospheric re-entry in a tumbling, spinning manner. With such a re-entry, the heating may be considered to be uniformly distributed about the capsule. Since the capsule ends contained more material than the side walls, as well as aluminum oxide end caps, only the sides of the capsules were analyzed to determine capsule integrity during the re-entry heating period. Heat transfer will occur in the radial direction under the assumption of uniform heating and, for this reason, only unit depth of the capsule was considered. In all cases, the Haynes-25 portion of the capsule comprised one element 0.050 inch thick, and the Fiberfrax was divided into two elements, each 0.050 inch thick. The tantalum liner appears as one element of thickness 0.006, 0.012, or 0.020 inches, depending on the capsule in which it was contained.

The flare material was not included in any of the analytical models, because it was found during preliminary studies that the Fiberfrax, with a heat conductivity of 10^{-6} Btu/in.-sec-°R at $T = 1000$ °R, blocks most of the heat input to the flare.

C. HEAT TRANSFER ANALYSIS

1. Generator Assembly

In this analysis, two main objectives were sought. These were the time-temperature histories of the thermocouples and the disassembly characteristics of the generator. Both of these objectives were attainable through the use of the heat transfer program, FB090. The inputs include the heat flux, attitude, and velocity as functions of time obtained from the re-entry trajectory; the element dimensions obtained from the analytical model; and the material thermodynamic properties. The trajectory parameters are shown graphically in Fig. V-1, the element dimensions are listed in Appendix E, and the material thermodynamic properties are tabulated in Appendix F. Heating distribution on the generator is shown in Fig. V-10.

During the analysis, as elements of the models reached their ablation enthalpies and were considered to be ablated, the heating and radiation parameters were altered to encompass the shape and size change of the models. Thus, the program (FB090) was stopped and restarted several times during the analysis of each model so that these changes could be incorporated. Finally, the determination of the removal times for the Min-K disks was based on the ablation of the elements on the housing wall adjacent to the bottom edge of the disks.

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Fig. V-10. q/q_{stag} Versus l/r Flat-Faced Cylinder

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2. External Capsules

The heat transfer analysis of the external fuel capsules was conducted in two steps. From 400,000 feet until the Haynes-25 elements have ablated, Heating Code FB090 calculated temperature and enthalpy histories for all elements. The second step was a calculation to find the time required to oxidize the tantalum liner once it had been exposed.

The trajectory information is shown graphically in Fig. V-2. Elemental geometric properties and material physical properties are given in Appendix E and Appendix F, respectively. Enthalpy information is included in the code description.

Since the heating rates provided by the trajectory code are based upon the stagnation point of a hemisphere, modifying factors were required to apply the heating rate values to a tumbling cylinder. These modifying factors are shown in Table V-2 (Ref. V-3).

TABLE V-2
Modification Factor to Hemispherical
Stagnation Heating Equation

<u>Condition</u>	<u>Stagnation Heating Rate</u>	<u>Surface Average Factor</u>
Sphere	1.0	0.312
Cylinder (normal to air flow)	0.707	0.321
Flat plate (cylinder parallel to air flow)	0.500	1.20
Cylinder (tumbling)	0.584	0.321

Therefore, a right circular cylinder, entering the atmosphere tumbling in the pitch plane, will experience aerodynamic heating as determined by the relationship below:

$$q_{\text{surface average cylinder tumbling}} = q_{\text{stagnation sphere}} \\ \times 0.707 \times 0.321 \times 0.584 = 0.1325 q_{\text{stagnation sphere}}$$

In order to compute the time needed to oxidize the tantalum liner, an empirical equation was derived from test data summarized in Appendix A. The equation is

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$$t = \frac{dx}{0.030} (1.96 \times 10^4 \dot{q}^{-1.2} - 27.6)$$

where

t = time (sec)

dx = thickness (in.)

$\dot{q}$ = stagnation heating rate (Btu/ft²-sec)

The equation is limited to the following range of approximate values for dx and $\dot{q}_s$

$$0.01 \leq dx \leq 0.03 \text{ (in.)}$$

$$30 \leq \dot{q}_s \leq 300 \text{ (Btu/ft}^2\text{-sec)}$$

The heating rate, $\dot{q}_s$, is the stagnation point heating rate on a flat-faced cylinder, and dx is the amount of material oxidized in the axial direction. It was decided that the heating rate to use for the capsules in a tumbling, spinning re-entry would be trajectory heating rate modified by the correction factor 0.133. As noted before, this reduces the heating rate from the stagnation point on a hemisphere to surface average heating rate on a tumbling, spinning cylinder.

The procedure used to calculate oxidation time for the tantalum liner involved averaging the heating rate over a time period beginning with the time when the liner is first exposed and using this average value to compute a time required to oxidize the liner. If the time intervals for averaging and the computed time agree, the result is taken as the correct time.

D. SUMMARY OF ANALYSES

1. Generator Structure

The analysis described above has determined the time-temperature variation of the thermocouples located in various areas of the generator and the expected disassembly characteristics of the generator during re-entry.

The thermocouple time-temperature predictions are presented as curves to best show the expected trend of heat transfer activity during re-entry. Of the 29 thermocouples, curves for 25 of them are shown, 3 of the remaining being symmetrical with 3 other locations, and 1 being

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in an area for which insufficient material thermodynamic data was available. Specifically, T-17 is symmetrical with T-18, T-22 with T-21, T-23 with T-24, and T-27 was located in the E-300, for which little data was available. However, it is expected that T-27 should behave in a manner not unlike that of T-28. The predicted performance of each thermocouple is reported in a later chapter, where it is compared with that information recorded during the flight test.

Generator Disassembly

Preflight analyses concerning the disintegration of the generator show the following events to occur at times and altitudes along the nominal trajectory.

<u>Event</u>	<u>Time from 400,000 ft (sec)</u>	<u>Altitude (ft)</u>
Top cover ablation	79.1	200,000
1st Min-K disk removal	80.1	197,000
2nd Min-K disk removal	82.7	188,000
Capsule release	97.4	143,000

It is obvious that, if the housing adjacent to the Min-K sections is destroyed, generator disassembly will occur regardless of the amount of magnesium remaining attached to the module bars. It was predicted that capsule release would occur near 140,000 feet altitude. Flare exposure will follow immediately after capsule release.

2. External Capsules

Assuming a tumbling, spinning re-entry from 400,000 feet, flare exposure altitudes for 50H, 50H6T, 50H12T, and 50H20T capsules have been computed. The exposure altitude required to ablate the Haynes-25 plus the additional altitude needed for tantalum oxidation are given in Table V-3.

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TABLE V-3

Flare Exposure for RFD-2 External Fuel Capsule

Capsule Designation	Haynes-25 Ablation		Tantalum Oxidation		Flare Exposure Altitude (ft)
	Altitude (ft)	Time (sec)	Altitude (ft)	Time (sec)	
50H	178,300	85.6	--	--	178,300
50H6T	178,300	85.6	137,000	100.6	137,000
50H12T	178,400	86.5	No	No	No
50H20T	170,100	89.3	No	No	No

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VI. POSTFLIGHT ANALYSIS

The nominal mission assigned to a three-stage Scout missile was to place the RFD-2 payload into a re-entry trajectory which would have nominally impacted at a geodetic longitude of 64.30 degrees west and geodetic latitude of 29.92 degrees north. However, the actual impact point occurred at a geodetic longitude of 63.75 degrees west and geodetic latitude of 29.98 degrees north, as a result of a trajectory 20 nautical miles left of nominal and 27 nautical miles farther down-range. Comparison of the nominal predicted and observed conditions for the experiment is shown in Table VI-1.

As a result of data reduction following the preflight analysis, several changes were incorporated into the generator postflight analysis.

Based upon the temperature gradients observed in the preflight analysis, a decision was made to simplify the postflight analysis by using two heat transfer models rather than four. Thus, each section (through the main rib and through the web) would be represented completely by one heat transfer model. Further, the problem of obtaining early histories of the thermocouples in the lower half of the generator was eliminated. Previously, the heat transfer models representing the lower halves were not analyzed until the top cover plate was ablated.

Since the time interval between the first element ablation and the last element ablation on the top cover plate was short, the previously used procedure of updating the heating inputs for the heat transfer models after each element ablated was eliminated.

TABLE VI-1

Trajectory Data Comparison--Preflight and Actual RFD-2

	<u>Preflight Nominal Predicted</u>	<u>Actual</u>	<u>Error</u>
Velocity (earth relative, fps)	19,021	18,857	$\approx 3.04 \sigma$ slow
Altitude (feet)	401,066	433,276	$\approx 2.14 \sigma$ high
Re-entry angle (degrees)	-6.09340	-6.25	$\approx 0.050 \sigma$ steep
Range errors (naut mi)	0	-2.8	$\approx 0.76 \sigma$ uprange
Cross-range errors (naut mi)	0	9.6 N.E.	$\approx 2.85 \sigma$ N.E.
Azimuth angle (degrees)	130.3	128.5	$\approx 4.52 \sigma$

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A. GENERATOR ANALYSIS

1. Trajectory

For the analysis of the generator during the RFD-2 re-entry, Sandia trajectory 11032 was used. This trajectory was generated based upon radar, optical, and accelerometer data acquired during the experiment. Re-entry, for both the generator and the external capsules, was assumed to begin at the time of external capsule release, $T + 293.18$ seconds. The conditions at this time were:

Altitude (ft)	400,652
Earth relative velocity (ft/sec)	18,911
Flight path angle (deg)	-6.818
Flight azimuth (deg)	128.9
Latitude (deg N)	34.02
Longitude (deg W)	69.28

Attitude measurements recorded by the RV verified that the orientation of the generator during its re-entry was a zero-degree angle of attack with minor oscillations.

The trajectory parameters of interest are shown in Fig. VI-1.

During the determination of the RFD-2 re-entry trajectory from the reduction of radar, optical, and accelerometer data, the 1962 ICAO standard atmosphere was used. This atmospheric model approximated the atmospheric conditions that existed during the launching and flight of the RFD-2 re-entry vehicle. A comparison of re-entry conditions was made by using the standard atmosphere model and atmospheric data obtained from an Arcus rocket launched during the same day as the RFD-2 flight. Listed below is a comparison between re-entry data obtained using the 1962 ICAO standard atmosphere as opposed to data based on the actual atmospheric conditions for that day. The points of comparison are maximum aerodynamic heating and maximum dynamic pressure (approximately):

	Maximum DQC		Maximum Q	
	Actual Data	Sounding Data	Actual Data	Sounding Data
Time	399.00	399.00	408.00	408.00
Altitude	95,744.3	95,711.3	71,002.4	71,058.9
Latitude	30.53	30.53	30.30	30.30
Longitude	-64.46	-64.46	-64.16	-64.17
VT	16,463	16,472	11,595	11,463
Gamma	-10.8127	-10.8109	-11.5643	-11.5706
Q	5491.0	5575.5	8911.2	9120.7
QC	11,048	11,029	15,314	15,325
DQC	551.84	556.66	330.27	326.19
Mach No.	16.6614	16.6735	11.9347	11.8942

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Fig. VI-1. Sandia Trajectory No. 11032 Used in the Postflight Analysis

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2. Aerodynamic Heating Data

Two distinct aerodynamic heating distributions were applied to the generator in an effort to determine the effects of each. These distributions were:

- (1) Lees' theory for a flat-faced cylinder and correlated data (Scheider).
- (2) Rhodes & Bloxsom data, as modified by Klett of Sandia Corporation.

The distribution based on Lees' theory considered the generator as a flat-faced cylinder and incorporated Lees' theory over the top surface, both along the ribs and on the web between the ribs. The correlated data for separated flow was applied to the top cover flange and the housing. These distributions are shown in Figs. IV-9 and IV-11, respectively.

Modified Rhodes and Bloxsom test data, as shown in Figs. IV-6, IV-7 and IV-10, were applied to the generator. This analysis considered separate distributions for the section through the main rib and through the web. The distribution along the flange of the top cover and down the housing was the same for both sections.

Heating rates based upon free-molecular flow theory were calculated for the generator and compared with continuum flow theory data. This is shown in Fig. VI-2, where data for both regions are plotted and the assumed transition region is faired in.

3. Heat Transfer Data

Two separate heat transfer models for the generator were set up, based on the sections shown in Fig. V-4. These models were in the shape of a rectangular slab, 0.25 inch thick and are shown, with their respective elements, in Figs. VI-3 and VI-4. Using the aerodynamic heating data shown in Figs. IV-9, IV-11, and VI-2 in Computer Code FB090, the heat transfer models provided temperature distributions and ablation times of the elements. These temperature histories are shown in Chapter VII.

4. Re-entry Structural Characteristics

The generator housing is constructed of magnesium alloy tube stock HM31A, Condition F. Figure VI-5 presents creep data for this alloy as a function of temperature for the standard 0.2% total strain condition. Since there is a lack of strain hardening at elevated temperatures, the yield and ultimate tensile stresses are nearly equal in magnitude (Refs.

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Fig. VI-2. Comparison of Free Molecular and Continuum Heating at Stagnation Point

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Fig. VI-3. Heat Transfer Model of Section Through Main Rib

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Fig. VI-4. Heat Transfer Model of Section Through Web

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Fig. VI-5. Short Time Creep Data--0.2% Total Strain at Temperature for HM31A Tubing Cond F

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VI-1 and VI-2). Based upon this fact, it was assumed that the ultimate strength corresponds with the 0.2% curve shown in Fig. VI-5. The melt temperature ranges between 1120° and 1200° F. Values above 900° F are estimated, using melt temperature as an end point.

The structural failure is a result of a combination of temperature and pressure effects. Temperature, of course, is generated by the areodynamic viscous forces. The pressure forces, however, are established by the 120 preloaded springs in the fuel block assembly and/or the aerodynamic pressure within the housing.

The generator housing temperatures selected for use in this analysis are the mean values between those calculated for Thermocouples T-9, T-12, and T-15 and those calculated for Thermocouples T-10, T-14, and T-16, Chapter V-D. Average temperature values were used for the side wall analysis, since it is not possible to analyze the time-dependency factor in the failure of segments of the housing which will be left in the low temperature areas near the aluminum module bars. A curve of average values is shown in Fig. VI-6 together with a spring temperature curve.

The spring temperatures are shown to remain less than 150° F during the re-entry; therefore, the spring constant should remain essentially fixed. The spring constant is equal to 38.8 lb/in. and the displacement per spring is nominally 0.069 inches in the radial direction. The resulting equivalent internal pressure of the aluminum module bar against the generator housing is computed by means of the following equation:

$$P_{eq} = \frac{\text{Total spring force}}{\text{Area}} = \frac{Nk\delta}{\pi D_i L}$$

where:

k = spring constant = 38.8 lb/in.

N = number of springs = 120

δ = displacement = 0.069 in.

D_i = inside diameter of housing = 5.125 in.

L = length = 6.125 in.

Hence,

$$P_{eq} = 3.26 \text{ psi}$$

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Fig. VI-6. Nominal Housing and Spring Temperature Versus Time During Re-entry

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The circumferential stress in the housing is equal to

$$\sigma_{\theta} = \frac{P_{eq} \times R}{t}$$

where:

R = housing radius = 2.613 in.

t = housing thickness = 0.102 in.

Hence:

$$\sigma_{\theta} = 83.4 \text{ psi}$$

The aerodynamic pressure within the generator housing can only arise if the top cover plate is removed to expose the internal components, air passages, etc., to the free stream. Analytical calculations using the Martin FB090 Structural Heating program, Chapter IV-C, show that this cover plate is ablated away by $t = 370$ seconds.

The stagnation pressure is the maximum obtainable aerodynamic pressure.

$$P_{stag} = C_p \frac{1}{2} \rho_{\infty} V_{\infty}^2$$

The Newtonian value for the stagnation pressure coefficient, C_p , is equal to 2.00 for elastic collision; hence,

$$P_{stag} = 2 \times \text{dynamic pressure}$$

Figure VI-7 shows the stagnation pressure versus time for Sandia Trajectory No. 11032, postflight analysis.

The internal pressure necessary to obtain shell rupture is determined by the following equation:

$$P_{req} = \frac{t \sigma_{ult} \times 144}{R}$$

where:

t = wall thickness = 0.102 in.

σ_{ult} = ultimate stress from Fig. VI-5 in psi

R = housing radius = 2.613 in.

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Fig. VI-7. Stagnation Pressure During Re-entry (Sandia Trajectory No. 11032)

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The available internal pressure is obtained from Fig. VI-7. The time/temperature relationship is derived from Figs. VI-5 and VI-6. The following table summarizes the regime from 380 seconds to generator failure. The altitudes are obtained from Sandia Trajectory No. 11032.

Time (sec)	Temperature (°F)	Soak Time = 0.1 min		Soak Time = 1.0 min		P _{avail} (psf) (aero press.)	P _{avail} (psf) (total)	Altitude (ft)
		σ_{ult} (psi)	P _{req} (psf)	σ_{ult} (psi)	P _{req} (psf)			
380	1008	500	2810	350	1970	910	2111	158,355
381	1020	350	1970	250	1405	1040	2241	156,837
382	1070	250	1405	250	1405	1190	2391	151,711
383	1090	250	1405	250	1405	1350	2551	148,378
384	1115	250	1405	250	1405	1550	2751	145,841

It can be seen from this analysis that the structure will fail at an altitude of approximately 158,000 feet, if the assumptions are valid. If air flow exists within the generator, the actual pressure experienced by the outer housing will be somewhat lower than stagnation pressure. This seems probable because test data on flat faced bodies show pressures at the outer edge to be less than stagnation values. On the other hand, there is conservative selection of wall temperatures and ultimate stress values; i.e., average wall temperatures and maximum melt temperatures for magnesium are used. For example, if the stagnation pressure is reduced by 20% the required pressure balance is obtained at an altitude of approximately 157,000 feet.

5. Summary of Analysis

The results of this analysis are separated into two areas: first, the predicted thermocouple histories; and, second, the disassembly history of the generator.

Curves depicting the predicted thermocouple histories developed from this analysis, as well as those for the preflight analysis, the thermocouple data obtained by telemetry during the actual flight, and a discussion of these curves and a comparison of the data will be found in Chapter VII.

Disassembly of the generator was predicated upon removal of the top cover plate. With the top cover gone, the housing will receive a significant increase in aerodynamic heating; also, aerodynamic pressure forces will initiate displacement of the generator internal components. The results of this analysis indicate that disassembly should occur at 86.8 seconds after re-entry at 400,000 feet, which corresponds to T + 380.0 seconds, or an altitude of 158,300 feet.

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B. EXTERNAL FUEL CAPSULE EXPERIMENT

In the preflight section of this report, theoretical re-entry trajectories were generated to determine analytically the fate of the four external fuel capsules as they re-entered the atmosphere. The results of this study are summarized in Chapter V. The theoretical trajectories generated, however, were not representative of the actual re-entry trajectories followed by the external capsules during the October RFD-2 flight.

In order to utilize the actual flight data, the preflight analysis was repeated, using actual re-entry trajectory data along with more refined capsule data. The object of this postflight theoretical study was to determine whether the actual capsule re-entry results could be duplicated by a refined theoretical study or, in general, to determine how closely theoretical studies agreed with actual experimental data.

The postflight theoretical trajectories were generated, using Code UB024, with the initial starting point taken from actual RFD-2 flight data. The 1962 ICAO atmosphere was used in the trajectory calculations (as opposed to the 1959 atmosphere used in the preflight analysis), along with the assumption that the capsules re-enter in a tumbling, spinning mode. The capsule weights used were the measured values shown in the following table.

<u>Capsule Designation</u>	<u>Tracer Material</u>	<u>Weight (lb)</u>
50H	Thallium	0.828
50H6T	Silver	0.812
50H12T	Indium	0.731
50H20T	Strontium	0.635

Figures VI-8 and VI-9 give the re-entry trajectory followed by each capsule; the stagnation point heating rates are also given.

The re-entry trajectories and heating rates generated by Code UB024 were used in Code FB090 to determine the effects of aerodynamic heating on each capsule. In these studies, the stagnation point heating rate to each capsule was modified to account for the capsule tumble-spin assumption.

The results of the above ablation study are shown in Table VI-2. In the determination of the flare exposure altitude, it was assumed that the insulation breaks away from the flare material at the instant all the Haynes-25 has ablated.

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Fig. VI-8. RFD-2 External Fuel Capsule Experiment--Re-entry Trajectory and Aerodynamic Stagnation Point Heating Rate

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Fig. VI-9. RFD-2 External Fuel Capsule Experiment--Re-entry Trajectory and Aerodynamic Stagnation Point Heating Rate

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Since the 50H6T capsule flare material was not exposed during the assumption of a tumbling, spinning re-entry, another UB024 and FB090 program run was made assuming that the re-entry of the capsule was only in the spinning mode. The re-entry trajectory and stagnation point heating rate for this case are shown in Fig. VI-10. The Haynes-25 was found to ablate completely at the altitude shown in Table VI-2. The time required for the oxidation of the tantalum liner was calculated with the empirical equation given in the preflight analysis. In this case, the liner did oxidize completely, exposing the flare material at the altitude also given in the table.

An ablation analysis of the 50H capsule re-entering in a spinning mode was performed, based on the ablation studies described above. The results of this study are shown in Table VI-2.

It can be seen that an analytical analysis of the external fuel capsule experiment predicts that only the thallium tracer in the 50H capsule will be exposed if the assumption is made that the capsules re-enter in a tumbling, spinning mode. However, if it is assumed that the 50H and 50H6T capsules re-enter only in a spinning mode, then the tracer material in each capsule will be exposed.

A comparison between the above analytical results and the experimental results of the actual RFD-2 flight is discussed in the next section.

TABLE VI-2
Flare Exposure Altitudes of RFD-2 External Fuel Capsules

Capsule Designation	Haynes-25 Ablation		Tantalum Oxidation		Flare Exposure Altitude
	Altitude (ft)	Time* (sec)	Altitude (ft)	Time (sec)	
50H	166,500	378.2	--		166,500
50H6T	165,500	378.6	None		--
50H12T	160,800	380.6	--		--
50H20T	None		None		--
50H**	204,000	365.4	--		204,000
50H6T**	203,400	365.8	177,000	374.5	177,000

*Time from launch.

**Assumed to be spinning normal to airflow about longitudinal axis.

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Fig. VI-10. RFD-2 External Fuel Capsule Experiment--Re-entry Trajectory and Aerodynamic Stagnation Point Heating Rate

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VII. COMPARATIVE STUDY

The previous sections of this report have presented the aerodynamic heat flux, trajectory parameters, heat transfer codes, experimental data, and a summary of the preflight and postflight analyses. This section is concerned with a comparison of the RFD-2 flight test results with the calculated values, both preflight and postflight, and concludes with a discussion of the applicability of the method to a satellite re-entering the earth's atmosphere from orbit.

Interpretations of the RFD-2 flight test results to provide specific modifications to the codes or the input thereto were limited. Rather, for this specific case, it was deemed essential that the information available from theory and experimental test be utilized to calculate the thermodynamics of the SNAP generator. These results are then compared with the flight test data. The engineering accuracy is determined from this comparison. Once this has been done, it is befitting that the differences, if any, be discussed and analyzed. Then recommendations pertaining to possible changes in the method of analysis for future action are in order.

A. FLIGHT DATA EVALUATION (SANDIA CORPORATION)

1. Trajectory Analysis

Four types of data obtained from the flight were used in the definition of the RV trajectory. These were:

- (1) Radar data.
- (2) Optical data.
- (3) Time of loss of telemetry signal.
- (4) Accelerometer data.

Figure VII-1 depicts the time at which each of the above was obtained.

Radar tracking was lost at about 368 seconds, at which time the RV's earth relative velocity was 19,182 fps, altitude was 197,367 feet and re-entry angle was -9.552 degrees. All data presented for later times are based on the optical data matching by a theoretical trajectory through 402 seconds and on the theoretical trajectory for times after 402 seconds. The final trajectory established was Sandia Trajectory 11033, Fig. VII-2.

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Fig. VII-1. Methods of Data Acquisition as a Function of Time

a. Radar data

The NASA FPS-16 radar at Bermuda tracked the C-band beacons in the RV. Data are available from this radar for the time intervals:

198.1 through 209.3 seconds

209.8 through 219.9 seconds

234.8 through 366.2 seconds

367.3 through 368.4 seconds.

For matching purposes, only data after third stage burnout (at about 265 seconds) were used.

The NASA FPQ-6 radar at Wallops Island tracked the C-band beacon on the third stage of the Scout launch vehicle. Although data were available from launch to $T + 336$ seconds, only the data from $T + 265$ (third stage burnout) through $T + 278$ (third stage separation) were used for matching purposes.

b. Optical data

All optical data on the RV trajectory are based on the Sandia fixed-axis plate cameras at High Point. Optical data for trajectory purposes are available from both 24- and 12-inch f.1 - lens plate cameras for the time interval from approximately 353 to approximately 402 seconds.

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Fig. VII-2. Sandia Trajectory 11033

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c. Time of loss of TM signal

The time of loss of TM signal may be assumed to be the time of water impact. The downrange elements listed below, which were the three TM-receiving stations closest to the impact point, lost the TM signal at the times shown (time is in seconds after launch):

AFSWC Aircraft 617	502.0
Range Recoverer	501.6
Sampan Hitch	501.2

d. Accelerometer data

Output of a spring-mass-damper accelerometer with a full-scale range of ± 35 g was telemetered from launch to 470 seconds. (At 470 seconds, the transmitter used for real-time data was switched to the delayed-time data.) This instrument will resolve accelerations smaller than 0.35 g, and accuracy of the accelerometer and TM link is within $\pm 5\%$ of full scale. The record provided by this accelerometer offers the only data available for trajectory definition from 402 until 470 seconds.

2. RV Generator Data

Identification of the generator and RV from the films was obvious. At 367.8 seconds (198,000 feet) and 377.8 seconds (166,000 feet), the motion picture films showed small objects separated from the generator. Magnesium spectra, were observed on the spectral films from 364.00 seconds (210,000 feet) to 389.40 seconds (127,000 feet). The times at which the objects separated correlate with the times given for the generator-lid disassembly and can-wall melting from the telemetered thermocouple data.

The generator trace on the plate-camera films became much brighter at 380.59 seconds (156,400 feet). At 380.80 seconds, the motion picture films recorded a brilliant flare-up of the generator, and the magnesium spectra, already visible on the spectral films, became more intense from 380.60 to 381.60 seconds. Hence, generator disassembly must have occurred between 380 and 382 seconds. This conclusion is supported by the fact that chromium spectral radiation was evident from 380.5 to 399.0 seconds. Some of the generator internal components and the generator mounting plate are of stainless steel, which contains chromium.

Flares were noted on the plate films immediately after the time given for generator disassembly. Times of these flares were 381.90, 382.20, 382.80, 383.10, and 385.30 seconds. These times agree

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reasonably well with the times the internal flares were seen on the motion picture films: 382.00, 383.13, 383.31, and 385.73 seconds. Tentative confirmation that these were the internal capsule tracers is given by spectral identification of barium at 382 to 383 seconds and intensity increases in the sodium and lithium radiation at 380.8 seconds.

3. External Capsules

In addition to the RV generator and third stage motor, approximately eight small objects are visible on the plate films. At the time of writing, the detail analysis of these films was incomplete. On the motion picture films, two small objects appeared behind the RV and third stage motor at 362.90 seconds. These are probably the iridium and strontium capsules, but no confirmation has been established at this time. At 366.00 seconds, two more small objects appeared behind the RV and directly above the third stage motor. One object flared green at 370.00 seconds, agreeing exactly with the spectral data for thallium. The remaining object flared at 372.00 seconds. It has not been definitely identified, but in view of its relative location in the re-entry pattern and time of flaring, it is deduced that it must be the silver-loaded capsule.

Figure VII-3 summarizes the data on the RV generator and external capsules given above.

4. Telemetry Data

The thermocouple data obtained as part of the TM information is presented in the postflight heat transfer comparative analysis. The temperatures as a function of time for the different locations are given in Figs. VII-4 through VII-29.

The time histories of the contact switches located in the base of the generator are presented in Table VII-1. These switches were incorporated in the design to indicate the beginning of disassembly of the generator. The data given in Table VII-1 indicate that the generator fuel capsules moved freely in the generator during re-entry and that, at 357.3 seconds, they no longer were in contact with the switches.

B. GENERATOR COMPARATIVE STUDY

The flight test data showed that the RFD-2 generator broke up at an altitude of 156,223 feet. According to the analysis summarized in Chapter VI, the system should break up at an altitude of 158,300 feet, well within the accepted ten percent range for engineering accuracy. Hence, the primary objective of the program, i.e., the proof for the

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Fig. VII-3. Comparison of Events Recorded by the Photometers and the Framing, Plate, and Spectral Cameras

NOTE:

— Postflight (Lees) - - - Preflight
- - - Postflight (R&B) — Telemetry

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NOTE:

— Postflight (Lees) - - - Preflight
 - - - Postflight (R&B) — Telemetry

Fig. VII-8. T-5 Data

Fig. VII-9. T-6 Data

Fig. VII-10. T-7 Data

Fig. VII-11. T-8 Data

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NOTE:

— Postflight (Lees) - - - Preflight
 - - - Postflight (R&B) — Telemetry

Fig. VII-12. T-9 Data

Fig. VII-13. T-10 Data

Fig. VII-14. T-11 Data

Fig. VII-15. T-12 Data

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NOTE:

— Postflight (Lees) - - - - - Preflight
- - - - - Postflight (R&B) — Telemetry

Fig. VII-20. T-17 and T-18 Data

Fig. VII-21. T-19 Data

Fig. VII-22. T-20 Data

Fig. VII-23. T-21 Data

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NOTE:

———— Postflight (Lees) - - - - - Preflight
- - - - - Postflight (R&B) ——— Telemetry

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NOTE:

———— Postflight (Lees) - - - - - Preflight
- - - - - Postflight (R&B) — · — · — Telemetry

Fig. VII-28. T-28 Data

Fig. VII-29. T-29 Data

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TABLE VII-1
RFD-2 Switch Data

<u>Time</u>	<u>Switch 1</u>	<u>Switch 2</u>	<u>Switch 3</u>	<u>Switch 4</u>
344.1	Closed	Closed	Closed	Closed
344.3	Closed	Closed	Closed	15K Ω
344.5	Closed	Open	Closed	4.5K Ω
344.7	Closed	2.8K Ω	Closed	Closed
344.9	Closed	2.0K Ω	Closed	0.4K Ω
345.1	Closed	Closed	Closed	0.8K Ω
345.3	Closed	Closed	Closed	Closed
345.5	Closed	Open	Closed	Closed
345.7	Closed	Closed	Closed	Closed
346.3	Closed	4.5K Ω	Closed	Closed
346.5	Closed	Open	Closed	Closed
346.9	Closed	Open	Closed	4.5K Ω
347.1	Closed	Open	Closed	Open
347.3	Closed	Closed	Closed	Open
348.3	Open	Open	Closed	Open
351.9	Open	Open	Open	Open
354.5	Open	Open	Closed	Open
356.3	Open	Open	5.5K Ω	Open
357.1	Open	Open	15K Ω	Open
357.3	Open	Open	Open	Open

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analytical method of prediction for burnup of an inert isotopic generator during ballistic re-entry, has been met.

A comparison of the calculated and test internal temperatures, Figs. VII-4 through VII-29, shows that measurable differences exist between the two values for a given set of conditions. It can be assumed that either the temperature data are not true representations of the internal heat in the system or the external theoretical heating is not representative of the actual heating. Careful review of all data and theory, together with an examination of the internal makeup of the generator, leads to the belief that the former is the more realistic case. Arguments are presented below.

The postflight analysis is based on the two analytical models shown in Figs. VI-3 and VI-4, which represent two cuts through the generator. For the section taken through the aluminum module bar and rib (heat sink), the telemetry data indicate temperatures are higher than predicted by analytical methods. For the section taken through the web and Min-K between the ribs (insulation), the telemetry data indicate temperatures lower than predicted by the analysis. There are exceptions to this generalization. Thermocouples T-19 and T-20, Figs. VII-21 and VII-22 (located on the section taken through the main rib), show lower temperatures than predicted. Internal Thermocouples T-17, T-18, and T-21 through T-29 show no significant rise from ambient values either test or calculated.

It should be noted that the preflight analysis is considerably different from the postflight analysis and telemetry data, particularly in the magnitude of the temperature values at specific times. However, for the most part, the shapes of the preflight and postflight curves are quite similar. If the difference in initial environmental temperatures (694°R for preflight and 520°R for postflight) is rectified, the curves would be nearly identical.

The time-temperature histories of the telemetry data for Thermocouples T-9, T-11 and T-12, located on the inside surface of the external magnesium shell adjacent to the aluminum module (Figs. VII-12, VII-15 and VII-18), and those adjacent to the Min-K insulation strip, T-10, T-14 and T-16 (Figs. VII-13, VII-17 and VII-19), are all quite similar if not identical. Calculated data, however, show that the temperatures are lower than telemetry values near the aluminum module (heat sink) and higher in the region of the Min-K (insulation), as would be expected ideally.

Discussion of the above phenomenon has led to the conclusion that the most probable cause is the introduction of error due to the necessary modifications made in the generator to install thermocouple instrumentation. In particular, the milled grooves which were required to provide

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paths for the thermocouple leads in the module bar and the Min-K insulation also provided air gaps directly behind the thermocouple leads. These "dead" spaces create identical insulation barriers, thereby contributing to the similarity in the telemetry readings of the two areas. Information is available on the effect of contact resistance arising from such air gaps for the steady-state heating conditions. These have been used in the preliminary design of the generator. Numerous tests were then conducted to optimize the final design. In contrast, there is little knowledge pertaining to the contact resistance and its effect on transient heat transfer. In this case, the contact resistance can vary with time and temperature as well as the rate of heat transfer through the segments of the generator. For instance, the aluminum module bars are spring loaded, forcing contact with the outer magnesium shell. As the temperature rises and the metal softens, the contact resistance will decrease.

These factors make the thermocouple data obtained on the RFD-2 inappropriate for direct use in the analysis of an actual re-entry case because of the incorrect internal geometry and the unknown quantity associated with contact resistance. It is useful, however, as backup information to predict trends. The conservative procedure used to date assumes an idealized case (zero contact resistance) and has predicted the burnup characteristics quite accurately.

C. EXTERNAL CAPSULES

According to data evaluated by Sandia at the time of this writing, the thallium capsule, 50H, has been traced and positively identified as being ablated to expose the inner flare material. The silver capsule was traced along its trajectory, but the flare material was not visible in any instrumentation. The other two external capsules were not traced or identified in any way. Reduction of the spectrographic and optical data showed that complete melting of the thallium flare occurred at an altitude of 187,000 feet. It should be noted that the reduction of data on the external capsules has not been completed. However, a comparison with theory will be made, using the capsule which has been positively identified. This comparison follows.

The theoretical altitudes of release for the tracer determined in the postflight analysis for the 50H capsule are presented together with the experimental result in the following table:

<u>Method Used to Obtain Result</u>	<u>Mode of Re-entry</u>	<u>Flare Exposure Altitude (feet)</u>
Analytical	Tumble-spin	166, 500
Analytical	Spin only	204, 000
Experimental	---	187, 000

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The tumbling of the capsule is confined to the pitch plane, and the spinning is about the longitudinal axis, which is normal to the air flow.

The experimental value is approximately the average of the two analytical results. From this it can be concluded that the motion of the capsule was more complicated during the actual re-entry than the modes assumed. Its actual motion is open to conjecture.

From the analytical results given above, it can be concluded that the most critical 50H capsule re-entry mode (of the two considered) for capsule ablation occurred when it tumbled and spun simultaneously. Capsule penetration into the atmosphere was increased, and tracer exposure was delayed with this type of re-entry motion. The least critical re-entry mode of those assumed in the theoretical studies occurred when the capsule was spinning only. This type of re-entry motion yielded the earliest tracer exposure.

D. ORBITAL DECAY ANALYSIS

In the prior discussion of the RFD-2 flight test and analysis it was shown that the method of determining generator burnup is realistic and conservative. Therefore, it is considered applicable to other trajectories such as the case of orbital decay. Several factors must be considered for this more general case which are not covered in the RFD-2 discussion. Some of these factors are discussed below.

Whenever a body such as a SNAP generator falls into the earth's atmosphere from orbit, it is probable that it will tumble. If this happens, the heating rates will be much lower than those for the stabilized vehicle. Reference VII-1 shows that a tumbling-spinning cylinder in free molecular flow has an average heat rate equal to 10.1% of the stagnation point value. For the continuum flow regime this value increases to 13.3% (Ref. V-3). For the situation where the body is not spinning, but is tumbling end for end, the weighted heating rate on the sides or coverplate is equal to 31.8% of the unit area values.

There are two trajectory programs available for use in analyzing the orbital decay problem other than the point mass programs UB003 and UB024 described previously. One is a three-degree-of-freedom pitch plane program, UB104, which requires an input of normal force, axial force, and pitching moment (Ref. VII-1). The other is a six-degree-of-freedom program, UB109 (Ref. VII-2), which requires an additional input of side force, yawing moment, and rolling moment. This latter program is the most realistic, since the vehicle motion is not constrained.

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Both of these programs are formulated within the framework of the Martin UNITRACK interpretive language program, which is a mechanized logic process for the systematic arrangement and computation of differential equations, both basic and auxiliary. Because the external force and moment equations are separate from the main equations of motion, they are readily changed to suit the configuration under study. For instance, in the Nimbus-SNAP 19 safety analysis (UB104 program), the force and moment data of the Nimbus without solar platforms and the data of the platforms alone were separate inputs. This permitted the platforms to rotate about their trunnions while the satellite tumbled about its center of gravity in the pitch plane. In this case, time histories of altitude, velocity, body angle of attack, platform incidence, Mach number, stagnation heat rate, dynamic pressure, body pitch rate, platform pitch rate, etc., were recorded to aid in the analysis. The program is so versatile that it was possible to include instructions to disregard the solar platform force and moment data after the platform normal force exceeded a value equal to that required to break the trunnion supporting them.

The above-mentioned procedure for evaluating the disintegration of a generator re-entering from orbit was applied to the Nimbus-SNAP 19 satellite. Due to the geometry of the craft, it was found that it would re-enter in a tumbling mode with the generator partially shielded so that the tumbling factor for aerodynamic heating was equal to 10% of the stagnation heating. Figure VII-30 shows a plot of heat flux versus time. Integrating this curve for Time 0 to 1440 seconds, at which point the side outer skin of the generator had ablated, the total stagnation heat to the generator is $18,800 \text{ Btu/ft}^2$. The net total aerodynamic heat input required for destruction of the tumbling generator is, therefore, 1880 Btu/ft^2 .

A qualitative comparison of the RFD-2 results and those obtained on the SNAP 19 can be made by comparing the pertinent data for local areas of equal thickness. The skin of the SNAP 19 is made of magnesium and is 0.10 inch thick, backed up by Min-K. The web area of the magnesium cover of the RFD-2 is likewise 0.10 inch thick and is backed up by Min-K insulation. The heat transfer analysis shows that this web area ablated when the total heat input reached 2012 Btu/ft^2 . This agreement between the SNAP 19 and the RFD-2 analysis is excellent and gives substance to the analytical method for determining burnup.

E. RECOMMENDATIONS AND CONCLUSIONS

With respect to the generator system, and in the light of the comparison discussed above, it is believed that additional studies should be initiated to define the interface effects as a function of mechanical

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Fig. VII-30. Aerodynamic Heating SNAP 19-- $\dot{q}$ Based on Generator Diameter

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gaps. Such a study would include surface condition, pressures between interfaces, gap size, and transient heating for specimens of materials used in generator construction. The results of this study would be integrated into the FB090 program, thereby providing a more sophisticated analytical tool. As far as predicting burnup of systems typical of the SNAP 19 configurations, the RFD-2 experiment has proved that current methods of analysis are sufficient.

Since experimental data for three of the four external fuel capsules are not conclusive at this point, little can be said, in conclusion, of the external experiment. However, this report will be amended to analyze more fully the external fuel capsule experiment as additional data become available.

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APPENDIX A

SUMMARY OF TEST PROGRAMS

This appendix summarizes the results of an experimental test program designed to demonstrate the characteristic behavior of space power system materials and components when exposed to a re-entry environment. Specifically, the conclusions were used to assist the prediction and evaluation of the performance of the RFD-2 experiment. Details of the test program may be found in Martin Company Report MND-3283-1, "RFD-2 Program, Summary Ground Test Report."

The program consisted of high temperature materials compatibility tests, two series of plasma arc tests, and wind tunnel tests.

A. HIGH TEMPERATURE MATERIALS COMPATIBILITY TEST

High temperature materials compatibility tests were designed to select the best foil material to prevent chemical and/or physical reactions between graphite, the heat accumulator block material, and Haynes-25, the fuel capsule material. Tests were also conducted to evaluate various ceramic materials which might be used as a substitute for the generator heat accumulator block.

Five different metal foils were tested in combination with Haynes-25 and graphite: titanium, zirconium, tantalum, tungsten, and columbium. Each foil was placed between a cylinder of graphite and a specimen of Haynes-25 and heated for 15 minutes at a temperature above the melting point of Haynes-25 (approximately 2400° F). Each run was repeated twice, once in air and once in a hydrogen atmosphere. The latter to eliminate oxidation effects of the graphite.

Tests to find a substitute material for graphite were made on seven different ceramic materials: ZrB_2 ; borolite--a ZrB_2 and CrB_2 mixture; LT-1-23% Al_2O_3 and 77% Cr; LT-1B-19% Al_2O_3 , 59% Cr, 20% Mo, and 2% TiO_2 ; BeO; Al_2O_3 and CrB_2 . A small sample of each material was placed in contact with a sample of Haynes-25 and heated as in the foil experiments.

The results of these tests showed that zirconium foil was the best material for preventing chemical reaction and subsequent adhering between Haynes-25 and graphite. The foil material oxidized to a light fluffy substance which broke up easily in an air stream.

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Titanium foil was a second best material. Of the ceramic materials tested BeO and LT-1 showed the greatest resistance to chemical and mechanical reactions.

B. PLASMA ARC TESTS

A two-series plasma arc test program was conducted to evaluate dynamic thermal characteristics of materials used in the RFD-2 generator when exposed to aerothermodynamic forces of re-entry. Specific objectives of these tests were to:

- (1) Determine ablation rates of materials such as tantalum, Haynes-25, magnesium, and Min-K insulation
- (2) Determine the rate of chemical reactions of graphite and boron nitride
- (3) Investigate the effects of oxidation on all these materials, especially tantalum
- (4) Evaluate the use of aluminum oxide on the ends of fuel capsules to prevent melting of the fuel capsule before it is released from the generator structure during re-entry.

Test models, numbering 34, were designed in accordance with actual generator components. All were fabricated from flight generator stock material and most were full-scale. These tests indicated that:

- (1) The oxidation characteristics of tantalum do not appear to be affected by surface wetting of the Haynes-25 material.
- (2) The ablation rate of tantalum is faster than that which can be computed using a theoretical oxidation technique. The test data indicated that the time required to ablate tantalum as a function of thickness and aerodynamic heating is equal to

$$\Delta t = \frac{T}{0.03} \left[1.96 \times 10^4 q^{-1.2} - 27.6 \right]$$

where:

T = material thickness (inches)

q = heat flux, corrected (Btu/ft²-sec)

t = time for ablation (seconds)

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This heating rate is a fixed fraction of the stagnation point heat transfer rate, $\dot{q}_s$, which depends upon the mode of capsule re-entry, e. g. spinning-tumbling, etc. The stagnation point heating is generally found from the equation developed by Detra, Kemp, and Riddell:

$$\dot{q}_s = \frac{17,600}{\sqrt{R}} \sqrt{\frac{\rho}{\rho_o}} \left(\frac{V}{V_c} \right)^{3.15} \left[\frac{h_{s1} - h_{ws}}{h_{s1} - (h_{ws})_{300}} \right]$$

In this equation, the density, ρ , is a function of altitude, while the velocity, V , depends upon the type of re-entry trajectory. The variation of ρ with altitude is a function of the type of atmosphere chosen, while velocity changes can be attributed to the body geometry and initial re-entry conditions. The tantalum ablation equation is based on a heating rate dependent on gas enthalpy and pressure which can be related to a ρV factor for re-entry. Therefore, the ablation equation can be used within present knowledge for all conditions of re-entry, so long as proper heating factor corrections are made.

- (3) The computed ablation rate of Haynes-25 was for all practical purposes the same as the ablation rate experienced in the test.
- (4) Al_2O_3 caps on the ends of the fuel capsules will delay the melting of Haynes-25 when the capsules are still in the generator. The burn-up characteristics of the capsule after it is released from the generator and tumbling during re-entry will not be altered significantly.
- (5) The generator housing ablates very rapidly; however, the process is not exothermic.
- (6) Segments of graphite were not welded or adhered as a result of intimate contact with the molten Haynes-25 material.
- (7) Zirconium foil did not affect the separation of fuel capsules from the heat accumulator block.

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C. WIND TUNNEL TESTS

A series of wind tunnel tests were conducted to measure separating force moments and to observe disassembly of the RFD-2 graphite heat accumulator block. These tests were designed to evaluate the forces acting on heat accumulator block configurations at various angles of attack and to record the behavior of a full-scale heat accumulator block under simulated re-entry conditions at a zero degree angle of attack. A total of 15 tests were conducted, 12 on force models and 3 on actual flight hardware with simulated fuel capsules. The test environment simulated a re-entry condition equivalent to an altitude of approximately 200,000 feet and a velocity of approximately Mach 20.

The wind tunnel tests were conducted in the Martin Company's Experimental Fluid Mechanics Hypersonic Facility, capable of simulating environmental conditions in a re-entry flight corridor of altitudes from 140,000 to 240,000 feet and Mach numbers from 15 to 24. Although the running time for the hot shot tunnel is from about 20 to 100 milliseconds, there is sufficient time to obtain force and moment data through the use of normal strain gage balances, pressure data using small transducers, and heat transfer rates using miniaturized thermocouple gages.

Two test specimens were used in this program, a free-flight model and a force model.

The free-flight model consisted of the actual heat accumulator block with simulated fuel capsules. The block was painted white and the capsules were marked to facilitate photographic coverage and observations. The free-flight model was suspended in the tunnel by nylon thread. This thread melted away very early when exposed to the initial shock wave, leaving the model free in the air stream.

The force model was constructed of aluminum and molded tooling plastic. It was instrumented with small pressure transducers and strain gages and was suspended in the air flow by a sting assembly.

Four angles of attack were studied: 0° , 10° , 20° , and 30° . The action was recorded on 16mm film taken by a Fastax camera operating at 8000 frames per second.

It can be concluded from this test that the heat accumulator block will separate cleanly from the fuel capsules (Fig. III-6). No segment interferes with any other as they leave the capsules. This is true for all the angles of attack tested.

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APPENDIX B

ASSEMBLY PROCEDURES OF THE INERT RFD-2 GENERATOR

This appendix describes the procedures followed in the assembly of the RFD-2 generator.

A. SUBASSEMBLIES

The complete generator was constructed from four subassemblies: the housing assembly, the core assembly, the top cover assembly, and the bottom cover assembly. Thermocouples were provided with long leads (10 inches beyond the base) to facilitate assembly with the RV adapter section. Leads were identified as indicated in Fig. III-5. Table B-1 presents a complete list of drawings for the generator structure.

The housing assembly consisted of the magnesium housing and 10 thermocouples, T7 through T16. Thermocouple installations are shown in Fig. B-1.

TABLE B-1

Drawing Listing--RFD-2 Generator

<u>Drawing Number</u>	<u>Title</u>
439B0210000	Re-entry Test Model Assembly
439B0210001	Module Assembly
439B0210002	Assembly Procedure
439B0210003	Instrumentation Diagram
439B0210004	Potting Ring
439B0210005	Bottom Cover Assembly
439B0210006	Housing
439B0210007	Top Cover
439B0210008	Switch Bracket and Details
439B0210009	Insulation Discs
439B0210010	Internal Container Assembly
439B0210011	Internal Cylinder Detail

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TABLE B-1 (continued)

<u>Drawing Number</u>	<u>Title</u>
439B0210012	Fuel Block Assembly
439B0210013	Module Bar
439B0210014	Insulation, Module Strip
439B0210015	Piston
439B0210016	Clamp Plate
439B0210017	External Container Assembly
439B0210018	External Tube Details
439B0210019	External Cylinder Details
439B0210020	Spacer
439A1110500	Installation Tool
417-3021040	Capsule Details, Modified
417-3021041	Liner Details, Modified

The core assembly consisted of the foil-wrapped fuel capsules, fuel block, module bars, simulated thermoelectric modules, and associated thermocouples. The assembly procedure was as follows:

- (1) The installation tool was expanded to its fullest extent in preparation for insertion of the core assembly.
- (2) The fuel capsules were wrapped with zirconium foil on the ends and instrumented with Thermocouples T17, T18, T23, and T24 as shown in Fig. B-2.
- (3) The fuel block assembly was then instrumented with Thermocouples T21, T22, T25, and T26.
- (4) The fuel capsules were installed in the fuel block assembly as shown in Fig. B-3.
- (5) The module bar was assembled and instrumented with Thermocouples T19 and T20 as shown in Fig. B-4.
- (6) The module bar was inserted into the insulation module strips.
- (7) The core was assembled, placed in the installation tool, and compressed. The core assembly, compressed in the installation tool, is shown in Fig. B-5.

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Fig. B-1. Generator Housing

Fig. B-2. Internal Fuel Capsules

Fig. B-3. Fuel Block Assembly

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The top cover assembly consisted of the cover and six thermocouples, T1 through T6, attached to the cover per Drawing 439B0210003, as shown in Fig. B-6.

The bottom cover assembly consisted of the cover, three thermocouples, T27 through T29, and four high-temperature limit switches. The switches were attached to the adjustable brackets and were identified as shown on the drawing. Figure B-7 is a photograph of the base assembly.

B. INTEGRATED GENERATOR ASSEMBLIES

The complete generator unit, consisting of four subassemblies, was assembled in the following manner:

- (1) The core assembly was installed into the housing, by means of the installation tool, from the top end of the housing. Care was taken to avoid disturbing the thermocouples, as thermocouple leads extended out of the open bottom of the housing to ten inches from the base.
- (2) The installation tool was removed by adjusting the handles to permit the module assemblies to bear against the housing. The core was aligned so that T7 through T12 and T15 rested in the slot that was machined in one of the module bars. Clearance was provided in the insulation module strips for Thermocouples T8, T10, T13, T14, and T16.
- (3) The thermocouple leads were brought out through the base, and the top assembly was secured in its proper position. Figure B-8 shows a view of the core assembly in the housing, looking from the top, and Fig. B-9 is the view from the bottom.
- (4) An aluminum foil disc was placed on the bottom of the partially assembled generator and was pierced in the appropriate places to bring out the thermocouple leads. The foil was used to restrict the E-300 potting compound from flowing into the upper part of the generator.
- (5) The potting ring was positioned over the switches in the base and secured into place by pouring E-300 potting compound into the void areas surrounding the potting ring.
- (6) E-300 was poured into the base around the periphery of the internal core assembly, leaving room for the assembly of the potting ring when the base was brought into place.

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Fig. B-4. Module Bar Assembly

Fig. B-5. Installation Tool

Fig. B-6. Top Cover Plate

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Fig. B-7. Bottom Cover Plate with
Switch Installation

Fig. B-8. Core Installed in Housing
--Top View

Fig. B-9. Core Installed in Housing
--Bottom View

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- (7) The partially assembled generator and base-potting ring combination was placed into an oven and cured at 250° F for 48 hours.
- (8) Vacuum grease was used around the plungers of the switch to protect the actuation mechanism from becoming damaged by potting compound.
- (9) The base-potting ring was placed in the base of the generator and secured into position. Then, the thermocouples and switch leads were brought out through the three holes in the base of the generator.
- (10) Two additional layers of E-300 were forced into the base openings and cured as before.
- (11) The four switches were adjusted by means of socket head set screws in the cover to make contact with the bottom of each container assembly. Each switch was checked to ensure that it was in the closed-circuit position.
- (12) The operation of the switches was rechecked after the final cure by loosening the base and observing the distance the base moved away from the housing when continuities of the switch circuits were interrupted. This completed the assembly of the generator.

C. INSTALLATION OF THE GENERATOR ON THE RE-ENTRY VEHICLE

The assembled generator was shipped to Sandia Corporation for installation with the adapter package. The adapter contained reference junctions for the thermocouples and was provided with receptacles, wired to the thermoelectric leads and switch leads, for proper interfacing with the telemetry instrumentation in the re-entry vehicle. Figure B-10 shows one of four external capsules attached to the exterior of the generator and carried piggyback during the re-entry.

Figure B-11 shows the protector cage used to surround the generator to protect it during handling.

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Fig. B-10. External Fuel Capsule

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Fig. B-11. Generator Protective Cage

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APPENDIX C
STRUCTURAL ANALYSIS--RFD-2 GENERATOR

This appendix presents dynamic and structural analyses of the RFD-2 generator. The dynamic analysis gives g loadings as a function of frequency based on load data for the prototype vehicle, X-248 (Ref. C-1). Also, the resonant frequencies, in both thrust and transverse planes, for the generator housing were calculated. In the structural analysis, stress levels were calculated for structural components based on load factors and component resonant frequencies. Stress allowables were calculated on the basis of two-thirds material yield stresses at room temperature.

A. MATERIAL PROPERTIES

Structural properties of materials used in the construction of the RFD-2 generator are given below. Unless stated otherwise, values are for ambient conditions.

1. Graphite (Ref. C-2)

Grade-ATJ

Tensile strength, S_t

With grain $S_t = 1790$ psi

Against grain $S_t = 1420$ psi

Compressive strength, S_c

With grain $S_c = 8270$ psi

Against grain $S_c = 8540$ psi

Flexure strength, S_f

With grain $S_f = 4010$ psi

Against grain $S_f = 3580$ psi

Young's modulus, E

With grain, $E = 1.4 \times 10^6$ psi

Against grain, $E = 1.15 \times 10^6$ psi

$\frac{\text{Crushing strength}}{\text{Flexure strength}} \approx 2.07$

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2. Min-K Insulation

Density, ρ

Side panels--20 lb/ft³

Upper disks--28 lb/ft³

3. Magnesium (HM31A-F, extrusion) (Ref. C-2)

Young's modulus, E

$E = 6.5 \times 10^6$ psi

0.2% yield tensile strength, S_t

$S_t = 18,000$ psi

0.2% yield compressive strength, S_c

$S_c = 16,000$ psi

Ultimate strength, S_{ut}

$S_{ut} = 30,000$ psi

4. Magnesium (HM21A-T8, sheet) (Ref. C-2)

Young's modulus, E

$E = 6.5 \times 10^6$ psi

0.2% yield tensile strength, S_t

$S_t = 25,000$ psi

0.2% yield compressive strength, S_c

$S_c = 15,000$ psi

Ultimate strength, S_{ut}

$S_{ut} = 34,000$ psi

5. Titanium (6Al-4V AMS 4911 or 4929, Annealed Bar) (Ref. C-2)

Young's modulus, E

$E = 16.5 \times 10^6$ psi

0.2% yield tensile strength, S_t

$S_t = 120,000$ psi

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Ultimate strength, S_{ut}

$$S_{ut} = 130,000 \text{ psi}$$

6. Aluminum (Al 6063-T5) (Ref. C-3)

Young's modulus, E

$$E = 10.0 \times 10^6 \text{ psi}$$

0.2% Yield tensile strength, S_t

$$S_t = 21,000 \text{ psi}$$

Ultimate strength, S_{ut}

$$S_{ut} = 27,000 \text{ psi}$$

B. DYNAMIC ANALYSIS

1. Load Factors (Ref. C-1)

a. Shock (magnification factor = 2)

Thrust axis only = 60 g

b. Vibration + acceleration (magnification factor = 10)

Longitudinal acceleration = 15 g

Transverse acceleration = 3 g

Sinusoidal swept frequency + acceleration

<u>Axis</u>	<u>Frequency (cps)</u>	<u>Load Factor (g)</u>
Thrust	5	20
	10 to 50	35
	50 to 500	105
	500 to 2000	195
Transverse	5	6
	10 to 50	13
	50 to 500	23
	500 to 2000	43

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Special (sinusoidal + acceleration)

Thrust axis (525 to 625 cps) = 465 g

Transverse axis (525 to 625 cps) = 83 g

2. Resonances of Generator Components

a. Cantilever bending

The generator was assumed to be cantilevered through the attachment of its upper header to a nonyielding backup structure. It was considered as an elastic beam with uniformly distributed mass and constant stiffness. For the cantilver beam,

$$f = c \sqrt{\frac{gEI}{wl^4}}$$

where:

f = resonant frequency (cps)

c = modal constant = 0.56

g = acceleration of gravity = 386 in./sec²

E = modulus of elasticity = 6.5 x 10⁶ psi

w = weight per unit length of beam = 2.038 lb/in.

l = beam length = 9.125 in.

d = shell outside diameter = 5.5 in.

t = shell thickness = 0.093 in.

I = shell moment of inertia (in.⁴)

$$I = \frac{\pi d^3 t}{8} = 6.073 \text{ in.}^4$$

Therefore,

$$f = 582 \text{ cps}$$

b. Generator longitudinal resonance

Resonance of the generator was computed for excitation parallel to the center line. Loads in this plane were considered to be carried by the generator casing. For resonant frequencies,

$$f = \frac{1}{2\pi} \sqrt{\frac{K}{M}}$$

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K = spring constant (lb/in.) = p/δ
 M = mass (lb/sec²/in.) = p/g
 p = load (lb), generator weight $\cong 18.6$ lb
 δ = deflection (in.)
 A = area = $\pi dt = 1.606$ in.²
 ℓ' = generator length = 8.0 in.

Now,

$$E = \frac{p \ell'}{A \delta}$$

Hence,

$$\delta = \frac{p \ell'}{AE}$$

and

$$f = \frac{1}{2\pi} \sqrt{\frac{gAE}{pl'}} = 829 \text{ cps}$$

Stress levels and margins of safety were calculated for the generator components, based on resonant frequencies and corresponding g load factors calculated above.

1. Mounting Bolts

Three 1/4-28 alloy steel bolts Martin/Reference MS 20004.

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a. Geometry

A-A

b. Loading:

Axial--resonant frequency ≈ 829 cps
load factor = $g_v = 195$ g

Lateral--resonant frequency ≈ 582 cps
load factor = $g_H = 83$ g

Stress in mounting bolts:

(1) Due to axial loading

$$\begin{aligned} P_v &= \text{axial load} = \text{gen wt} \times g_v \\ &= 20 (195) \\ &= 3900 \text{ lb} \end{aligned}$$

Since 3 bolts

$$P/\text{bolt} = 1300 \text{ lb}$$

For 1/4 - 28 bolts, A = stress area = 0.0362 in.^2

$$S_t = \text{bolt tensile stress} = \frac{P/\text{bolt}}{A} = 35,912 \text{ psi}$$

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$$S_a = \text{allowable stress} = 2/3 S_{ult} = 2/3 (160,000)$$

$$S_a = 106,720 \text{ psi}$$

$$MS = \text{margin of safety} = \frac{S_a}{S_t} - 1 = 1.97$$

(2) Lateral loading

Load diagram

Loads on Bolt 1

where

$$y = 5-1/16 \text{ in.}, d_1 = 4-1/2 \text{ in.}, d_2 = 1-1/2 \text{ in.}, h = 1/2 \text{ in.}$$

$$r = 0.214 \text{ in. (outside radius under head of } 1/4 \times 28 \text{ internal wrenching hex head bolt)}$$

$$P_v = \text{gen wt} \times g_v = 20 (83) = 1660 \text{ lb}$$

$$R_1 = \frac{M d_1}{\sum n d^2} = \frac{P_v y d_1}{d_1^2 + 2 d_2^2}$$

$$R_1 = 1528 \text{ lb}$$

$$V_1 = \frac{P_v}{3} = 553 \text{ lb}$$

$$R_v = \frac{V_1 h}{r} = 1292 \text{ lb}$$

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Total tensile load in bolt = $P_t = R_1 + R_v = 2820 \text{ lb}$

Shear load in bolt = $V_1 = 553 \text{ lb}$

$S_t = \text{tensile stress} = \frac{P_t}{A} = 77,900 \text{ psi}$

$S_s = \text{shear stress} = \frac{V_1}{A} = 15,280 \text{ psi}$

$S_p = \text{max principal stress} = \frac{S_t}{2} + \sqrt{\left(\frac{S_t}{2}\right)^2 + S_s^2}$
 $= 80,750 \text{ psi}$

MS = margin of safety = $\frac{S_a}{S_p} - 1 = 0.32$

2. Generator Shell

Material--magnesium alloy HM 31A-F

a. Geometry

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2. Loading

Axial--resonant frequency ≈ 829 cps
load factor = $g_V = 195$ g

Lateral--resonant frequency ≈ 582 cps
load factor = $g_H = 83$ g

Min-K preload--the graphite fuel block has layers of Min-K insulation on both upper and lower ends. Upon generator assembly the Min-K is compressed to hold the fuel block in place. This preload was taken as 1000 lb (conservative estimate).

$$D = 5.125 \text{ in.}$$

$$h \approx 4.443 \text{ in.}$$

$$W = \text{gen wt} \approx 20 \text{ lb}$$

$$P_V = W g_V = 3900 \text{ lb}$$

$$P_H = W g_H = 1860 \text{ lb}$$

Stress in shell:

(1) Axial load (P)

$$S_{t_1} = \frac{P_V}{\text{area of shell}} \approx \frac{P_V}{\pi D t}$$

$$S_{t_1} = (\text{tensile stress}) = 2612 \text{ psi}$$

$$S_{t_2} = \text{stress due to Min-K preload} = \frac{1000}{\pi D t}$$

$$S_{t_2} = 668 \text{ psi}$$

$$S_t = \text{total stress} = S_{t_1} + S_{t_2} = 3280 \text{ psi}$$

$$S_a = \text{allowable stress} = \frac{2}{3} S_{t_y} = 12,000 \text{ psi}$$

$$MS = \frac{S_a}{S_t} - 1 = 2.14$$

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(2) Lateral load (P_H)

$$S_b = \text{bending stress} = \frac{MC}{I} \approx \frac{P_H h}{\pi R^2 t}$$

$$S_b = 4310 \text{ psi}$$

$$S_{t_2} = \text{stress due to Min-K preload} \approx 670 \text{ psi}$$

$$S_c = \text{combined stress} = S_b + S_{t_2} = 4980 \text{ psi}$$

$$MS = \frac{S_a}{S_c} - 1 = 1.4$$

3. Flange Bolts

At upper and lower flange there are six 1/4 x 28 UNF bolts made from titanium alloy 6Al-4V.

a. Load diagram and geometry

where

$$P_V = \text{gen wt} \times g_V = 3900 \text{ lb}$$

$$P_H = \text{gen wt} \times g_H = 1860 \text{ lb}$$

$$P_{\text{Min-K}} \approx 1000 \text{ lb}$$

$$h = 4.4375 \text{ in.}, d_1 = 6.594 \text{ in.}, d_2 = 5.023 \text{ in.}, d_3 = 1.883 \text{ in.},$$

$$d_4 = 0.313 \text{ in.}$$

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a. Vertical load

$$S_t = \text{tensile stress} = \frac{p_v + p_{\text{Min-K}}}{g A_B}$$

where

$$A_B = \text{area of } 1/4 - 28 \text{ bolt} = 0.0362 \text{ in.}^2$$

$$S_t = 22,560 \text{ psi}$$

$$S_a = \text{allowable stress} = 2/3 \times S_{t_y} = 2/3 (120,000)$$

$$S_a = 80,000 \text{ psi}$$

$$MS = \frac{S_a}{S_t} - 1 = 2.55$$

b. Lateral load

$$R_1 = \text{load in bolt due to } P_H = \frac{M d_1}{\Sigma d^2}$$

$$R_1 = \frac{P_H n d_1}{d_1^2 + 2d_2^2 + 2d_3^2 + d_4^2} = 540 \text{ lb}$$

$$R_{\text{Min-K}} = \text{load in Bolt 1 due to preload} = \frac{1000}{6} = 167 \text{ lb}$$

$$R_{\text{tot}} = R_1 + R_{\text{Min-K}} = 707 \text{ lb}$$

$$S_t = \text{tensile stress in bolt} = \frac{R_{\text{tot}}}{A_B}$$

$$S_t = 19,530 \text{ psi}$$

$$S_s = \text{shear stress in bolt} = \frac{P_H}{g A_B}$$

$$S_s = 8,564 \text{ psi}$$

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$$S_p = \text{max principal stress} = \frac{S_t}{2} + \sqrt{\left(\frac{S_t}{2}\right)^2 + S_s^2}$$

$$S_p = 22,765 \text{ psi}$$

$$MS = \frac{S_a}{S_p} - 1 = 2.52$$

D. REFERENCES

- C-1. "Recommended Mechanical Environmental Test Levels for Design Qualification and Flight Acceptance Testing of Scout Launched Spacecraft," August 8 1962, Scout Project Group--NASA, LRC.
- C-2. "Air Weapons Materials Handbook Metals and Alloys," ARDC TR 59-66, Air Research and Development Command, U. S. Air Force, December 1959.
- C-3. The Dow Metals Products Company, Catalog 141-227-61.

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APPENDIX D
RFD-2 THERMOCOUPLE RESISTANCE READINGS

The 29 thermocouples utilized in the RFD-2 test generator were checked electrically and thermally prior to assembly and in conjunction with the generator structure to ensure proper system function during the flight test program. Contact checks were made to ensure continuity between thermocouple leads and the component structure to which they were attached. Temperature checks were made with a Brown potentiometer 1-302, ME49665, to ensure thermocouple response to an outside heat source. Also, polarity of each couple was assured after assembly. Resistance readings were taken with a Simpson meter, Model No. 220, 1-169, ME49623 and recorded for the flight unit and its backup. These data are presented in Table D-1

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TABLE D-1

Thermocouple Test Data--RFD-2 Flight Generators

Thermocouple Number	Thermocouple Type	Resistance Record (ohms)				$\Delta\Omega$		Temperature Test		Polarity Check	
		Preassembly		Post Assembly							
		Unit 1	Unit 2	Unit 1	Unit 2	Unit 1	Unit 2	Unit 1	Unit 2	Unit 1	Unit 2
T1	Cr/Al	11.3	11.4	11.0	11.5	-0.3	+0.1	Positive		Positive	
T2	Cr/Al	11.8	11.0	11.6	11.2	-0.2	+0.2				
T3	Cr/Al	10.5	11.1	10.8	11.3	-0.3	+0.2				
T4	Cr/Al	11.5	10.8	11.5	10.9	0	+0.1				
T5	Cr/Al	11.5	11.2	11.6	11.5	+0.1	+0.3				
T6	Cr/Al	11.5	11.2	11.5	11.3	0	+0.1				
T7	Cr/Al	11.2	11.2	11.5	11.4	+0.3	+0.2				
T8	Cr/Al	11.0	11.4	8.0	11.2	-3.0	-0.2				
T9	Cr/Al	11.5	10.8	11.5	10.8	0	0				
T10	Cr/Al	11.8	11.2	11.5	11.1	+0.3	-0.1				
T11	Cr/Al	11.2	11.0	11.0	11.0	+0.2	0				
T12	Cr/Al	12.5	12.0	12.2	12.0	-0.3	0				
T13	Cr/Al	11.2	10.7	11.0	10.8	+0.2	-0.1				
T14	Cr/Al	11.5	12.2	11.3	12.1	+0.2	-0.1				
T15	Cr/Al	11.6	11.0	11.0	10.8	+0.6	-0.2				
T16	Cr/Al	11.5	11.8	11.5	11.8	0	0	Positive		Positive	
T17	Cr/Al	3.4	3.7	3.6	3.7	+0.2	0				
T18	Cr/Al	3.5	3.7	3.6	3.7	+0.1	0				
T19	Cr/Al	11.8	11.2	11.5	11.4	-0.3	+0.2				
T20	Cr/Al	11.8	11.4	11.5	11.5	-0.3	0				
T21	Pt/13% Rh	2.4	3.7	2.4	3.8	0	+0.1				
T22	Pt/13% Rh	2.5	3.7	2.4	3.8	+0.1	+0.1				
T23	Pt/13% Rh	2.7	3.0	3.0	3.2	-0.3	+0.2				
T24	Pt/13% Rh	2.4	2.4	2.4	2.5	0	+0.1				
T25	Pt/13% Rh	3.2	3.8	3.5	3.7	+0.3	-0.1				
T26	Pt/13% Rh	2.8	3.1	2.6	3.2	+0.2	+0.1				
T27	Pt/13% Rh	2.9	2.5	3.0	2.5	+0.1	0				
T28	Pt/13% Rh	2.9	2.5	3.0	2.5	+0.1	0				
T29	Pt/13% Rh	2.2	2.9	2.3	2.9	+0.1	0				

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APPENDIX E

ELEMENTAL DETAILS OF PREFLIGHT ANALYTICAL MODELS

A detailed description of the analytical models used in the preflight study of the RFD-2 generator is given in this section. The sequence of elements chosen to represent the two typical sections cut through the generator are shown in Figs. E-1 through E-4. As was pointed out in Chapter V, each section was divided into two segments. Elemental dimensions are given in Tables E-1 through E-4.

Elemental geometric properties of the external capsules used in the RFD-2 program are given in Table E-5. This information supports data present in the preflight analysis, Chapter V of this report.

TABLE E-1

Elemental Data for Model 1, Section 1

<u>Element</u>	<u>Dimensions</u> <u>W x H (in.)</u>	<u>Element</u>	<u>Dimensions</u> <u>W x H (in.)</u>
1	0.400 x 0.125	9	0.500 x 0.200
2	0.500 x 0.125	10	0.500 x 0.200
3	0.500 x 0.125	11
4	0.500 x 0.125		
5		12	0.400 x 0.187
6	0.400 x 0.200	13	0.500 x 0.187
7	0.500 x 0.200	14	0.500 x 0.187
8	0.500 x 0.200	15	0.500 x 0.187
		16	0.500 x 0.187

TABLE E-1 (continued)

<u>Element</u>	<u>Dimensions W x H (in.)</u>	<u>Element</u>	<u>Dimensions W x H (in.)</u>
17	0.318 x 0.187	46	0.455 x 0.266
18	0.283 x 0.187	47	0.280 x 0.266
19	0.280 x 0.187	48	0.219 x 0.266
20	0.280 x 0.374	49	0.400 x 0.266
21	0.219 x 0.187	50	0.500 x 0.266
22	0.400 x 0.125	51	0.500 x 0.266
23	0.500 x 0.125	52	0.500 x 0.266
24	0.500 x 0.125	53	0.500 x 0.266
25	0.500 x 0.125	54	0.146 x 0.266
26	0.500 x 0.125	55	0.455 x 0.110
27	0.318 x 0.125	56	0.280 x 0.110
28	0.283 x 0.125	57	0.280 x 0.532
29	0.280 x 0.125	58	0.219 x 0.110
30	0.219 x 0.125	59	0.104 x 0.156
31	0.400 x 0.125	60	0.900 x 0.125
32	0.500 x 0.125	61	1.000 x 0.125
33	0.500 x 0.125	62	0.647 x 0.125
34	0.500 x 0.125	63	0.104 x 0.125
35	0.500 x 0.125	64	0.900 x 0.125
36	0.146 x 0.125	65	1.000 x 0.125
37	0.455 x 0.125	66	0.647 x 0.125
38	0.280 x 0.125	67	0.104 x 0.125
39	0.219 x 0.125	68	0.900 x 0.125
40	0.400 x 0.266	69	1.000 x 0.125
41	0.500 x 0.266	70	0.647 x 0.125
42	0.500 x 0.266	71	0.104 x 0.125
43	0.500 x 0.266	72	0.900 x 0.125
44	0.500 x 0.266	73	1.000 x 0.125
45	0.146 x 0.266	74	0.647 x 0.125

TABLE E-1 (continued)

<u>Element</u>	<u>Dimensions W x H (in.)</u>	<u>Element</u>	<u>Dimensions W x H (in.)</u>
75	0.104 x 0.125	104	0.282 x 0.296
76	0.900 x 0.125	105	0.718 x 0.296
77	1.000 x 0.125	106	0.626 x 0.296
78	0.647 x 0.125	107	0.104 x 0.296
79	0.104 x 0.125	108	0.282 x 0.266
80	0.282 x 0.201	109	0.718 x 0.266
81	0.718 x 0.201	110	0.626 x 0.266
82	0.626 x 0.201	111	0.104 x 0.266
83	0.104 x 0.201	112	0.282 x 0.296
84	0.282 x 0.201	113	0.718 x 0.296
85	0.718 x 0.201	114	0.626 x 0.296
86	0.626 x 0.201	115	0.104 x 0.296
87	0.104 x 0.201	116	0.282 x 0.266
88	0.282 x 0.296	117	0.718 x 0.266
89	0.718 x 0.296	118	0.626 x 0.266
90	0.626 x 0.296	119	0.104 x 0.266
91	0.104 x 0.296	120	0.282 x 0.296
92	0.282 x 0.266	121	0.178 x 0.296
93	0.718 x 0.266	122	0.626 x 0.296
94	0.626 x 0.266	123	0.104 x 0.296
95	0.104 x 0.266	124	0.282 x 0.266
96	0.282 x 0.296	125	0.718 x 0.266
97	0.718 x 0.296	126	0.626 x 0.266
98	0.626 x 0.296	127	0.104 x 0.166
99	0.104 x 0.296	128	0.561 x 0.100
100	0.282 x 0.266	129	0.282 x 0.296
101	0.718 x 0.266	130	0.718 x 0.296
102	0.626 x 0.266	131	0.626 x 0.296
103	0.104 x 0.266	132	0.561 x 0.110

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TABLE E-1 (continued)

<u>Element</u>	<u>Dimensions</u> <u>W x H (in.)</u>	<u>Element</u>	<u>Dimensions</u> <u>W x H (in.)</u>
133	0.104 x 0.196	136	0.626 x 0.266
134	0.282 x 0.266	137	0.104 x 0.266
135	0.718 x 0.266		

TABLE E-2

Elemental Data for Model 1, Section 2

<u>Element</u>	<u>Dimensions</u> <u>W x H (in.)</u>	<u>Element</u>	<u>Dimensions</u> <u>W x H (in.)</u>
1	0.062 x 0.187	14	0.718 x 0.235
2	0.491 x 0.187	15	0.626 x 0.235
3	0.491 x 0.187	16	0.104 x 0.235
4	0.135 x 0.187	17	0.062 x 0.296
5	0.718 x 0.187	18	0.186 x 0.296
6	0.626 x 0.187	19	0.186 x 0.296
7	0.104 x 0.187	20	0.135 x 0.296
8	0.062 x 0.238	21	0.718 x 0.296
9	0.271	22	0.626 x 0.296
	23	0.104 x 0.296
10	0.219	24	0.062 x 0.266
	25	0.186 x 0.266
11	0.219	26	0.186 x 0.266
	27	0.135 x 0.266
12	0.271	28	0.718 x 0.266
	29	0.626 x 0.266
13	0.135 x 0.238	30	0.104 x 0.266
		31	0.062 x 0.296
		32	0.186 x 0.296
		33	0.186 x 0.296
		34	0.135 x 0.296

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TABLE E-2 (continued)

<u>Element</u>	<u>Dimensions</u> <u>W x H (in.)</u>	<u>Element</u>	<u>Dimensions</u> <u>W x H (in.)</u>
35	0.718 x 0.296	64	0.626 x 0.296
36	0.626 x 0.296	65	0.104 x 0.296
37	0.104 x 0.296	66	0.062 x 0.266
38	0.062 x 0.266	67	0.186 x 0.266
39	0.186 x 0.266	68	0.186 x 0.266
40	0.186 x 0.266	69	0.135 x 0.266
41	0.135 x 0.266	70	0.718 x 0.266
42	0.718 x 0.266	71	0.626 x 0.266
43	0.626 x 0.266	72	0.104 x 0.266
44	0.104 x 0.266	73	0.062 x 0.296
45	0.062 x 0.296	74	0.186 x 0.296
46	0.186 x 0.296	75	0.186 x 0.296
47	0.186 x 0.296	76	0.135 x 0.296
48	0.135 x 0.296	77	0.718 x 0.296
49	0.718 x 0.296	78	0.626 x 0.296
50	0.626 x 0.296	79	0.104 x 0.296
51	0.104 x 0.296	80	0.062 x 0.266
52	0.062 x 0.266	81	0.186 x 0.266
53	0.186 x 0.266	82	0.186 x 0.266
54	0.186 x 0.266	83	0.135 x 0.266
55	0.135 x 0.266	84	0.718 x 0.266
56	0.718 x 0.266	85	0.626 x 0.266
57	0.626 x 0.266	86	0.104 x 0.266
58	0.104 x 0.266	87	0.458 x 0.100
59	0.062 x 0.296	88	0.062 x 0.296
60	0.186 x 0.296	89	0.186 x 0.296
61	0.186 x 0.296	90	0.186 x 0.296
62	0.135 x 0.296	91	0.135 x 0.296
63	0.718 x 0.296	92	0.718 x 0.296

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TABLE E-2 (continued)

<u>Element</u>	<u>Dimensions W x H (in.)</u>	<u>Element</u>	<u>Dimensions W x H (in.)</u>
93	0.626 x 0.296	122	0.626 x 0.296
94	0.104 x 0.296	123	0.104 x 0.296
95	0.458 x 0.100	124	0.062 x 0.266
96	0.062 x 0.266	125	0.186 x 0.266
97	0.186 x 0.266	126	0.186 x 0.266
98	0.186 x 0.266	127	0.135 x 0.266
99	0.135 x 0.266	128	0.718 x 0.266
100	0.718 x 0.266	129	0.626 x 0.266
101	0.626 x 0.266	130	0.104 x 0.266
102	0.104 x 0.266	131	0.062 x 0.296
103	0.062 x 0.296	132	0.186 x 0.296
104	0.186 x 0.296	133	0.186 x 0.296
105	0.186 x 0.296	134	0.135 x 0.296
106	0.135 x 0.296	135	0.718 x 0.296
107	0.718 x 0.296	136	0.626 x 0.296
108	0.626 x 0.296	137	0.104 x 0.296
109	0.104 x 0.296	138	0.062 x 0.266
110	0.062 x 0.266	139	0.186 x 0.266
111	0.186 x 0.266	140	0.186 x 0.266
112	0.186 x 0.266	141	0.135 x 0.266
113	0.135 x 0.266	142	0.718 x 0.266
114	0.718 x 0.266	143	0.626 x 0.266
115	0.626 x 0.266	144	0.104 x 0.266
116	0.104 x 0.266	145	0.062 x 0.296
117	0.062 x 0.296	146	0.186 x 0.296
118	0.186 x 0.296	147	0.186 x 0.296
119	0.186 x 0.296	148	0.135 x 0.296
120	0.135 x 0.296	149	0.718 x 0.296
121	0.718 x 0.296	150	0.626 x 0.296

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TABLE E-2 (continued)

<u>Element</u>	<u>Dimensions</u> <u>W x H (in.)</u>	<u>Element</u>	<u>Dimensions</u> <u>W x H (in.)</u>
151	0.104 x 0.296	159	0.626 x 0.238
152	0.062 x 0.238	160	0.104 x 0.238
153		161	0.062 x 0.187
		162	0.491 x 0.187
		163	0.491 x 0.187
		164	0.135 x 0.187
154		165	0.718 x 0.187
		166	0.626 x 0.187
		167	0.104 x 0.187
		168	0.104 x 1.240
155		169	0.104 x 1.240
		170	0.939 x 0.281
		171	0.148 x 0.281
		172	0.939 x 0.312
156		173	0.148 x 0.312
		174	0.148 x 0.325
		175	1.191 x 0.312
		176	1.191 x 0.325
157	0.135 x 0.238	177	1.191 x 0.312
158	0.718 x 0.238	178	1.191 x 0.325

TABLE E-3

Elemental Data for Model 2, Section 1

<u>Element</u>	<u>Dimensions</u> <u>W x H (in.)</u>	<u>Element</u>	<u>Dimensions</u> <u>W x H (in.)</u>
1	0.450 x 0.269	5	0.450 x 0.269
2	0.450 x 0.269	6	0.450 x 0.269
3	0.281 x 0.269	7	0.281 x 0.269
4	0.163 x 0.269	8	0.163 x 0.269

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TABLE E-3 (continued)

<u>Element</u>	<u>Dimensions W x H (in.)</u>	<u>Element</u>	<u>Dimensions W x H (in.)</u>
9	0.104 x 0.212	38	0.281 x 0.250
10	0.283 x 0.212	39	0.163 x 0.250
11	0.280 x 0.212	40	0.417 x 0.250
12	0.280 x 0.373	41	0.417 x 0.250
13	0.220 x 0.212	42	0.417 x 0.250
14	0.450 x 0.100	43	0.104 x 0.250
15	0.450 x 0.100	44	0.283 x 0.250
16	0.281 x 0.100	45	0.280 x 0.250
17	0.163 x 0.100	46	0.280 x 0.532
18	0.417 x 0.100	47	0.220 x 0.250
19	0.417 x 0.100	48	0.450 x 0.156
20	0.417 x 0.100	49	0.450 x 0.156
21	0.104 x 0.100	50	0.281 x 0.156
22	0.283 x 0.100	51	0.163 x 0.156
23	0.280 x 0.100	52	0.417 x 0.156
24	0.220 x 0.100	53	0.417 x 0.156
25	0.450 x 0.250	54	0.417 x 0.156
26	0.450 x 0.250	55	0.104 x 0.156
27	0.281 x 0.250	56	0.450 x 0.208
28	0.163 x 0.250	57	0.450 x 0.208
29	0.417 x 0.250	58	0.281 x 0.208
30	0.417 x 0.250	59	0.163 x 0.208
31	0.417 x 0.250	60	0.417 x 0.208
32	0.104 x 0.250	61	0.417 x 0.208
33	0.283 x 0.250	62	0.417 x 0.208
34	0.280 x 0.250	63	0.104 x 0.208
35	0.220 x 0.250	64	0.450 x 0.208
36	0.450 x 0.250	65	0.450 x 0.208
37	0.450 x 0.250	66	0.281 x 0.208

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TABLE E-3 (continued)

<u>Element</u>	<u>Dimensions</u> <u>W x H (in.)</u>	<u>Element</u>	<u>Dimensions</u> <u>W x H (in.)</u>
67	0.163 x 0.208	96	0.417 x 0.311
68	0.417 x 0.208	97	0.104 x 0.311
69	0.417 x 0.208	98	0.281 x 0.311
70	0.417 x 0.208	99	0.163 x 0.311
71	0.104 x 0.208	100	0.417 x 0.311
72	0.450 x 0.208	101	0.417 x 0.311
73	0.450 x 0.208	102	0.417 x 0.311
74	0.281 x 0.208	103	0.104 x 0.311
75	0.163 x 0.208	104	0.281 x 0.311
76	0.417 x 0.208	105	0.163 x 0.311
77	0.417 x 0.208	106	0.417 x 0.311
78	0.417 x 0.208	107	0.417 x 0.311
79	0.104 x 0.208	108	0.417 x 0.311
80	0.281 x 0.311	109	0.104 x 0.311
81	0.163 x 0.311	110	0.281 x 0.311
82	0.417 x 0.311	111	0.163 x 0.311
83	0.417 x 0.311	112	0.417 x 0.311
84	0.417 x 0.311	113	0.417 x 0.311
85	0.104 x 0.311	114	0.417 x 0.311
86	0.281 x 0.311	115	0.104 x 0.311
87	0.163 x 0.311	116	0.281 x 0.311
88	0.417 x 0.311	117	0.163 x 0.311
89	0.417 x 0.311	118	0.417 x 0.311
90	0.417 x 0.311	119	0.417 x 0.311
91	0.104 x 0.311	120	0.417 x 0.311
92	0.281 x 0.311	121	0.104 x 0.311
93	0.163 x 0.311	122	0.281 x 0.311
94	0.417 x 0.311	123	0.163 x 0.311
95	0.417 x 0.311	124	0.417 x 0.311

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TABLE E-3 (continued)

<u>Element</u>	<u>Dimensions</u> <u>W x H (in.)</u>	<u>Element</u>	<u>Dimensions</u> <u>W x H (in.)</u>
125	0.417 x 0.311	142	0.417 x 0.200
126	0.417 x 0.311	143	0.417 x 0.200
127	0.104 x 0.311	144	0.417 x 0.200
128	0.281 x 0.311	145	0.104 x 0.200
129	0.163 x 0.311	146	0.459 x 0.200
130	0.417 x 0.311	147	0.281 x 0.311
131	0.417 x 0.311	148	0.163 x 0.311
132	0.417 x 0.311	149	0.417 x 0.311
133	0.104 x 0.311	150	0.417 x 0.311
134	0.281 x 0.311	151	0.417 x 0.311
135	0.163 x 0.311	152	0.104 x 0.311
136	0.417 x 0.311	153	0.281 x 0.311
137	0.417 x 0.311	154	0.163 x 0.311
138	0.417 x 0.311	155	0.417 x 0.311
139	0.104 x 0.311	156	0.417 x 0.311
140	0.281 x 0.200	157	0.417 x 0.311
141	0.163 x 0.200	158	0.104 x 0.311

TABLE E-4

Elemental Data for Model 2, Section 2

<u>Element</u>	<u>Dimensions</u> <u>W x H (in.)</u>	<u>Element</u>	<u>Dimensions</u> <u>W x H (in.)</u>
1	0.250 x 0.187	8	0.104 x 0.187
2	0.491 x 0.187	9	0.250 x 0.238
3	0.491 x 0.187	10	
4	0.200 x 0.187		
5	0.376 x 0.187		
6	0.376 x 0.187		
7	0.376 x 0.187

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TABLE E-4 (continued)

<u>Element</u>	<u>Dimensions</u> <u>W x H (in.)</u>	<u>Element</u>	<u>Dimensions</u> <u>W x H (in.)</u>
11		31	0.200 x 0.538
12		32	0.376 x 0.538
13		33	0.376 x 0.538
14	0.200 x 0.238	34	0.376 x 0.538
15	0.376 x 0.238	35	0.104 x 0.269
16	0.376 x 0.238	36	0.104 x 0.269
17	0.376 x 0.238	37	0.250 x 0.538
18	0.104 x 0.238	38	0.186 x 0.538
19	0.250 x 0.538	39	0.186 x 0.538
20	0.186 x 0.538	40	0.200 x 0.538
21	0.186 x 0.538	41	0.376 x 0.538
22	0.200 x 0.538	42	0.376 x 0.538
23	0.376 x 0.538	43	0.376 x 0.538
24	0.376 x 0.538	44	0.104 x 0.269
25	0.376 x 0.538	45	0.104 x 0.269
26	0.104 x 0.269	46	0.250 x 0.538
27	0.104 x 0.269	47	0.186 x 0.538
28	0.250 x 0.538	48	0.186 x 0.538
29	0.186 x 0.538	49	0.200 x 0.538
30	0.186 x 0.538	50	0.376 x 0.538
		51	0.376 x 0.538
		52	0.376 x 0.538
		53	0.104 x 0.269
		54	0.104 x 0.269
		55	0.250 x 0.538
		56	0.186 x 0.538
		57	0.186 x 0.538
		58	0.200 x 0.538
		59	0.376 x 0.538

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TABLE E-4 (continued)

<u>Element</u>	<u>Dimensions</u> <u>W x H (in.)</u>	<u>Element</u>	<u>Dimensions</u> <u>W x H (in.)</u>
60	0.376 x 0.538	89	0.104 x 0.269
61	0.376 x 0.538	90	0.104 x 0.269
62	0.104 x 0.169	91	0.250 x 0.538
63	0.104 x 0.169	92	0.186 x 0.538
64	0.250 x 0.200	93	0.186 x 0.538
65	0.186 x 0.200	94	0.200 x 0.538
66	0.186 x 0.200	95	0.376 x 0.538
67	0.200 x 0.200	96	0.376 x 0.538
68	0.376 x 0.200	97	0.376 x 0.538
69	0.376 x 0.200	98	0.104 x 0.269
70	0.376 x 0.200	99	0.104 x 0.269
71	0.104 x 0.200	100	0.250 x 0.538
72	0.458 x 0.200	101	0.186 x 0.538
73	0.250 x 0.538	102	0.186 x 0.538
74	0.186 x 0.538	103	0.200 x 0.538
75	0.186 x 0.538	104	0.376 x 0.538
76	0.200 x 0.538	105	0.376 x 0.538
77	0.376 x 0.538	106	0.376 x 0.538
78	0.376 x 0.538	107	0.104 x 0.269
79	0.376 x 0.538	108	0.104 x 0.269
80	0.104 x 0.269	109	0.250 x 0.312
81	0.104 x 0.269	110	0.186 x 0.312
82	0.250 x 0.538	111	0.186 x 0.312
83	0.186 x 0.538	112	0.200 x 0.312
84	0.186 x 0.538	113	0.376 x 0.312
85	0.200 x 0.538	114	0.376 x 0.312
86	0.376 x 0.538	115	0.376 x 0.312
87	0.376 x 0.538	116	0.104 x 0.156
88	0.376 x 0.538	117	0.104 x 0.156

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TABLE E-4 (continued)

<u>Element</u>	<u>Dimensions</u> <u>W x H (in.)</u>	<u>Element</u>	<u>Dimensions</u> <u>W x H (in.)</u>
118	0.250 x 0.238	127	0.104 x 0.238
119		128	0.250 x 0.187
	129	0.491 x 0.187
120		130	0.491 x 0.187
	131	0.200 x 0.187
121		132	0.376 x 0.187
	133	0.376 x 0.187
122		134	0.376 x 0.187
	135	0.104 x 0.187
123	0.200 x 0.238	136	0.104 x 0.620
124	0.376 x 0.238	137	0.104 x 0.620
125	0.376 x 0.238	138	0.104 x 0.620
126	0.376 x 0.238	139	0.104 x 0.620
		140	0.938 x 0.281
		141	0.938 x 0.312
		142	0.148 x 0.281
		143	0.148 x 0.312
		144	0.148 x 0.325
		145	1.190 x 0.312
		146	1.190 x 0.325
		147	1.190 x 0.312
		148	1.190 x 0.325

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TABLE E-5
Element Geometric Properties

<u>Model</u>	<u>Element</u>	<u>R_T</u>	<u>R_U</u>	<u>A_T</u>	<u>A_U</u>	<u>V</u>
50 H	1	0.42	0.37	2.638	2.324	0.12409
	2	0.37	0.32	2.324	2.01	0.1083
	3	0.32	0.27	2.01	1.696	0.0926
50 H6T	1	0.42	0.37	2.638	2.324	0.12409
	2	0.37	0.364	2.324	2.286	0.0138
	3	0.364	0.314	2.286	1.972	0.1064
	4	0.314	0.264	1.972	1.658	0.0907
50 H12T	1	0.42	0.37	2.639	2.325	0.12409
	2	0.37	0.358	2.325	2.249	0.02733
	3	0.358	0.308	2.249	1.935	0.10474
	4	0.308	0.258	1.935	1.621	0.08891
50 H20T	1	0.44	0.39	2.765	2.45	0.13038
	2	0.39	0.37	2.45	2.325	0.04775
	3	0.37	0.32	2.325	2.011	0.10839
	4	0.32	0.27	2.011	1.696	0.09268

Note: Definition of Symbols:

R = radius (in.)

A = element surface area normal to heat flow (in.²)

V = element volume (in.³)

Subscripts

T = element top with respect to heat flow direction. Thus, top of element is where heat enters

U = element bottom with respect to heat flow.

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	20			5	4	3	2	1
			11	10	9	8	7	6
21	19	18	17	16	15	14	13	12
30	29	28	27	26	25	24	23	22
39	38	37	36	35	34	33	32	31
48	47	46	45	44	43	42	41	40
58	56	55	54	53	52	51	50	49
	57		59	62	61		60	
			63	66	65		64	
			67	70	69		68	
			71	74	73		72	
			75	78	77		76	
			79	82	81	80		
			83	86	85	84		
			87	90	89	88		
			91	94	93	92		
			95	98	97	96		
			99	102	101	100		
			103	106	105	104		
			107	110	109	108		
			111	114	113	112		
			115	118	117	116		
			119	122	121	120		
			123	126	125	124		
			127	131	130	129		
			128	136	135	134		
			132					
			133					
			137					

Fig. E-1. Model 1 Section 1 Element Configuration, Section A-A,
Fig. V-4

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	7	6	5	4	3		2		1	
	16	15	14	13	12	11	10	9	8	
	23	22	21	20	19				18	17
	30	29	28	27	26				25	24
	37	36	35	34	33				32	31
	44	43	42	41	40				39	38
	51	50	49	48	47				46	45
	58	57	56	55	54				53	52
	65	64	63	62	61				60	59
	72	71	70	69	68				67	66
	79	78	77	76	75				74	73
	86	85	84	83	82				81	80
87										
95										
	94	93	92	91	90			89	88	
	102	101	100	99	98			97	96	
	109	108	107	106	105			104	103	
	116	115	114	113	112			111	110	
	123	122	121	120	119			118	117	
	130	129	128	127	126			125	124	
	137	136	135	134	133			132	131	
	144	143	142	141	140			139	138	
	151	150	149	148	147			146	145	
	160	159	158	157	156	155	154	153	152	
	167	166	165	164	157	163		162		
	168									
	169									
170	171									
172	173	175			177					
	174	176			178					

Fig. E-2. Model 1 Section 2 Element Configuration, Section A-A,
Fig. V-4

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	12						4	3	2	1
13	11	10	9				8	7	6	5
24	23	22	21	20	19	18	17	16	15	14
35	34	33	32	31	30	29	28	27	26	25
47	45	44	43	42	41	40	39	38	37	36
	46		55	54	53	52	51	50	49	48
			63	62	61	60	59	58	57	56
			71	70	69	68	67	66	65	64
			79	78	77	76	75	74	73	72
			85	84	83	82	81	80		
			91	90	89	88	87	86		
			97	96	95	94	93	92		
			103	102	101	100	99	98		
			109	108	107	106	105	104		
			115	114	113	112	111	110		
			121	120	119	118	117	116		
			127	126	125	124	123	122		
			133	132	131	130	129	128		
			139	138	137	136	135	134		
		146	145	144	143	142	141	140		
			152	151	150	149	148	147		
			158	157	156	155	154	153		

Fig. E-3. Model 2, Section 1 Element Configuration, Section B-B,
Fig. V-4

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	8	7	6	5	4	3		2		1	
	18	17	16	15	14	13	12	11	10	9	
	26	25	24	23	22	21				20	19
	27										
	35	34	33	32	31	30				29	28
	36										
	44	43	42	41	40	39				38	37
	45										
	53	52	51	50	49	48				47	46
	54										
	62	61	60	59	58	57				56	55
	63										
72	71	70	69	68	67	66				65	64
	80	79	78	77	76	75				74	73
	81										
	89	88	87				85	84	83	82	
	90										
	98	97	96	95	94	93				92	91
	99										
	107	106	105	104	103	102				101	100
	108										
	116	115	114	113	112	111				110	109
	117										
	127	126	125	124	123	122	121	120	119	118	
	135	134	133	132	131	130		129		128	
	136										
	137										
	138										
	139										
140		142									
141		143	145			147					
	144		146			148					

Fig. E-4. Model 2 Section 2 Element Configuration, Section B-B,
Fig. V-4

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APPENDIX F

MATERIAL PROPERTIES

Material properties used in the RFD-2 Study are given below:

Material	Density, ρ (lb/in. ³)	Tempera- ture, T (°R)	Thermal Conductivity, K (Btu/in. -sec-°R)	Emissivity, ϵ	Enthalpy, J (Btu/lb)
Magnesium	0.064	500	1.85×10^{-3}	0.2	405
		673	1.85×10^{-3}		
		853	1.87×10^{-3}		
		1123	1.90×10^{-3}		
		1580			
		1790	2.05×10^{-3}		
		2280		0.2	800
Steel	0.281	250		0.05	274
		500	1.74×10^{-4}	0.08	
		750	1.99×10^{-4}	0.09	
		1000	2.22×10^{-4}	0.09	
		1250	2.41×10^{-4}	0.1	
		1500	2.64×10^{-4}	0.15	
		1750	2.92×10^{-4}	0.25	
		2000	3.21×10^{-4}	0.4	
		2250	3.52×10^{-4}	0.54	309
		2500	3.84×10^{-4}	0.6	343
		3200	4.7×10^{-4}	0.77	439
Aluminum	0.0978	100			2.25
		400	3.15×10^{-3}	0.36	45.5
		600	2.96×10^{-3}		87.7
		1000	2.69×10^{-3}		190.0
		1300	2.52×10^{-3}	0.39	270.0

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Material	Density, ρ (lb/in. ³)	Temperature, T (°R)	Thermal Conductivity, K (Btu/in. -sec-°R)	Emissivity, ϵ	Enthalpy, J (Btu/lb)
Aluminum		1600	2.45×10^{-3}		345.0
		1678		0.414	365.8
		1678			535.8
		1800	2.52×10^{-3}	0.42	575.0
Aluminum oxide	0.1447	200	3.0×10^{-4}	0.77	
		600	1.97×10^{-4}	0.67	55.8
		1200	8.3×10^{-5}	0.49	
		1400	6.0×10^{-5}	0.44	
		1800	3.8×10^{-5}	0.34	
		2000	3.6×10^{-5}		426.4
		2400	3.9×10^{-5}		
		2600		0.26	
		3200		0.26	801.1
		3600	4.4×10^{-5}		
		4160			1121
		4160			9173
		4400	4.4×10^{-5}	0.29	9300
Haynes-25	0.33	0	1.0×10^{-4}	0.8	0
		1000	2.17×10^{-4}		100
		1750			200
		2000	3.42×10^{-4}		
		2400			300
		3030			416
		3030			526
		3200	4.5×10^{-4}	0.8	
		4000			600

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Material	Density, ρ (lb/in. ³)	Temperature, T (°R)	Thermal Conductivity, K (Btu/in.-sec-°R)	Emissivity, ϵ	Enthalpy, J (Btu/lb)
Tantalum	0.598	500	8.33×10^{-4}	0.85	
		1000	8.80×10^{-4}		
		2000	9.71×10^{-4}	0.79	
		3000	1.04×10^{-3}	0.77	
		5000	1.16×10^{-3}	0.71	
		5870			269
		5870			2115
		6500	1.18×10^{-3}	0.67	2143
		7000		0.65	
Fiberfrax	0.0111	500		0.7	76.3
		700			111.8
		1000	9.5×10^{-7}	0.7	179.8
		1500	14.4×10^{-7}		316.5
		2000	19.7×10^{-7}		467
		2500	26.5×10^{-7}		626
		3000	34.5×10^{-7}		790
		3500	42.5×10^{-7}		951

Graphite:

Density, $\rho = 0.0582 \text{ lb/in.}^3$

Thermal conductivity, K (Btu/sec-in.-°R)

$$K = 0.29604 \times 10^{-2} - 0.18017 \times 10^{-5} T + 0.4844 \times 10^{-9} T^2 - 0.4607 \times 10^{-13} T^3$$

Emissivity, $\epsilon = 0.8$

$$E = -0.0423 + 0.10426 \times 10^{-2} T - 0.236 \times 10^{-6} T^2 - 0.143 \times 10^{-10} T^3$$

Enthalpy, J (Btu/lb)

$$T = 534.2 + 2.6794 J - 0.2136 \times 10^{-3} J^2$$

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Min K:

Density, $\rho = 0.011574 \text{ lb/in.}^3$

Thermal conductivity, K (Btu/sec-in. -°R)

$K = 0.245 \times 10^{-6} + 0.20125 \times 10^{-9} T$

Emissivity, $\epsilon = 0.2$

Enthalpy, J (Btu/lb)

$T = 295.5 + 3.6934 J$

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WIND-3283-2