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SNAP 17A SYSTEM SAFETY
PHASE I FINAL SUMMARY REPORT
PART 2

MND-3307-33-1 (pt. 2)

August 1964

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ERRATA

Page

4. 2 Paragraph 4, line 1 reads ". . . Section 4. 4. 1. 5"; change to read ". . . Section 4. 4. 4. 3".
4. 69 Paragraph 5, line 1 underline "Trajectory".
Paragraph 6, line 5 reads "Appendix R-4"; change to read "Appendix R, Table R-5".
4. 75 Paragraph 1, line 9 reads "Appendix R-1"; change to read "Appendix R-A".
4. 76 Item (1), line 3 reads "... or "; change to read "... and".
Item (2), line 4 reads "... Appendix R-5"; change to read "... Appendix R-A".
Item (3), line 7 reads "... Appendix R-5"; change to read "... Appendix R-E".
4. 78 Paragraph 2, line 2 reads "... Appendix R-6"; change to read "... Appendix R-F".
4. 82 Paragraph 3, line 13 , insert "(Ref. 4.68)" after "Orbital Flight Handbook".
4. 108 Figure 4.76 reads " $\begin{matrix} H & V \\ \text{Top} & \text{Bottom} \end{matrix}$ "; change to read " $\begin{matrix} V & H \\ \text{Top} & \text{Bottom} \end{matrix}$ ".
4. 124 Paragraph 2, line 9 reads "... Lampoc"; change to read "... Lompoc".
4. 125 Paragraph 3, line 2 reads "... Lampoc"; change to read "... Lompoc".
4. 131 Paragraph 2, line 10 reads "... decreased"; change to read "... decreases".
4. 135 Paragraph 8, line 5 reads "... (Ref. 4.21)"; change to read "... (Ref. 4.24)".
4. 146 Line 3 reads "... (Ref. 4.4.2)"; change to read "... (Ref. 4.45)".
Equation 1 and legend reads "... μ "; change to read "... u".
4. 147 Equation 2 reads "... μ "; change to read "... u".

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- 4.148 Lines 2 and 3 read ". . . Lampac"; change to read ". . . Lompoc".
The table reads "Cg"; change to read "Cy".
- 4.149 Paragraph 3, line 25 reads ". . . (from Ref. 4.43)"; change to read ". . . (from Ref. 4.42)".
- 4.150 In tables, it reads ". . . Lampac"; change to read ". . . Lompoc".
- 4.155 Line 9 reads ". . . (Ref. 4.46 and 4.46)", change to read ". . . (Refs. 4.45 and 4.46)".
Paragraph 2, line 11 reads ". . . in"; change to read ". . . in."
- 4.158 Equations need brackets as follow
- $$A_2 = \frac{k_1 A_o}{k_2 - k_1} \left[e^{-(k_1 + \lambda)t} - e^{-(k_2 + \lambda)t} \right]$$
- $$A_3 = \frac{A_o}{k_2 - k_1} \left[k_1 e^{-(k_2 + \lambda)t} - k_2 e^{-(k_1 + \lambda)t} + (k_2 - k_1) e^{-\lambda t} \right]$$
- 4.161 Paragraph 3, line 12 reads ". . . 28"; change to read ". . . 280".
- 4.167 Add "R" to upper right hand drawing on radial arrow.
- 4.177 Table 4.23 reads "(Btu/fr-°F-hr)"; change to read "(Btu/ft-°F-hr)".
- 4.179 Paragraph 2, line 3 reads ". . . onductivity", change to read ". . . conductivity".
- 4.181 Paragraph 6, line 2 reads ". . . (Fig. 4.111)"; change to read ". . . (Fig. 4.114)".
- 4.205 Paragraph 6, line 2 reads ". . . burned"; change to read ". . . buried".
- 4.206 Paragraph 4, line 3 reads ". . . contain the shield"; change to read ". . . contain and shield".

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- 4.209 Paragraph 7, line 6 reads ". . . beheath"; change to read ". . . beneath".
- R-1 Paragraph 2, line 2 reads ". . . oblate"; change to read ". . . spherical".
- R-6 Line 5 reads " $q \times k$ "; change to read " $\dot{q}_{inf}$ ".
Line 6 reads " q_{c+r} "; change to read " $\dot{q}_{c+r}$ ".
- R-13 Line 4 add $R_e = \text{Btu/ft}^2\text{-hr-}^\circ\text{F}$
 $D_o = \text{ft}$
 $K = \text{Btu/ft-}^\circ\text{F-sec}$
 $G = \text{lb/ft}^2\text{-sec}$
 $\mu = \text{lb/ft-sec}$
 $C_p = \text{Btu/lb-}^\circ\text{F}$
Paragraph 1, line 3 reads ". . . external"; change to read ". . . internal".
Paragraph 1, line 4 delete ". . . according to the re-entry trajectory".
- S-1 Paragraph 1, line 5 reads ". . . favorable"; change to read ". . . favorable".
- S-2 Primary heading and paragraph 1, line 1 reads ". . . spiney"; change to read ". . . spiny".

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FOREWORD

This report has been prepared by Martin-Nuclear under U. S. Atomic Energy Commission Contract AT(30-1)-3307 and in conformance with the Phase I requirements of the Statement of Work of the contract. This document, in conjunction with those listed, furnishes:

- (1) A report of the design and development effort accomplished under the Phase I program.
- (2) Specifications to govern design fabrication, test and delivery of prototype equipment.
- (3) A development plan for accomplishing a two-phase program to produce nuclear fueled, thermoelectric power supplies for flight tests.

This series of reports consists of the following.

Volume No.	Title
MND-3307-33-1 Part 1	SNAP 17A System, Phase I Final Summary Report
MND-3307-33-1 Part 2	SNAP 17A System, Safety-- Phase I Final Summary Report
MND-3307-33-2	SNAP 17A System, Phases II and III Development Plan
MND-3307-33-3	SNAP 17A System, Specifi- cations
MND-3307-33-4	SNAP 17A System, Costs-- Phases II and III.

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ACKNOWLEDGMENTS

The major technical contributions to Part 2 of the technical volume were made by:

C. Riggs	General Nuclear Safety
R. Anderson	Aerothermal Analyses
R. Miskuff	Fuel Capsule Impact Test
L. Tolchinsky	Fuel Capsule Materials Study
J. Himes	Design of Capsules and Test Equipment

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4.1

4.0 NUCLEAR SAFETY

This volume considers the influence of nuclear safety on the design of the SNAP 17A radioisotopic thermoelectric generator for an earth-orbiting satellite. It assesses quantitative, configuration criteria, and material selection consistent with the fundamental philosophy that the general public not be exposed to undue hazards in the course of fabrication, transportation, launch, and ultimate disposition of the strontium-90 fuel.

The first objective is to delineate the nuclear hazards and define an approach, based on experience and analysis, which is capable of satisfying the fundamental philosophy during each of the mission phases. Following this, several criteria, procedures, and countermeasures were formulated that were necessary to mitigate or eliminate the severity of each potentially hazardous event, subject to the provisions of the safety approach.

The final objectives are to evolve a preliminary design for the generator system which meets design safety criteria and performance criteria for the generator, and to demonstrate, in detail, that the design is consistent with the safety criteria.

The four sections on safety include: the safety approach and derived criteria; general safety, in which the environmental conditions and hazards concomitant with activity release are evaluated; aerothermodynamic analysis--the effect upon the fuel capsules in all possible configurations when re-entering the atmosphere; and fuel containment, dealing primarily with capsule design and material selection as it relates to earth impact, seawater corrosion, oxidation, and sublimation.

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4.1 SAFETY APPROACH AND DESIGN CRITERIA

The fundamental criteria established refer to hazards resulting from the exposure of humans, directly or indirectly, to ionizing radiation. This exposure may be a consequence of the external aggregation of a substantial quantity of radioisotope or through ingestion of significantly smaller quantities. Therefore, the safety approach is that there must be precluded, within reasonable probability limits during all phases of the MACS mission, the deposition of activity in excess of a maximum permissible concentration in the lower atmosphere and in the biosphere.

A satisfactory approach is one which, in the event of deposition of large activity concentrations on land masses, allows total recovery of fuel within an interval which is short compared with a characteristic time for exposure of individuals to the activity. For impact on water, a satisfactory approach allows for total recovery of the fuel, in a short time interval as previously defined, in the case of shallow water deposition, or the fuel must remain intact in deep water until great depths are reached.

A satisfactory approach is one that affords containment in the event that the location of the fuel is known or is predictable. "Known," in this sense, must be precise in the case of land masses or shallow water regions but may be general in the case of deep water. The MACS and RTG, however, are to be inserted in a 5000-mile orbit. In the event of orbital decay during the mission lifetime or prior to the time at which the activity content of the system is negligible, the location of the impact point would be unknown and unpredictable. Simply containing the fuel in the case of orbital decay, therefore, would not satisfy requirements.

An alternative approach which is sufficient in the case of orbital decay is one which affords burnup of the fuel, leaving the residual fuel in a particulate dispersion at altitudes in excess of 100,000 feet. It is shown in Section 4.4.1.5 that, if particles have a maximum size on the order of one micron, the radiological hazard owing to the ultimate settling of such particulate to the lower atmosphere and the earth's surface is negligible, taking into account direct radiation, surface contamination, and particle inhalation.

A satisfactory safety approach for the overall MACS mission may be defined in a twofold manner: the containment system of the RTG will be designed so the fuel remains contained in the event of abort or accident leading to return of the fuel to the surface of the earth prior to orbital insertion; in the event of re-entry subsequent to orbital insertion, the containment system will be designed so as to be aero-

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thermodynamically consumed in the upper atmosphere in a manner which precludes violation of the fundamental safety philosophy.

It should be clear that the adoption of the intact and burnup approaches entails a contradiction during the ascent trajectory-orbital insertion phase of the mission. An objective of the safety analysis which follows is to show that the transition from intact re-entry to the burnup mode entails no significant violation of the fundamental philosophy.

Having specified the nuclear safety approach, design criteria consistent with this approach and applicable to each phase during the mission lifetime may be enumerated. The specific nuclear safety design criteria are as follows:

- (1) Shipment of radioisotopic fuel shall be in accordance with applicable Federal, State, and Local regulations
- (2) Occupational radiation exposures shall be governed by AECM Chapter 0550 and 0524.
- (3) The design objective of fuel containment provisions shall be to provide for absolute containment of the fuel under all credible missile abort induced conditions. It is recognized, however, that the mission may result in one exception to this, namely, a partial burnup zone. For all conditions, the generator housing assembly may be considered for containment purposes, provided it is clearly shown in the safety analysis that such a consideration is realistic.
- (4) The fuel capsule shall contain the fuel when subjected to the most stringent condition of terminal free fall velocity impact against a granite surface. The generator housing assembly may be considered for containment purposes provided it is clearly shown in the safety analysis that such a consideration is realistic.
- (5) The generator system shall be designed in such a manner as to permit exposure of the radioactive fuel at an altitude of approximately 200,000 feet during orbital re-entry. The radiobiological effect upon the environment due to dispersal of the fuel above 100,000 feet shall be shown to be acceptably low.
- (6) The integrity of the fuel capsule (corrosion resistance) shall be maintained to permit adequate time for sea recovery operations in the event the capsule is impacted within recoverable sea depths.

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- (7) In the event of fuel capsule submergence in seawater to depths beyond possible sea recovery, it is desirable that fuel containment be maintained to assure that the radiobiological effect upon the environment will be acceptably low.
- (8) Partial burnup zone associated with high velocity, preorbital re-entry shall be over deep sea ocean areas.

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4.2 FUEL CONTAINMENT DEVELOPMENT

A primary objective of the first phase of the safety has been to assist in the development of a practical design of a fuel containment structure which meets the safety criteria set out in the preceding section. To this end, analyses and experiments have been carried out on the configuration of the fuel containment and the selection of material for the capsule. Extensive tests have been carried out in developing the optimum weld design and procedure, keeping in mind that the welding must be performed remotely in a hot cell environment.

4.2.1 Container Requirements

The development of a fuel capsule for the SNAP 17A, satisfying both the design requirements and the established safety criteria, requires that all major factors influencing fuel containment must be evaluated.

The capsule must survive all credible handling and launch accidents. These require assurance that containment can be maintained for impact on a granite surface at free fall terminal velocity, earth burial, launch pad propellant detonation and fire, and exposure to seawater for at least one year.

The mission plan calls for exposure of the radioactive fuel by aerothermodynamic processes at an altitude of approximately 200,000 feet during orbital re-entry. This imposes somewhat contradictory requirements on the configuration of the fuel capsule, but these have been reconciled in the design.

The containment material must be chemically compatible with the isotope fuel form.

To enhance the facility and safety of handling and remote fueling of the generator in the launch vehicle, the configuration of the fuel capsule and generator assembly must be considered.

The weld design and welding procedures must be developed to facilitate safe operation within the hot cell. Closely associated with this is a requirement for practical and safe fueling in the hot cell and cleaning after welding.

4.2.2 Configuration

During the preliminary study of the SNAP 17A, an investigation was made to determine the most feasible fuel capsule design. Different fuel core assemblies, employing from one to six fuel capsules, were con-

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sidered. After analyzing all designs, it was decided that the six-capsule design would be the most feasible with respect to re-entry burnup and earth impact. The one-capsule design allows a reduction in weight, but the capsule release altitude required for complete capsule burnup is much higher than for the six-capsule design, and the impact characteristics for the six-capsule design are more favorable than those of the one-capsule design.

The design of the capsule for each configuration was initially based upon experimental information from previous test programs (Refs. 4.1 and 4.2). The end caps and the mating section of the cylindrical portion have been designed so as to allow the impact energy to flow into the side-wall of the capsule, without overstressing the mating area, by eliminating the major stress riser in the design. In addition, end caps have been designed with a truncated conical external surface to provide a self-centering mechanical guide for remote assembly, thereby simplifying assembly procedures.

The end cap for the single capsule is a truncated conical shape selected to reduce weight. This design provides an effective means for transmitting impact energy to the side wall without overstressing the weld area with large bending moments.

Haynes-25 has been initially selected from several materials as the most promising fuel capsule material. The materials evaluation study is presented in Section 4.2.3.

The use of a capsule inner liner to increase the long-term corrosion resistance in seawater was considered, but was found to be unnecessary. Haynes-25 is conservatively estimated to have a corrosion rate in seawater of 0.1 mil per day (Ref. 4). Thus, for the thinnest wall proposed, 80 mils, the fuel capsule will provide containment for two to three years. The chemical compatibility of possible liner materials with the radioisotope fuel is also examined in the following section.

4.2.3 Material Selection and Evaluation

4.2.3.1 Fuel Capsule Material

A review of the potential fuel capsule materials was conducted to determine what materials may perform best for the isotopic fuel containment. The basic material properties of interest were:

- (1) Impact and tensile strength in the temperature range of 1600° to 1750° F.
- (2) Oxidation resistance.
- (3) Fabricability.

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TABLE 4.1

Properties of Some Superalloys
(data taken at 1600° F, except where specified)

Alloy and Heat Treatment	Tensile Ultimate (psi)	Tensile Yield (psi)	Charpy Impact (ft-lb)	Weldability	Machinability	High Temperature Oxidation Resistance
Haynes-25 (solution treated)	41,000	39,000	120.0	Good	Good	Good
Hastelloy C (solution treated)	56,000	45,000	NA*	Good	Good	Good
Rene 41 (aged)	90,000	80,000	NA	Satisfactory	Good	Satisfactory
Waspaloy (aged)	76,000	75,000	NA	Poor	Poor	Satisfactory
Udimet 500 (aged)	85,000	66,000	NA	Poor	Poor	Satisfactory
Udimet 700 (aged)	102,000	92,000	NA	Poor	Poor	Satisfactory
Hastelloy X (solution treated)	30,000	25,000	58.0 (1500° F)	Good	Good	Excellent

*Not available

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The materials considered were:

- (1) Haynes-25
- (2) Hastelloy C
- (3) René 41
- (4) Waspaloy
- (5) Udimet 500 and 700
- (6) Hastelloy X

Available data shown in Table 1 indicate that Haynes-25 is the best overall fuel capsule material, but René 41 and Hastelloy C are also being considered as backup materials. A limited Charpy impact program was performed for the Martin Company and Haynes Stellite to ascertain the impact strengths of René 41, Hastelloy C, and Haynes-25 at 1600° F. The results are shown in the following letter from the Union Carbide Corporation.

4.2.3.2 Liner Material

Should a launch abort occur, the capsule will most likely fall into the sea. If the capsule falls into shallow water, release of the fuel may be hazardous; consequently, a material is needed with good seawater corrosion resistance to allow time for reasonable recovery efforts. In the event the capsule cannot be recovered, the material will be required to resist corrosion for a long enough period of time to permit reasonable recovery attempts. Because the superalloy offers a less-than-adequate combination of strength and corrosion resistance, it may be advantageous to use a thin inner liner of highly corrosion-resistant material which is not required to support the impact loads.

Two materials best suited for this purpose are pure tantalum and titanium, which are essentially inert to seawater. Compatibility of these materials with the isotopic fuel is discussed in the next section.

4.2.3.3 Material Evaluation

Compatibility of Pure Tantalum and Titanium with Sr-90 Isotopic Fuel. An experiment was conducted to establish whether the proposed inner liner materials, tantalum and titanium, were chemically compatible with the Sr-90 isotopic fuel. Figure 4.1 shows the composite used for the test.

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4.9

UNION CARBIDE CORPORATION

STELLITE DIVISION

GENERAL OFFICE, KOKOMO, INDIANA 46901

July 9, 1964

Martin-Marietta Corporation
Martin Company
Baltimore 3, Maryland

Attention: Mr. F. J. Linardi
Mail No. 714

Subject: Purchase No. 4E-4483
Our No. 99849

Gentlemen:

Listed below are test results which we relayed to your Mr. John Mueller on June 29, 1964, by telephone.

The data shown below are the results of the 1600°F Charpy V-notched impact tests as ordered on subject purchase order:

<u>Alloy</u>	<u>Condition</u>	<u>Foot-Pounds</u>
HAYNES alloy No. 25	-	50, 50, 50
HAYNES alloy No. 25	Welded	56, 63, 64
HASTELLOY alloy C	Welded	18, 25, 18
Rene' 41	Welded	22, 14, 21

The specimens were prepared by the Martin-Marietta Corporation. The test procedure followed was (1) charge into a 1650°F furnace, (2) hold for 10 minutes after furnace stabilizes, (3) remove and place on anvil, and (4) break after predetermined cooling interval. No unusual circumstances were noted.

Our invoice, as well as the broken specimens, will be forwarded under separate cover.

Very truly yours,

STELLITE DIVISION

A. J. Ortstadt

AJO:ps

CC: Mr. John Mueller
Mail No. 727

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Fig. 4.1. Compatibility Composite

The composite shown in Fig. 4.1 was placed in a Burrell open air furnace for 25 hours at 1700° F. After removing the capsule from the furnace, it was opened, and the specimens were removed and microscopically examined. Figure 4.2 shows that a reaction occurred with the titanium but not with the tantalum. This clearly indicates that tantalum is the preferred material for the capsule liner from a compatibility viewpoint.

Compatibility of Haynes-25, Hastelloy C, and René 41 with Sr-90 Isotopic Fuel. In the event that an inner liner of tantalum should be unnecessary, the isotopic fuel will be in direct contact with the capsule. Because of this possibility, an experiment similar to the one previously described was conducted to establish whether the proposed fuel capsule materials were chemically compatible with the Sr-90 isotopic fuel. The composite used for the test was similar to that shown in Fig. 4.1. The composite was placed in a Burrell open air furnace for 200 hours at 1800° F. After removing the composite from the furnace, it was opened and the specimens were microscopically examined. Table 4.2 shows the extent of surface effects on the materials in terms of the metallographically determined depth from the surface at which diffusion or reaction products can be detected.

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Mag 75X

Mag 75X

Fig. 4.2. Comparison of Titanium and Tantalum Compatibility Specimens

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TABLE 4.2

Depth of Reaction Detected in Proposed Container Materials

<u>Material</u>	<u>Depth of Reaction (in.)</u>
Haynes-25	0.001
Hastelloy C	0.001
René' 41	0.0025

It is seen that all three materials react to some degree with the Sr-90 fuel. Because the test was qualitative in nature, further work will be performed to establish the depth of penetration quantitatively.

Stability of Haynes-25 and Its Oxide. An experiment was conducted with the proposed fuel capsule material, Haynes-25, to determine whether Haynes-25 oxide will vaporize or flake off during operation in space. Retention of this oxide is desirable to maintain containment and to obtain the proper fuel capsule emissivity at 1700° to 1800° F. The minimum design emissivity of 0.7 cannot be achieved with unoxidized Haynes-25.

The cap of a Haynes-25 capsule was held in an open furnace at 2200° F for one hour, at which time the oxidation rate had stabilized. It was then weighed and placed in a Brew Vacuum furnace at 1800° F for 11 hours. The highest vacuum that can be obtained in this furnace is 1×10^{-5} torr, which does not approach the ultra high vacuum encountered in space. Nevertheless, even at this relatively poor vacuum, very little of the oxide coating was retained and the base metal was thermally etched (see Fig. 4.3).

Because of the thermal etching that occurred on the Haynes-25 cap, an experiment was conducted to establish the rate of vaporization of unoxidized Haynes-25 at 1750° F and 1×10^{-5} torr. The investigation was initiated to determine how much of the fuel capsule would be lost due to vaporization during the five-year mission life of the generator. The results of the study are given in Table 4.3. The same specimen was used in all three runs. As can be seen from the data, the rate of vaporization continually decreased. This is an indication that some constituent in the alloy, probably chromium, with its relatively high vapor pressure, is being preferentially vaporized. It should be understood that, because the ultrahigh vacuum encountered in space cannot be easily simulated, vaporization rates obtained experimentally will be slightly low.

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Fig. 4.3. Haynes-25 End Cap After Removal from Brew Vacuum Furnace
(dark areas are remaining patches of oxide)

TABLE 4.3
Capsule Material Vaporization Losses

<u>Material</u>	<u>Time of Run (hr)</u>	<u>Rate of Vaporization (gm/cm²/hr)</u>	<u>Anticipated 5-Year Loss (gm/cm²)</u>	<u>Approximate Penetration in 5 Years (in.)</u>
Haynes-25 (first run)	30	1.83×10^{-5}	0.80	0.033
Haynes-25 (second run)	30	0.44×10^{-5}	0.19	0.008
Haynes-25 (third run)	64	0.25×10^{-5}	0.11	0.005

A theoretical consideration of the vaporization rates of the primary elements in Haynes-25 is given in Table 4.4. Rate of evaporation was calculated by the Langmuir equation, $R = 206.9P \frac{M}{T}$

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where

- R = rate of evaporation ($\text{gm}/\text{cm}^2/\text{hr}$)
 M = molecular weight of element
 T = temperature ($^{\circ}\text{K}$)
 P = vapor pressure of element at $T^{\circ}\text{K}$

TABLE 4.4
 Evaporation Rate of Haynes-25 Constituents According
 to Langmuir Equation

<u>Pure Element</u>	<u>Wt % in Alloy</u>	<u>R at 1750° F ($\text{gm}/\text{cm}^2/\text{hr}$)</u>
Cr	20	1.70×10^{-5}
Ni	10	0.18×10^{-5}
Co	50	0.014×10^{-5}
W	15	Nil

It is difficult to compare Tables 4.3 and 4.4 because Haynes-25 alloy undoubtedly contains certain impurities which may be quite volatile at 1750° F. However, it may reasonably be assumed that the more volatile constituents would boil off the surface first, leaving a surface rich in cobalt and nickel. The evaporation rate would, therefore, ultimately approach that of cobalt. The experimental data presented in Table 4.3 tend to substantiate this and indicate that the evaporation rate will become almost insignificant after the first loss. Dalton's partial pressure law does not apply to the data because the experimental runs were made in a chamber that was continuously being pumped down. Dalton's law applies to a closed system.

If one considers the vacuum encountered in space as being analogous to a dynamic vacuum, such as exists in the vacuum furnace, then the data obtained in the Brew furnace can be considered as being representative of the worst conditions that would exist in the case of the fuel capsule. Actually, the fuel capsule and its immediate surroundings can be envisioned as a dynamic vacuum system and the likelihood of the metal vapors being pumped out of the system and into the relative freedom of space are the same as that of a residual gas atom being pumped out of a closed vacuum system. There is one basic difference however. In the case of a gaseous atmosphere in a closed vacuum

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system, there is a fixed number of gas molecules to start with; in the case of the fuel capsule material, there is in a sense an inexhaustible supply of metal vapor atoms being liberated at the surface of the heated capsule. The problem is a complex one and not readily amenable to treatment by simple formulae.

A study is presently under way to develop a capsule coating that will not only minimize evaporation of the capsule material in space but also provide the proper emissivity for the fuel capsule. Various carbides, borides, silicides, and oxide coatings will be investigated, along with methods of applying the coating to the capsule without grossly affecting the mechanical properties of the substrate. Preliminary work so far indicates that development of a coating that will meet all of the requirements will be a difficult task.

4.2.4 Fabrication and Fueling

4.2.4.1 Weld Development, Series A

A weld study was initiated to develop a weld specification for the proposed SNAP 17A fuel capsules. Wall thicknesses of 0.100, 0.125, and 0.150 in. were studied.

Material	Haynes-25
Initial weld process	Automatic TIG (no filler rod), sealed chamber filled with Argon gas at one atmosphere
Initial joint design	End cap butted to barrel
Initial weld position	Horizontal, capsule in vertical position with electrode horizontally positioned

The initial weld technique was dictated by the equipment that would be available during the actual welding of the capsule in the hot cell, that is, no automatic wire feeding apparatus is incorporated in the hot cell weld operation, which necessitated a butt joint design. This technique was subsequently changed due to an inability to reliably obtain 100% weld penetration in the 0.150-inch wall capsule and also prevent blowout. The weld position of the capsule was changed to the horizontal with the electrode located in a vertical orientation to effect 100% penetration. Little additional penetration was actually obtained in this position, due to a tendency for the molten puddle to flow down around the seam and overhang. (Haynes-25 has a very low surface tension just above its melting point.) Prior to changing the weld position of the capsule, it was decided to weld "out of chamber" with a conventional heliarc torch. This more closely simulated the actual

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welding operation in the hot cell. It was also found that the use of helium shielding gas resulted in a cleaner weld bead and more consistent penetration around the seam.

To get 100% weld penetration, it was decided to chamfer both the end cap and barrel, thus forming a V groove (120° groove x one-half the thickness of the barrel wall). This joint design requires a filler pass, which at this time is not feasible in the hot cell operation. The addition of an automatic wire feed system for the hot cell operation is now being studied.

4.2.4.2 Capsule Fabrication

The following steps describe the fabrication procedure for the SNAP 17 fuel capsule:

- (1) Tack weld the bottom cap to the barrel (3 or 4 spots).
- (2) Automatically TIG weld (no filler rod) the bottom cap to barrel.
- (3) Allow capsule assembly to cool as much as possible before making fill passes.
- (4) Fuel the capsules.
- (5) Weld top end cap as in Steps 1, 2, and 3.

4.2.5 Capsule Quality Control

During Phase I, quality control verification was made of the test capsule details, assemblies, and welding operations to ensure a high quality test capsule, in accordance with quality procedures that would be implemented on the flight line fuel capsules.

Listed are specific check points and actual drawing requirements that were verified:

- (1) All purchase orders placed for raw material as specified on capsule drawings have been reviewed by Quality Control to assure that the applicable approved Material Specification is applied. Quality requirements for test reports from supplier and proper coding to assure receipt of material to the Nuclear control area. Assure that the supplier is on approved buyer's list.
- (2) Upon receipt of all material, Quality Control performs receiving inspections, functions which include identification

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checks, visual, dimensional, test report verification to specific requirement of applicable specification against subject material. Random samples of materials are pulled to be verified in the Quality Control laboratory.

- (3) The raw material is pulled from stock and by specified detail assigned to an Assembly Traveler, which is a controlled work order assuring a quantity of details to be fabricated to the applicable drawing called out on the Assembly Traveler. Quality checks the raw material visually, dimensionally, and for identification. It is stamped in applicable block indicating verification of effort.
- (4) The verified raw material and Assembly Traveler (including a copy of applicable drawing) are forwarded to the fabrication area, where a Quality inspector performs required inspection applicable to the specific items, such as spacer, end capsule, assembly, etc.
- (5) Upon completion of inspection of all requirements on the drawing, the inspector stamps in applicable block, indicating inspection complete and an item verified to the applicable Engineering requirements.
- (6) Quality performs, as applicable to specified approved processes, inspections of weld, dye penetrant checks, X-rays, etc. Assures that all equipment and/or facilities have been calibrated within active calibration period.
- (7) Documentation is maintained and a permanent record is on file.

4.2.6 Impact Test Program

The objectives of the fuel capsule impact test program were to evaluate significant design parameters, and to develop a feasible fuel capsule design. Appropriate terminal velocities, temperatures, angle of impact, etc., were used in the tests.

Experience gained on previous impact test programs in capsule design, testing methods, capsule support, and specimen heating was utilized in the SNAP 17A impact test program. To achieve the optimum fuel capsule design, the impact test program was subdivided into three series. Each test series consisted of the impact test, an analysis of the test results, and fuel capsule design modifications based on the test results. This method of testing permitted a broad investigation into the design parameters and offered a logical sequence in selecting the final fuel capsule design.

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The impact test program included an evaluation of five fuel capsule designs and three fuel containment materials.

4.2.6.1 Test Program Formulation

A major consideration in the program formulation was the determination of the temperature and velocity for all abort conditions where the fuel capsule would impact the earth. The fuel capsules were assumed to be released at various points along the ascent trajectory. A total of five abort points was considered; later aborts would result in partial burnup of the fuel capsule prior to impact (see Fig. 4.4 and Table 4.5).

The objective of the fuel capsule impact test was to evaluate different fuel capsule designs and to determine a feasible fuel capsule design that would comply with the nuclear safety design criteria. Basically, the fuel capsule must contain the radionuclide under all earth impact conditions.

To test the earth impact effects, design parameters (weld, shape, etc.), and the impact characteristics of a particular design, the test was subdivided into three test series.

Series A. Initial study of macroscopic impact effects and test design parameters to establish the most severe test conditions and to reduce the number of design parameters.

Series B. Fuel capsule testing, based on Series A, to determine optimum design parameters and establish a feasible fuel capsule design.

Series C. Development test of the fuel capsule design in Series B to evaluate the feasible design.

Due to the nature of this program, a continuous test firing schedule could not be achieved. Information developed in each test series affected the design and manufacture of the specimens (fuel capsule) to be tested in the next series. The interim period between test series was limited to the time required for data reduction, design change, manufacture, fabrication, and instrumentation.

The turnaround method of impact testing was employed in which a target of large mass compared to the test specimen is impacted against the stationary specimen. This test method provides a conservative approach to the design of the fuel capsule and was employed because it affords several advantages over other techniques (direct testing), for example:

- (1) Better control of the specimen impact temperature.
- (2) Fuel capsule impact angle variance capability.

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Fig. 4.4. $T_0 = 1700^{\circ}\text{F}$, Capsule Impact Temperature Study ($^{\circ}\text{F}$)

TABLE 4.5

Fuel Capsule Impact Velocity and Temperature as a Function of Altitude

<u>Abort Conditions</u>			<u>Impact Altitudes</u>								
Time from Launch (sec)	Altitude (ft)	Velocity (fps)	<u>5000 feet</u>		<u>3000 feet</u>		<u>1000 feet</u>		Sea Level Velocity (fps)	<u>Capsule</u>	
			Velocity (fps)	Temper- ature (°F)	Velocity (fps)	Temper- ature (°F)	Velocity (°F)	Temper- ature (°F)		Small	Large
10	420	121	--	--	--	--	--	--	168 ¹	X	
20	3,028	335	--	--	192	1520	239	1402	239 ²	X	
30	7,424	555	257	1350	251	1258	246	1210	241 ²	X	
50	23,370	1,059	262	970	252	930	248	900	241 ²	X	
50 ³	23,370	1,059	378	1437	367	1420	357	1407	348 ²		X
180	416,718	13,358	--	--	--	--	--	--	--	X	

1. Terminal velocity not yet achieved.
2. Terminal velocity achieved.
3. Large capsule.

TABLE 4.5 Fuel Capsule Impact Velocity and Temperature as a Function of Altitude

- (3) Multicapsule test per firing.
- (4) Better fuel capsule instrumentation.

A theoretical evaluation of impact testing, using the conventional method of propelling the test specimen into a target and the turn-around method of propelling the target against the test specimen, was made to show that the two methods of testing are compatible. The theoretical study shows that the tests are compatible, with no significant change in the test results. Impact tests substantiated the results obtained from the theoretical study. A detailed description of the analysis and laboratory tests for both methods of testing is presented in Appendix P.

A temperature profile was made of the six-capsule design to obtain the heatup time required and the cooldown rate after the heaters are removed. Figure 4.5 gives the time increments for heating the capsule, and Fig. 4.6 shows the cooldown rates.

4.2.6.2 Test Facility

The test program was conducted at Aberdeen Proving Ground (APG), Aberdeen, Maryland. The APG rocket sled facility was used to propel the target into the test capsules. The facility consists of a dual-rail track 2448 feet long, a specially designed rocket sled, and velocity measuring equipment. The rocket sled, illustrated in Fig. 4.7, is affixed to the track by replaceable aluminum shoes which permit easy installation. The targets are rigidly mounted on the sled by an angle iron frame: the frame permits easy installation and removal of the targets. A schematic of the test facility, equipment, instrumentation, and fuel capsule is presented in Fig. 4.8.

Two fuel capsules were tested with each rocket firing, providing identical test conditions for better comparison. The capsules were suspended over the track in the direct path of the moving target by 31-gauge Nichrome wire. The capsules were heated to their normal generator operating temperature prior to impact by an array of quartz lamps. The heaters were then electromechanically removed from around the capsule prior to impact (see Fig. 4.8). The temperature of the capsule is recorded until the instant of impact by a chromel-alumel thermocouple. Both technical (high speed data) and documentary cameras were used to record the impact event. A fuel capsule recovery facility was constructed to catch the impacted fuel capsule and to minimize any postimpact or secondary impact effects upon the capsule.

Fig. 4.5. Mean Capsule Temperature During Heating--Nominal Diameter 1.5 In.

Fig. 4.6. Mean Capsule Wall Temperature During Cool-Down--Nominal Diameter 1.5 In.

Fig. 4.7. Rocket Sled Used for the SNAP 17A Impact Test

Fig. 4.8. Capsule Impact Test Setup

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For a detailed description of the track equipment, prefiring, firing and postfiring events see Appendix Q.

4.3.6.3 Test Specimen

The initial six-capsule design was developed from past experience on other SNAP programs and from conditions imposed by the SNAP 17A program. See Fig. 4.9 for the six-capsule design and Fig. 4.10 for the one capsule design.

The capsules are welded and fueled as described in detail in Section 4.2.6.6. A thermocouple is attached to the capsule with Sauereisen cement over the thermocouple to ensure a true temperature reading.

4.2.6.4 Test Development

Since it is necessary to appraise the integrity of the fuel capsule design when subjected to impact forces, a high velocity impact test program was developed. After the design parameters were established and the test specimens fabricated and instrumented, an experimental impact test program was carried out to evaluate the fuel capsule design.

The purpose of this impact test program is to determine the degree of damage and possible mode of failure of the test specimens. The test parameters are established by the fuel capsule configuration, which determines the terminal impact velocity and corresponding impact temperature. Granite was chosen as the target material, since little momentum is transferred to the granite from the impacted specimen; therefore, most of the energy is available to deform the specimen. Granite represents a typical rigid material on which the specimen might impact.

4.2.6.5 Test Data Reduction

All capsules were first checked for surface cracks, using a fluorescent penetrant technique (zyglo). This test is a sensitive, nondestructive way of detecting minute discontinuities that are open to the surface, such as cracks. The procedure consists of applying fluorescent liquid penetrant, which enters into discontinuities. The excess penetrant is then removed and the specimen is viewed under ultraviolet radiation or black light. Minute amounts of the penetrant seeping back out through cracks or pores fluoresces, thus making these discontinuities visible. Penetrant is often circled in emerging from discontinuities by the application of a thin, powdery film of developer material, which acts as a blotter. Lines indicate cracks or similar discontinuities. The spread of an indication gives a rough evaluation of the size of the discontinuity beneath the surface. Of necessity, inspection is confined to surfaces.

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Fig. 4.9. Six-Capsule Design

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Fig. 4.10. One-Capsule Design

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The fluorescent penetrant test was followed by a helium pressure test to determine if any of the impacted capsules had ruptured.

The procedure for the pressure test is as follows:

- (1) Three capsules are placed in a tube-like chamber.
- (2) The chamber is sealed, and helium gas is then introduced until the chamber pressure is 400 psi. This pressure is maintained for 20 minutes.
- (3) A valve on the chamber is then opened which allows the helium to escape rapidly and reduce the chamber pressure to one atmosphere.
- (4) The capsules are removed from the chamber as fast as possible and immersed in alcohol.
- (5) If any ruptures are present in the capsules, they are made visible by the bubbling action in the alcohol caused when the helium gas which entered the capsules through the ruptures escapes. If the rupture is too large, the helium will escape during the interval required to remove the capsule from the chamber and submerge in the alcohol.

Following this test, all capsules are sectioned through ruptured or impacted areas for metallographic examination. Information from the test is analyzed and capsule design modifications are made.

4.2.6.6 Impact Test Results

As pointed out in the test program, the impact tests were subdivided into three series. This method of testing permitted varying the design parameters to optimize the selection of a feasible fuel capsule design. The test plan is shown in Fig. 4.11 along with the test parameters.

Series A. The fuel capsule design, as shown in Fig. 4.9, was welded using the following procedure:

A penetration pass was made on the bottom end cap using these parameters:

- (1) Weld position--capsule assembly horizontally positioned with electrode in flat, or down-hand, orientation. Electrode is stationary while assembly rotates.
- (2) Joint design--120-degree V-groove by 1/2 the thickness of the barrel wall

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Impact Test Parameters				
Series	Material	Temperature (°F)	Velocity (fps)	Impact Angle (deg)
Series A (14 capsules)	Haynes 25	850 1350 1600	250	0 45 90
Series B (14 capsules)	Haynes 25	850 1350	250	0 45
Series C (8 capsules)	Haynes 25 Hastelloy C Hastelloy N	1200	221	45

WT = wall thickness

Fig. 4-11. Impact Test Plan

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(3) Weld process--automatic TIG, no filler rod.

<u>Wall Thickness (in.)</u>	<u>Amperage</u>	<u>Voltage</u>	<u>Rotation Time (sec)</u>
0.150 (3-inch OD)	125	15.5	60
0.150 (1.44-inch OD)	105	14.5	22
0.125 (1.39-inch OD)	95	13.0	22
0.100 (1.34-inch OD)	85	12.0	22

The top end cap penetration pass was made, using the same procedure as for the bottom end cap, with a slight modification of the groove as described in the next paragraph.

An immediate problem encountered while welding the top end cap was a tendency for the molten weld metal to blow out at the closure point of the weld. This phenomenon was caused by the inability of the hot air inside the capsule to escape as the welding of the seam progressed. The internal pressure was developed as the gas expanded due to the welding arc heat. This difficulty was eliminated by grinding a small slot in the land of the barrel, which allowed the air inside the capsule to bleed off until final closure was made. The weld was begun 1/4 inch to the side of the slot, with the slot itself welded shut at the end of the weld.

The TIG fill pass on both end caps was made manually, using 1/16-inch Haynes-25 filler rod. No facilities are currently available for automatic wire feeding. This method of wire feeding will be necessary in the hot cell operation, since the fuel capsule will contain radioactive material. Weld settings used for the manual fill pass were 75 amperes and 11 volts. Approximately 2.5 inches of 1/16-inch rod were consumed per groove inch.

The simulated fuel for the Series A test specimens was anhydrous barium chloride, BaCl_2 . The fuel material was heated to approximately 1050°C to melt the BaCl_2 . The simulated fuel was poured directly into the fuel capsules. While the initial charge was still molten, additional BaCl_2 was added to make the complete charge.

The impact test capsules for Series B and C were filled with a simulated fuel (inert strontium fluoride) using a pellet-pressing technique. The fuel material was calcined in air at 1100°C for 16 hours. After calcining, the fuel material was ball milled for approximately one hour to crush and grind the material preparatory to pellet pressing. Pellets of the simulated fuel were pressed at 40 tsi. Four pellets were

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placed end-to-end to make up the final desired fuel height for each test series. The pellets were then machined, as a group, to a diameter of 1.200 inches and inserted into the fuel capsules. The fabrication process is illustrated in Figs. 4.12 through 4.17.

The Series A impact test was initiated using the test parameters shown in Table 4.6. Figures 4.18 and 4.19 show the impact event for the fuel capsules used in both the six-capsule design and one-capsule design. Photographs were taken of the Series A impacted test specimens to show the deformation inflicted by different angles of impact and the damage attributed by secondary impact (see Figs. 4.20 through 4.27). A summary of the zygló and pressure test results are given in Table 4.7. Macrographs were taken of the sectioned test specimens to show the structural effects caused by impact (see Figs. 4.28 through 4.39). The two macrographs in each figure are from the same capsule. The impacted or damaged end of each capsule was cut off and then cut down the center through the impacted area. The weld areas are shown 180 degrees apart. The test parameters (velocity, temperature, angle of impact) used for the Series A test specimens are shown on the individual macrographs.

An investigation of the test results revealed the following:

- (1) Weld penetration for Capsule 3 was poor. This was attributed to the fact that the end cap had accidentally shifted while in the holding fixture during welding.
- (2) All capsules showed a tendency to crack at the interface between the capsule wall and the locating step in the end cap which is used for locating the cap in the barrel. It was evident from the macrographs that the locating step had not been fused to the cylinder wall, thereby resulting in a stress riser which initiated a crack in the weld area.
- (3) The impact energy is distributed more evenly in the six-capsule design than in the one-capsule design.
- (4) Spacer was omitted in the impacted end of Capsule 8.

Based on the test results, the following recommendations are made:

- (1) Examination of sectioned impact specimens indicate that the ratio of end cap thickness to capsule wall thickness should be approximately 2.0 for maximum energy absorption with the present end cap configuration. (This ratio was 1.66 for the failed specimen previously discussed.)

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Fig. 4.12. Fuel Capsule Before Fabrication

Fig. 4.13. Machining of Fuel Core

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Fig. 4.15. Capsule Before Final Closure

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Fig. 4.16. Final Welding

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Fig. 4.17. Completed Fuel Capsule

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Fig. 4.18. Impact Event of the Six-Capsule Design--Capsule Impacted on a 45-Degree Angle

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Fig. 4.19. Impact Event of the One-Capsule Design--Capsule Impacted on a 45-Degree Angle

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Fig. 4.20. Six-Capsule Design

Fig. 4.21. Six-Capsule Design

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Fig. 4.22. Six-Capsule Design

Fig. 4.23. Six-Capsule Design

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Fig. 4.24. Six-Capsule Design

Fig. 4.25. Six-Capsule Design

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Fig. 4.26. Six-Capsule Design

Fig. 4.27. Capsule 15A and 16A--Wall Thickness, 0.150 In.; Temperature, 1335° F; Angle at Impact, 15A at 0 Deg, 16A at 45 Deg; Velocity, 367 fps; Haynes 25

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Fig. 4.28. Capsule 2A--Wall Thickness, 0.150 In., Temperature, 1590° F, Angle at Impact, 45 Deg; Velocity, 259 fps; Haynes 25

Fig. 4.29. Capsule 3A--Wall Thickness, 0.150 In., Temperature, 1565° F, Angle at Impact, 0 Deg; Velocity, 257 fps, Haynes 25

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Fig. 4.30. Capsule 4A--Wall Thickness, 0.15 In.; Temperature, 1570° F; Angle at Impact, 90 Deg; Velocity, 265 fps; Haynes 25

Fig. 4.31. Capsule 5A--Wall Thickness, 0.150 In.; Temperature, 1600° F; Angle at Impact, 45 Deg; Velocity, 259 fps; Haynes 25

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Fig. 4.32. Capsule 6A--Wall Thickness, 0.150 In.; Temperature, 1345° F; Angle at Impact, 15 Deg; Velocity, 260 fps; Haynes 25

Fig. 4.33. Capsule 7A--Wall Thickness, 0.100 In.; Temperature, 1590° F; Angle at Impact, 0 Deg; Velocity, 259 fps; Haynes 25

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Fig. 4.34. Capsule 8A--Wall Thickness, 0.100 In.; Temperature, 1605° F; Angle at Impact, 45 Deg; Velocity, 259 fps; Haynes 25

Fig. 4.35. Capsule 9A--Wall Thickness, 0.100 In.; Temperature, 1580° F; Angle at Impact, 90 Deg; Velocity, 265 fps; Haynes 25

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Fig. 4.36. Capsule 10A--Wall Thickness, 0.100 In.; Temperature, 1345° F; Angle at Impact, 45 Deg; Velocity, 260 fps; Haynes 25

Fig. 4.37. Capsule 12A--Wall Thickness, 0.100 In.; Temperature, 850° F; Angle at Impact, 45 Deg; Velocity, 260 fps; Haynes 25

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Fig. 4.38. Capsule 13A--Wall Thickness, 0.125 In.; Temperature, 1575° F; Angle at Impact, 0 Deg; Velocity, 257 fps; Haynes 25

Fig. 4.39. Capsule 14A--Wall Thickness, 0.125 In.; Temperature, 850° F; Angle at Impact, 45 Deg; Velocity, 260 fps; Haynes 25

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TABLE 4.6
Series A Impact Test Parameters

Capsule Number	Capsule Design	Wall Thickness (in.)	Welded Length (in.)	Capsule ID (in.)	Fuel/Total (gm)	Sled Weight at Impact (lb)	Temperature (°F)	Angle at Impact (deg)	Velocity (fps)
1	6 capsule	0.150	Capsule used for temperature profile						
2	6 capsule	0.150	7.244	1.207	357/1077	824.34	1590	45	259
3	6 capsule	0.150	7.234	1.207	329/1048	821.90	1565	0	257
4	6 capsule	0.150	7.249	1.207	350/1067.5	825.20	1570	90	265
5	6 capsule	0.150	7.244	1.207	355/1084.5	836.44	1600	45	259
6	6 capsule	0.150	7.248	1.207	351.5/1074	836.39	1345	15 Approx	260
7	6 capsule	0.100	7.252	1.207	356/855.5	836.44	1590	0	259
8	6 capsule	0.100	7.243	1.207	320.5/804	824.34	1605	45	259
9	6 capsule	0.100	7.254	1.207	349.5/846.5	825.20	1580	90	265
10	6 capsule	0.100	7.246	1.207	350.5/848	836.39	1345	45	260
11	6 capsule	0.100	7.242	1.207	342.5/844	Spare capsule			
12	6 capsule	0.100	7.241	1.207	323.5/823.5	837.79	850	45	260
13	6 capsule	0.125	7.234	1.207	329.5/946	821.90	1575	0	257
14	6 capsule	0.125	7.252	1.207	351/963.5	837.79	850	45	260
15	6 capsule	0.150	7.482	2.758	1919/4178	757.58	1335	0	367
16	1 capsule	0.150	7.488	2.758	1934/4199	757.58	1335	45	367

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TABLE 4.7
Series Zyglo and Pressure Test Results

<u>Capsule No.</u>	<u>Wall Thickness (in.)</u>	<u>Angle at Impact (deg)</u>	<u>Zyglo Test</u>	<u>Pressure Test</u>
2A	0.150	45	No surface cracks	No leak
3A	0.150	0	Crack in weld at impacted end	Leaked
4A	0.150	90	No surface cracks	No leak
5A	0.150	45	No surface cracks	No leak
6A	0.150	15	No surface cracks	No leak
7A	0.100	0	No surface cracks	No leak
8A	0.100	45	Crack in weld at impacted end	Leaked
9A	0.100	90	No surface cracks	No leak
10A	0.100	45	No surface cracks	No leak
12A	0.100	45	No surface cracks	No leak
13A	0.125	0	No surface cracks	No leak
14A	0.125	45	No surface cracks	No leak
15A	0.150	0	No surface cracks	No leak
16A	0.150	45	Capsule ruptured at impact	

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- (2) Modify the locating step in the end cap to eliminate the stress riser.
- (3) Reduce the cylinder wall thickness to ensure more energy absorption in the cylinder.

Series B. Because of the excess stress concentration created by the locating step in the end cap, it was decided to minimize the length of the step in the Series B capsules, thereby increasing the probability of getting the weld nugget to fuse the entire interface. In addition to shortening the locating step, the weld lands were reduced to 30 mils on all capsules. The thinner land made it easier to penetrate to the interface on the initial root pass. Concurrent with the change in the dimensions in the V groove joint, weld parameters also had to be adjusted.

Series B Weld Parameters

<u>Wall Thickness (in.)</u>	<u>Amperage</u>	<u>Voltage</u>	<u>Rotation Time (sec)</u>
0.080	60	11.5	26
0.100	70	12.5	26
0.125	80	13.5	26

Aside from changes in the weld parameters, the Series B capsules were welded using the procedure established for Series A; that is, a TIG root pass with no filler rod, followed by a manual fill pass.

Some difficulty was encountered during the manual fill pass. Because the weld land was thinner (0.030 inch) than for Series A, it was more difficult to prevent burning through the root pass while filling the groove. Each time the root pass was completely melted through, blow-out occurred. To eliminate this problem, it was necessary to manually fill the groove in short sections and allow the capsule to cool down before resuming.

Series B specimens were made with 0.080-, 0.100-, and 0.125-inch wall thicknesses, with the end cap modified to give the 2.0 ratio of the end cap thickness to the capsule wall thickness. Another modification was the reduction in the size of the end cap locating lip, so as to improve weld penetration and uniformity.

Table 4.8 shows the test parameters used in Series B. Fourteen fuel capsules were tested and analyzed. Photographs were taken of the Series B impacted test specimens to show the deformation and secondary impact effects (see Figs. 4.40 through 4.46). All capsules went through the Zyglo and helium pressure test. The test specimens that leaked were sectioned, and macrographs were taken of the section

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Fig. 4.40. Six-Capsule Design

Fig. 4.41. Six-Capsule Design

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Fig. 4.42. Six-Capsule Design

Fig. 4.43. Six-Capsule Design

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Fig. 4.44. Six-Capsule Design

Fig. 4.45. Six-Capsule Design

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Fig. 4.46. Six-Capsule Design

TABLE 4.8
Series B Test Parameters

Capsule Number	Capsule Design	Wall Thickness (in.)	Welded Length (in.)	Capsule ID (in.)	Fuel/Total (gm)	Sled Weight at Impact (lb)	Temperature (° F)	Angle at Impact (deg)	Velocity (fps)
1	6-capsule design	0.100	7.106	1.207	413/937	840.43	1585	0	258
2	6-capsule design	0.100	7.107	1.207	410/936	840.50	1355	0	259
3	6-capsule design	0.100	7.104	1.207	413/941	840.43	1595	45	258
4	6-capsule design	0.100	7.112	1.207	411/940	840.50	1365	45	259
5	6-capsule design	0.100	7.108	1.207	401.9/929	839.61	850	45	257
6	6-capsule design	0.080	7.117	1.207	413.5/849	849.76	1595	0	257
7	6-capsule design	0.080	7.117	1.207	413.5/843	841.18	1345	0	260
8	6-capsule design	0.080	7.115	1.207	410/842	849.76	1595	45	257
9	6-capsule design	0.080	7.114	1.207	409.5/839	841.18	1360	45	260
10	6-capsule design	0.080	7.115	1.207	412/843	839.61	855	45	257
11	6-capsule design	0.125	7.110	1.207	417/1065	840.23	1585	0	260
12	6-capsule design	0.125	7.106	1.207	412.5/1059	840.25	1360	0	260
13	6-capsule design	0.125	7.106	1.207	412/1059	840.23	1580	45	260
14	6-capsule design	0.125	7.108	1.207	411.5/1063	840.25	1350	45	260

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pieces (see Figs. 4.47 through 4.49). Results of the Zyglo and helium pressure tests are given in Table 4.9.

An investigation of the test results reveals the following:

- (1) Capsules 3 and 4 leaked, due to secondary impact.
- (2) The weld penetration was not consistent in each capsule.
- (3) The test results show that two of the 80-mil fuel capsules (8 and 10) had minute cracks in the weld. These minute cracks or hairline fractures were not considered to be detrimental, since fuel containment is not seriously compromised and since modifications can probably be made in the welding process to correct this condition.
- (4) Sectioning of the end caps showed that the titanium spacer had cut into the weld area and initiated cracks in the weld.

Based on the test results, the following recommendations were made:

- (1) Further test of the 80-mil capsules.
- (2) Refine the welding process.
- (3) Modify the titanium spacer.

Series C. Since time did not permit the manufacturing of a chill block to be used in welding, the process established in Series A was used for Series C. The sharp edges on the titanium spacers were rounded off to eliminate damage in the weld area.

Table 4.10 shows the test parameters used in Series C. Eight fuel capsules were tested and subsequently analyzed.

The test specimens which leaked were sectioned and macrographs were taken of the section pieces (see Figs. 4.50 through 4.52).

Table 4.11 shows the results of the tests. An investigation of the test results revealed the following:

- (1) Inconsistent weld penetration.
- (2) Capsules 1 and 8 leaked, due to secondary impact against the track alignment bolts.

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Fig. 4.47. Capsule 3B--Wall Thickness, 0.100 In.; Temperature, 595° F; Angle at Impact, 45 Deg; Velocity, 258 fps; Haynes 25

Fig. 4.48. Capsule 8B--Wall Thickness, 0.080 In.; Temperature, 1595° F; Angle at Impact, 45 Deg; Velocity, 257 fps; Haynes 25

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Fig. 4.49. Capsule 10B--Wall Thickness, 0.080 In.; Temperature, 855° F; Angle at Impact, 45 Deg; Velocity, 257 fps; Haynes 25

Fig. 4.50. Capsule 211C--Wall Thickness, 0.100 In.; Temperature, 1205° F; Angle at Impact, 45 Deg; Velocity, 217 fps; Hastelloy C

TABLE 4.9

Series B Zyglo and Helium Pressure Test Results

<u>Capsule No.</u>	<u>Wall Thickness (in.)</u>	<u>Angle at Impact (deg)</u>	<u>Zyglo Test</u>	<u>Pressure Test</u>
1B	0.100	0	No surface cracks	No leak
2B	0.100	0	No surface cracks	No leak
3B	0.100	45	Shallow crack in weld area	Leak (due to secondary impact against the rocket sled)
4B	0.100	45	Shallow crack in weld area	Leak (barrel sheared by rocket sled track)
5B	0.100	45	Shallow crack in weld area	No leak
6B	0.080	0	No surface cracks	No leak
7B	0.080	0	No surface cracks	No leak
8B	0.080	45	No surface cracks	Leak
9B	0.080	45	No surface cracks	No leak
10B	0.080	45	Crack in weld area	Leak
11B	0.125	0	No surface cracks	No leak
12B	0.125	0	No surface cracks	No leak
13B	0.125	45	Crack in weld area	No leak
14B	0.125	45	Crack in weld area	No leak

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Fig. 4.51. Capsule 6H25--Wall Thickness, 0.080 In.; Temperature, 1205° F; Angle at Impact, 45 Deg; Velocity, 220 fps; Haynes 25

Fig. 4.52. Capsule 8H25--Wall Thickness, 0.080 In.; Temperature, 1195° F; Angle at Impact, 45 Deg; Velocity, 221 fps; Haynes 25

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TABLE 4.10
Series C Test Parameters

Capsule Number	Capsule Design	Wall Thickness (in.)	Welded Length (in.)	Capsule ID (in.)	Fuel/Total (gm)	Sled Weight at Impact (lb)	Temperature (°F)	Angle at Impact (deg)	Velocity (fps)
1HC	6-capsule design	0.100	7.233	1.207	408.6/831	722.94	1200	45	217
2HC	6-capsule design	0.080	7.235	1.207	417.8/933.5	722.94	1205	45	217
3HN	6-capsule design	0.100	7.236	1.207	409.5/829.5	708.57	1195	45	222
4HN	6-capsule design	0.080	7.243	1.207	414.8/935.5	708.57	1205	45	222
5H25	6-capsule design	0.080	7.235	1.207	410.7/847.0	708.42	1200	45	220
6H25	6-capsule design	0.080	7.239	1.207	410.2/847.8	708.42	1205	45	220
7H25	6-capsule design	0.080	7.235	1.207	411.2/848.5	708.77	1205	45	221
8H25	6-capsule design	0.080	7.236	1.207	414/846.5	708.77	1195	45	221

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As shown by the test figures, many of the test specimens experienced damage from secondary impact against the track and track surroundings. The secondary impact velocities, due to rebounding of the test specimens off the granite blocks in the turnaround method, were higher than the initial impact velocities (Table 4.12). A few of the test specimens, as shown in the test results, leaked as a result of secondary impact. This can be attributed to the increase in velocity and impact with sharp angles (steel tracks, track alignment bolts, etc.). Although the secondary impact was of a more severe nature, it was possible to differentiate between the initial impact effects and secondary impact effects.

4.2.6.7 Conclusions and Recommendations

Final conclusions concerning the fuel containability of the SNAP 17A fuel structure cannot at this time be drawn from the results of the Phase I tests. However, preliminary conclusions and recommendations are presented to indicate both the progress made toward the development of a fuel capsule that will comply with the safety criteria and additional design considerations which have evolved from the Phase I tests to improve the fuel capsule design.

The tests indicated that, under the most severe conditions of impact velocity, temperature, and angle of impact, the fuel containment structure exhibited a high degree of fuel containment. For example, 30 (Haynes-25) fuel capsules were tested and the integrity (absolute containment) of only five of these was breached. The extent of damage to these capsules was very minor (minute cracks), as illustrated previously.

It appears that, as the dimensions of the fuel capsule increase (single-capsule design), the corresponding damage resulting from impact increases accordingly.

It was concluded from an analysis of the Series A test results that the cylinder wall thickness could be reduced without sacrificing the fuel capsule containment capability. Series B test results substantiated that the reduction in wall thickness led to a feasible design. Furthermore, the terminal impact velocity and impact temperature used in Series A and B were calculated for the heavier wall fuel capsule and the internal volume allowed for an inner liner. From the test results of Series A and B and the stringent test parameters imposed on the test specimens, the 80-mil fuel capsule was selected for the final test series. It was evident from the latter test results that an 80-mil fuel capsule can be developed that will satisfy the safety criteria.

The six-capsule design was confirmed as the most favorable design after analyzing the results of impact tests, the re-entry burnup study, and the earth burial and melt-down study.

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TABLE 4.12
Specimen Rebound Velocities

<u>Capsule No.</u> <u>Series A</u>	<u>Impact Velocities</u> <u>(fps $\pm$ 2.5)</u>	<u>Rebound Velocities</u> <u>(fps $\pm$ 5)</u>
1	--	--
2	259	291
3	257	No smear film
4	265	283
5	259	295
6	260	290
7	259	270
8	259	299
9	265	289
10	260	292
11	Spare specimen	
12	260	283
13	257	No smear film
14	260	287
Series B		
1	258	284
2	259	287
3	258	300
4	259	291
5	257	262

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<u>Capsule No. Series B</u>	<u>Impact Velocities (fps $\pm$ 2.5)</u>	<u>Rebound Velocities (fps $\pm$ 5)</u>
6	257	278
7	260	285
8	257	306
9	260	303
10	257	283
11	260	284
12	260	281
13	260	303
14	260	280
Series C		
1	217	237
2	217	235
3	222	250
4	222	246
5	220	245
6	220	246
7	221	244
8	221	243

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The following recommendations concerning the fuel capsule design are made in order that further optimization can be achieved:

- (1) Relocate the weld to a distance of approximately two inches from the tip of the end cap. This is the area in which the least damage was experienced.
- (2) Incorporate an automatic welding process, using a chill block to ensure consistency in the weld penetration.
- (3) Eliminate the spacer and press directly into the end cap.
- (4) Investigate the effects of having a hemispherical end cap.
- (5) Investigate the effects of having a tapered cylinder.

The maximum damage, which occurred to the 80-mil fuel capsule, consisted of minute cracks in the weld area. By implementing the recommendations, the minute cracks would probably be eliminated.

Further testing of the fuel capsule will be required to develop an optimum design, evaluate interrelationships between impact parameters, and to provide the desirable reliability at a high confidence level.

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4.3 AEROSPACE SAFETY ANALYSIS

The primary objective of the aerospace safety analysis for the MACS system was to evolve the generator, capsule assembly, and capsule designs which would satisfy the criterion of capsule burnup and fuel exposure at an altitude of approximately 200,000 feet subsequent to orbital decay of possible re-entry configurations of the system. The design, however, was constrained such that re-entry of the capsule, following an early abort during the ascent trajectory, occurs without rupturing the capsule upon impact.

Owing to the competing nature of these constraints and the consequent establishment of an interval in the ascent trajectory during which an abort leads to partial burnup of the capsule, a second objective of the study was to determine the region of impact from where a partially aerodynamically consumed capsule impacts to where burnup occurs at an altitude less than 200,000 feet. This region must be well defined and minimized from a design standpoint such that any release in this region would produce no undue radiological or radiobiological hazard to the general public.

All possible known re-entering configurations were investigated with respect to their burnup characteristics to determine their effect upon the ultimate disposition of the fuel. This was accomplished for the ascent abort cases by examining the re-entry trajectories of the following configurations: Agena D/dispenser, dispenser/satellites, satellite/RTG/gravity gradient system (retracted), generator and the fuel capsule. For the case of orbital decay, the configurations considered were Agena D/dispenser, dispenser/satellites, satellite/generator/GGS (retracted and extended) and the generator. With the trajectory information (histories of altitude, velocity and heating rates) and the appropriate heat transfer models for the various re-entry configurations, the aerodynamic breakup altitude for the generator and the fuel capsule assembly were determined. From this point, the burnup altitude was determined by using a fuel capsule heat transfer model and the specific fuel capsule trajectory from the point of capsule release.

The determination of heat fluxes incident upon the re-entering bodies was done, making use of previous experience with complex body shapes, owing to the lack of directly applicable experimental data on heating distributions for these configurations. The construction of heat transfer models for the complex configurations noted required detailed consideration since the heat transfer-ablation representation available was not fully three dimensional. In general, then, rigorous descriptions of physical mechanisms and mathematical models became subservient to the exigencies of engineering design.

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A detailed description of trajectories, configurations, results and conclusions is given in the following sections.

4.3.1 Payload and Trajectory

4.3.1.1 Payload

The payload for the Atlas/Agena D launch vehicle consists of seven MACS systems. Each system contains three basic items; an electronic package or satellite, radioisotope thermoelectric generator and a gravity gradient system. The seven systems, after assembly, are mounted on a truss-like structure designated as the dispenser.

Each system is assembled with the generator mounted on top of the satellite and the GGS mounted on top of the generator. A schematic of the composite design is illustrated in Fig. 4.53. The satellites are positioned in a staggered pattern along the length of the dispenser, as illustrated in Fig. 4.54. The dispenser is attached to the forward section of the Agena D vehicle and is enclosed in a fairing, which is ejected early in the ascent trajectory.

After the proper orbit of the Agena D/dispenser is achieved, the satellites are deployed by the dispenser at different points along its orbit. The satellites, on separation from the dispenser, obtain their operational orientation by the following steps: one, the generator is separated from the satellite by a six-foot extension mechanism, and two, the gravity gradient is deployed with approximately 100 feet of flexible tubing. This operational orientation of the MACS satellite is shown in Fig. 4.55. The GGS functions as a damper for any oscillations in the MACS system and it also orients the complete system such that the satellite is always pointing toward the earth as shown in Fig. 4.55.

Trajectory. The MACS system will be launched from PMR by an Atlas/Agena D launch vehicle (Appendix R-4) into a circular polar orbit. A nominal ascent trajectory (Refs. 4.4 and 4.5) was used for the aerospace safety evaluation of the MACS system and pertinent information is presented in Table 4.13.

4.3.2 Credible Aborts

During the normal sequence of a nominal launch and ascent trajectory, there are several points at which an abort or a malfunction resulting in an abort are most likely to occur. These points can be predicted by examination of the trajectory sequence of events (see Appendix R-4). Table 4.14 shows the credible abort points, the possible cause of the abort, and the possible resultant effects.

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Fig. 4.53. MACS Satellite/RTG/GGS(R) (RTG and GGS in Their Retracted or Stored Position)

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Fig. 4.54. Dispenser with MACS Satellites

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Fig. 4.55. MACS Satellite in Operational Orientation

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TABLE 4.13
Nominal Ascent Trajectory

Time from Launch (sec)	Vehicle Weight (lb)	Altitude (ft)	Relative Velocity (fps)	Latitude (deg)	Longitude (deg)	<u>Instantaneous Impact Point</u>		<u>Altitude (naut mi)</u>		Remarks
						<u>Latitude (deg)</u>	<u>Longitude (deg)</u>	<u>Apogee</u>	<u>Perigee</u>	
0	279,845	438	0	34.644N	120.593W	--	--			Liftoff.
65	178,624	38,912	1705	34.595N	120.595W	34.288N	120.607W			Maximum dynamic pressure.
133.724	71,688	201,640	8908	33.880N	120.617W	27.241N	120.906W			BECO.
136.727	63,536	212,148	8982	33.813N	120.619W	27.086N	120.913W			Jettison booster package.
200	46,002	410,095	11,377	32.176N	120.675W	22.410N	121.119W			Jettison nose firing.
280.844	24,597	618,170	17,065	29.223N	120.787W	9.000N	121.712W			SECO.
300.353	24,471	660,867	17,012	28.345N	120.822W	8.935N	121.715W			VECO.
305.353	15,807	670,776	16,994	28.120N	120.831W	8.935N	121.715W			Atlas/Agena separation.
349.799	15,807	740,227	16,871	26.129N	120.914W	8.934N	121.715W			Agena ullage ignition.
363.099	15,728	754,517	16,853	25.535N	120.940W	8.918N	121.716W			Steady-state thrust.
535	6350	727,007	25,443	16.199N	121.355W	62.202S	123.964W			Last impact point.
540	6077	722,884	25,861	15.858N	121.370W	--	--	367.4	72.2	In orbit.
582.522	3773	691,573	30,303	12.694N	121.507W	--	--	5015	115.2	Agena shutdown.
6425.65	3773	30,358,818	13,245	9.618S	34.107E	--	--	5000	114.1	Second Agena ullage ignition.
6462.37	2501	30,359,205	16,942	9.042S	33.959E	--	--	5002	4997.8	Second Agena shutdown.
6947.64	2501	30,355,313	16,953	0	32.011E	--	--	5002.5	4997.6	Orbit injection.

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TABLE 4.14
Credible Aborts

<u>Time (sec)</u>	<u>Cause of Abort</u>	<u>Possible Effect</u>	<u>Remedy</u>
T - 0.8	Atlas engine (s) malfunction.	Unpredictable path of payload.	Destroy launch vehicle.
T + 15	Failure of Atlas programmer to control pitch or roll program.	Launch vehicle path entering unsafe area.	Destroy launch vehicle.
T + 65	Maximum dynamic pressure.	Failure of a critical component.	Destroy launch vehicle.
T + 133.5	Failure of Atlas programmer to activate BECO or stop pitch control.	Vehicle in uncontrollable mode.	Destroy launch vehicle.
T + 136.7	Sustainer engine not centered, first stage not jet-tisoned.	Damage to sustainer engine; excess weight on vehicle; degradation of vehicle performance reducing chance of success.	Destroy launch vehicle.
T + 280.7	Failure of Atlas programmer to activate SECO.	Trajectory of vehicle uncertain.	Destroy launch vehicle.
T + 300.4	Failure of Mk II to activate VECO.	Trajectory of vehicle uncertain.	Destroy launch vehicle.
T + 302.9	Failure of separation system.	Agena unable to provide thrust.	Destroy launch vehicle.
T + 361.8	Agena D engine malfunctions.	Trajectory of payload uncertain.	Destroy Agena D with on-board destruct system.
T + 581.5	Failure of Agena D first burn cutoff.	Trajectory of payload uncertain.	Destroy Agena D.
T + 6437.7	Agena D engine malfunction.	Trajectory of payload uncertain.	Destroy Agena D.

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4.3.3 Method of Analysis

The aerothermodynamic study of the MACS system consisted of the determination of the re-entry trajectory of each configuration, the amount and distribution of the aerodynamic heating on the surface of each body, the heat transfer throughout each body, and the heatup and disassembly of each configuration until the exposure of the strontium-90 fuel to aerodynamic heating occurred. Digital computer programs were utilized in the determination of the trajectory parameters, heating rates, and the internal heat transfer for each configuration. These digital codes are described in Appendix R-1.

The aerothermodynamic study was divided into two general areas of investigation: ascent abort and orbital decay. For the abort case, the following bodies were considered re-entering from the nominal ascent trajectory: Agena D/dispenser; dispenser/satellites; satellite/RTG/GGS(R)*; generator; and the fuel capsule. These configurations were chosen because they are the most probable configurations to be re-entering as a result of an abort situation and also to determine their relative effect on the shift of the partial burnup zone. If a destruction system is required to separate the various bodies, the latter reason for choice of configurations will be used to establish which specific configurations should be separated by an explosive device to ensure high altitude burnup of the fuel capsule and resultant dispersion of the fuel.

In the orbital decay study, the same configurations were studied with the exception of the fuel capsule, since it is automatically considered for each initial configuration, and the addition of the satellite/RTG/GGS(E)** configuration. These configurations were considered to determine their effect upon the burnup altitude of the fuel capsule and whether a destruct system would be necessary to achieve satisfactory burnup conditions.

The parameters of primary importance for the re-entry analysis of each configuration are: (1) the initial conditions (velocity, flight path angle, azimuth and altitude); (2) trajectory (ballistic coefficient and aerodynamic coefficients of stability); (3) aerodynamic heating (characteristic radius and shape of the configuration); and (4) the thermodynamic properties of the materials (conductivity, specific heat, heat of transformations and emissivity). For the ascent abort study, the initial conditions for re-entry were considered to be the velocity, flight path angle, geodetic azimuth angle, and altitude at the abort point. The initial conditions for the orbital decay study are: inertial velocity = 25,686 fps; inertial flight path angle = -0.2 degree; inertial azimuth angle = 180

*(R)--RTG and GGS are in their retracted position.

** (E)--RTG extended from satellite by six feet and GGS retracted.

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degrees; and altitude = 400,000 feet. All trajectories are for tumbling configurations and the various parameters (weight, aerodynamic reference area, characteristic radius for aeroheating and ballistic coefficient) for each configuration including the capsule assembly are presented in Table 4.15. The thermodynamic properties for the various materials, comprising the re-entry configuration, used in the heat transfer and ablation analysis were taken from the handbooks and reported literature.

A schematic of the re-entry trajectory illustrating breakup of the different components of the system permitting fuel release is illustrated in Fig. 4.56. The method of analysis used to determine re-entry burnup considered both the trajectory and a detailed heat transfer model corresponding to the specific re-entry configuration.

A discussion of this analysis is presented.

- (1) A re-entry trajectory was determined for a configuration by one of the two trajectory codes; UB024 for the abort cases or UB003 for the orbital decay cases. A history of altitude, velocity, and heating rate was obtained from the trajectory code.
- (2) These curves were then used in the heat transfer and ablation code, FB090, to determine the effect of the aerodynamic heating on the generator. A description of the heat transfer model for the generator is presented in Appendix R-5.
- (3) When the outer housing of the generator was aerothermally consumed, the new trajectory for the fuel assembly was determined and used in FB090 to determine its burnup altitude. The fuel capsule burnup altitude was also determined in the same manner. The heat transfer models for the capsule assembly and the fuel capsule are described in Appendix R-5.

TABLE 4.15
Re-entry Configurations

<u>Re-entry Body</u>	<u>Weight (lb)</u>	<u>Aerodynamic Area (ft²)</u>	<u>Radius (ft)</u>	<u>Ballistic Coefficient (lb/ft²)</u>
Agna D/dispenser (at Agna D first ignition)	15,807	1.0	0.45	140

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Fig. 4.56. Events Occurring During Orbital Re-Entry

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TABLE 4.15 (continued)

<u>Re-entry Body</u>	<u>Weight (lb)</u>	<u>Aerodynamic Area (ft²)</u>	<u>Radius (ft)</u>	<u>Ballistic Coefficient (lb/ft²)</u>
Agena D/dispenser (at Agena D first shut- down)	3773	1.0	0.45	33.4
Dispenser/satellites	900	14.5	0.45	16.0
Satellite/RTG/GGS (R)	100	3.14	0.45	22.1
Satellite/RTG/GGS (E)	100	3.14	0.45	15.4
Generator	30	0.48	0.45	24.5
Capsule assembly	12.6	0.188	0.198	29.4
Capsule	1.80	0.0104	0.0558	33.7

NOTES:

R--RTG and GGS in retracted position.

E--RTG extended six feet from satellite with GGS in its retracted position.

4.3.3.1 Trajectories and Aerodynamic Heating

The trajectory analysis was performed by utilization of the two digital trajectory codes, UB024 (three dimensional) and UB003 (two dimensional). For the abort analysis, UB024 was used and the following configurations were considered re-entering first from the nominal ascent trajectory. Agena D (completely fueled)/dispenser, dispenser/satellites, satellite/RTG/GGS (R), generator and the fuel capsule. The two-dimensional code was used in the orbital decay analysis and the following configurations were considered re-entering first: Agena D (partially fueled)/dispenser, dispenser/satellites, satellite/RTG/GGS (retracted and extended) and the generator.

The drag curves for these configurations and the capsule assembly are presented in Appendix R-6. All of these curves are for a tumbling body and were determined except for the Agena D/payload or dispenser by the following expression:

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$$C_{D_{\text{tumbling}}} = \frac{C_{D_{\alpha = 0^\circ}} + C_{D_{\alpha = 90^\circ}}}{2}$$

where

$C_{D_{\text{tumbling}}}$ = tumbling drag coefficient based on some reference area, such as the cross sectional.

$C_{D_{\alpha = 0^\circ}}$ = drag coefficient at angle of attack of 0° based on the cross sectional area.

$C_{D_{\alpha = 90^\circ}}$ = drag coefficient at angle of attack of 90° based on the cross sectional area.

A combination of experimental drag values (Refs. 4.6 through 4.10) and Newtonian impact theory (Refs. 4.11 and 4.12) was used to determine these drag coefficients over the complete Mach number range for these different configurations.

The following assumptions and approximations were used in the trajectory and aeroheating analysis, since no aerodynamic experimental data (force and moment information, and aeroheating distributions over irregular shapes) for possible SNAP 17A configurations were available in Phase I:

- (1) All configurations were assumed to be in a tumbling orientation during their re-entry trajectory. This orientation was assumed because these bodies are not designed for aerodynamic stability, very little aerodynamic damping exists above 200,000 feet, and aerodynamic heating calculations are conservative for this orientation. If a configuration had some margin of stability, the vehicle could re-enter in either a stable or pitching orientation and, therefore, it would experience higher heating rates on those surfaces exposed to stagnation heating, as shown in Fig. 8 in Ref. 4.13.
- (2) Re-entry heating above 300,000 feet was not considered in the ascent trajectory abort analysis for aborts occurring prior to 537 seconds after launch. This provides a conservative approach because aeroheating does occur in this region, but its magnitude is relatively small with respect to the aerodynamic heating below this altitude. However, aerodynamic heating in this region increases as orbital velocity is approached. Therefore, aeroheating above 300,000 feet was considered for abort cases occurring within 0.3 second prior to orbital injection.

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Fig. 4.57. Comparison of Heating Above 300,000 Feet to That Below 300,000 Feet

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- (3) In the orbital decay analysis, re-entry heating above 300,000 feet was considered. The stagnation heating in this region was determined by the free molecular flow equation (Ref. 4.14):

$$q_{s/FM} = \frac{\gamma}{2J} \rho_{\infty} V_{\infty}^3$$

where

$q_{s/FM}$ = free molecular flow stagnation heating
(Btu/ft²-sec)

γ = 0.9 thermal accommodation coefficient
(Ref. 4.15)

J = 778 ft-lb/Btu mechanical equivalent of heat

ρ_{∞} = free stream density (slugs/ft³)

V_{∞} = vehicle velocity (fps).

Aerodynamic heating below this altitude was determined by the Detra, Kemp and Riddell method as given in Ref. 4.16. This method was used in the trajectory codes to determine their re-entry burnup characteristics. A typical re-entry heat rate and total integrated heat for the generator re-entering from orbit using this method are illustrated in Fig. 4.57.

- (4) For the re-entry analysis of the Agena D/dispenser, dispenser/satellites, and the satellite/RTG/GGS(R), the generator was considered to be attached to these configurations at all times, and its breakup was the only one considered. This assumption is conservative except for the Agena D/dispenser case because aerodynamic heating is directly proportional to the square root of the ballistic coefficient. Therefore, the aeroheating sensed by the generator model was controlled by the trajectory of the basic system (Agena D/dispenser, etc.). The shock wave pattern, the stability, flow perturbations, and other factors influencing burnup could not be rigorously analyzed in Phase I since this information must be determined experimentally. Possible re-entry configurations and their ballistic coefficients are given in Table 4.15.

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- (5) The heating distribution factor used in the analysis was the surface-average tumbling factor (13.3% of stagnation heating on a hemisphere) (Ref. 4.13). For the Agena D/dispenser, dispenser/satellites, and satellite/RTG/GGS(R) configurations, an additional factor of one-half was used to compensate for the time the generator is protected from the flow by these primary configurations. The heating distribution factor on the generator with these configurations was 6.7% of stagnation heating on a hemisphere.

The results of the aerospace safety evaluation using these assumptions are presented in Section 4.3.5.

4.3.4 Orbit Lifetime Analysis

There are several points along the launch and injection trajectory at which malfunction may occur. The majority of these malfunctions will probably result in the destruction of the vehicle system, but after a specific point in the launch trajectory, the Agena D and the satellite system will be in some orbit around the earth. As the Agena D continues to provide thrust to 581.52 seconds, the orbit progresses so that the orbit apogee will be at an altitude of 5000 nautical miles. However, if thrust should be terminated at any point after $T + 540$ seconds, an orbit will be established with a specific lifetime, dependent only on the perigee altitude, orbit eccentricity, and the vehicle ballistic coefficient as illustrated in Table 4.16. The table shows the orbital lifetimes at various time stages along the Agena D trajectory. The lifetimes were obtained from the Orbital Flight Handbook. The orbital lifetime for the Agena D/payload configuration established after the first burn of the Agena D was determined to be 4560 days. Orbital decay from this orbit would result in the release of radioactive fuel corresponding to the initial reactivity level.

TABLE 4.16
Agena D/Payload Orbit Lifetimes

Time After Launch (sec)	Perigee Altitude (naut mi)	Eccentricity	Ballistic Coefficient W/C_{DA}	Orbit Lifetime T_L (days)
540	72.243	0.0432	53.8	22.7
545	95.9977	0.068199	51.4	166
550	104.824	0.1026	49	456

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TABLE 4.16 (continued)

Time After Launch (sec)	Perigee Altitude (naut mi)	Eccentricity	Ballistic Coefficient $W/C_D A$	Orbit Lifetime T_L (days)
555	109.125	0.14082	46.5	837
560	111.56	0.18242	44	1420
565	113.06	0.22748	41.7	1813
570	114.0266	0.27634	39.3	2440
575	114.664	0.329458	36.9	3440
580	115.085	0.38743	34.4	4060
581	115.181	0.40615	33.8	4610
600	115.186	0.407995	33.4	4560
900	115.42	0.40787	33.4	4560
1200	115.41	0.40709	33.4	4560
1500	114.24	0.40669	33.4	4560
1800	112.57	0.40678	33.4	4560

4.3.5 Results

The results of the aerospace safety evaluation of the MACS system reveal for the abort study from the nominal ascent trajectory that the partial burnup region extends from 8° north latitude and 122° west longitude to 64° south latitude and 124° west longitude. The partial burnup region is illustrated in Figs. 4.58 and 4.59. Within the partial burnup region, three burnup zones for possible re-entry configurations have been defined: (1) fuel capsule, (2) generator, and (3) satellite/generator/GGS.

The analysis also indicated that for any abort occurring in the ascent trajectory after the partial burnup region would result in high altitude fuel release, above 200,000 feet.

The orbital decay study reveals the generator, fuel assembly and fuel capsules are designed to permit exposure of the radioactive fuel by aerothermodynamic heating at altitudes above 200,000 feet during re-entry. Therefore, the criterion established with respect to fuel release upon orbital re-entry was satisfied by all cases considered, except for the dispenser/satellite configuration. The analysis indicated that burnup of this configuration did not occur because of a half-factor

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Fig. 4.58. Partial Burnup Zone

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Fig. 4.59. Profile of Partial Burnup Zone

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used to reduce the magnitude of the heat rate which would result from flow perturbation and shadowing by surrounding objects. It is believed that this factor is extremely conservative; its magnitude can only be determined by experimentally testing the particular configuration.

The specific altitudes at which the radioactive fuel is exposed to aerodynamic heating for the various configurations analyzed were determined to be:

<u>Configuration</u>	<u>Altitude (ft)</u>
Generator	211,000
Satellite/RTG/GGS (extended)	210,000
Satellite/RTG/GGS (retracted)	204,000
Agena D/dispenser	209,000
Dispenser/satellite	--

A detailed discussion of the results of the ascent abort and orbital decay studies is given in the following sections.

4.3.5.1 Ascent Abort Study

A summary of the results from the ascent abort study, generator, fuel assembly, and fuel capsule breakup altitudes is presented in Table 4.17. For this study, the following initial configurations were considered re-entering from the abort points: Agena D/dispenser, dispenser/satellites, satellite/RTG/GGS(R), generator, and the strontium-90 fuel capsule. All abort points were during the first burn of the Agena D, which puts the entire payload into orbit.

Agena D/dispenser and dispenser/satellites configurations.- The Agena D/dispenser and the dispenser/satellites configurations (Cases 1 and 2, respectively) were investigated only from the first ignition point of the Agena D, approximately 305 seconds from launch. Histories of altitude, velocity, stagnation enthalpy, stagnation pressure, stagnation heating rate (cold wall), and integrated total heating are presented in Figs. 4.60 through 4.63.

The impact points for these configurations for an abort occurring at the first ignition point of the Agena D are 9.65° north latitude and 121.68° west longitude, and 10.13° north latitude and 121.66° west longitude, respectively.

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TABLE 4.17

Summary of the Results from the Abort Study

Case Number	Time from Launch (sec)	Altitude (ft)	Abort Point ⁽¹⁾		Latitude (deg)	Longitude (deg)	Initial Re-entry Configuration	Generator Analysis		Capsule Assembly Analysis		Fuel Capsule Analysis		Approximate Impact Point ⁽³⁾	
			Inertial Velocity (ft/sec)	Inertial Flight Path Angle (deg)				Fate of Generator	Burnup Altitude (ft)	Fate of Capsule Assembly's Strap	Breakup Altitude (ft)	Fate of Capsule's Wall	Release Altitude of Strontium-90 Fuel (ft)	Latitude (deg)	Longitude (deg)
1	305.353	670,776	17,001	6.7	28.12 N	120.83 W	Agema D/dispenser	Damaged	--	--	--	--	--	9.65 N	121.68 W
2							Dispenser/satellites	Undamaged	--	--	--	--	--	10.13 N	121.66 W
3-A	400	778,935	18,106	1.32	23.83 N	121.02 W	Satellite/RTG/GGS(R) ⁽¹⁾	Undamaged	--	--	--	--	--	7.70 N	121.76 W
3-B							Generator	Damaged	--	--	--	--	--	7.68 N	121.77 W
3-C							Fuel capsule					Damaged	--	7.61 N	121.77 W
4-A	420	783,532	18,879	0.406	22.85 N	121.06 W	Satellite/RTG/GGS(R)	Undamaged	--	--	--	--	--	6.22 N	121.83 W
4-B							Generator	Destroyed	130,500	Not broken	--	--	--	6.19 N	121.83 W
4-C							Fuel capsule					Damaged	--	6.10 N	121.83 W
5-A	440	782,729	19,733	-0.352	21.82 N	121.10 W	Satellite/RTG/GGS(R)	Undamaged	--	--	--	--	--	4.48 N	121.90 W
5-B							Generator	Destroyed	150,400	Not broken	--	--	--	4.45 N	121.90 W
5-C							Fuel capsule					Damaged	--	4.35 N	121.91 W
6-A	460	777,135	20,678	-0.953	20.75 N	121.15 W	Satellite/RTG/GGS(R)	Undamaged	--	--	--	--	--	2.37 N	121.99 W
6-B							Generator	Destroyed	165,700	Not broken	--	--	--	2.33 N	121.99 W
6-C							Fuel capsule					Destroyed	150,400	2.21 N	122.00 W
7-A	480	767,454	21,731	-1.39	19.63 N	121.20 W	Satellite/RTG/GGS(R)	Damaged	--	--	--	--	--	0.37 S	122.11 W
7-B							Generator	Destroyed	181,000	Not broken	--	--	--	0.42 A	122.11 W
7-C							Fuel capsule					Destroyed	173,500	0.72 S	122.12 W
8-A	500	754,502	22,917	-1.67	18.44 N	121.26 W	Satellite/RTG/GGS(R)	Damaged	--	--	--	--	--	4.38 S	122.27 W
8-B							Generator	Destroyed	197,700	Broken	188,000	Damaged	--	4.44 S	122.28 W
8-C							Fuel capsule					Destroyed	189,200	4.86 S	122.30 W
9-A	510	747,097	23,569	-1.75	17.83 N	121.28 W	Satellite/RTG/GGS(R)	Destroyed	148,000	Not broken	--	--	--	7.39 S	122.40 W
9-B							Generator	Destroyed	207,300	Broken	197,640	Damaged	--	7.46 S	122.40 W
9-C							Fuel capsule					Destroyed	197,900	7.99 S	122.43 W
10-A	520	739,253	24,269	-1.79	17.19 N	121.31 W	Satellite/RTG/GGS(R)	Destroyed	175,100	Not broken	--	--	--	11.96 S	122.59 W

TABLE 4.17 (continued)

Case Number	Time from Launch (sec)	Altitude (ft)	Abort Point ⁽¹⁾		Latitude (deg)	Longitude (deg)	Initial Re-entry Configuration	Generator Analysis		Capsule Assembly Analysis		Fuel Capsule Analysis		Approximate Impact Point ⁽³⁾			
			Inertial Velocity (ft/sec)	Inertial Flight Path Angle (deg)				Fate of Generator	Burnup Altitude (ft)	Fate of Capsule Assembly's Strap	Breakup Altitude (ft)	Fate of Capsule's Wall	Release Altitude of Strontium-90 Fuel (ft)	Latitude (deg)	Longitude (deg)		
10-B	530	731,125	25,024	-1.78	16.53 N	121.34 W	Generator	Destroyed	218,900	Broken	211,540	Destroyed	177,900	12.06 S	122.60 W		
10-C							Fuel capsule			Destroyed	208,200	12.78 S	122.63 W				
11-A							Satellite/RTG/GGS(R)	Destroyed	201,700	Broken	196,000	Damaged	--	21.08 S	122.97 W		
11-B	535	727,007	25,424	-1.76	16.20 N	121.36 W	Generator	Destroyed	235,500	Broken	229,330	Destroyed	203,800	21.24 S	122.97 W		
11-C							Fuel capsule			Destroyed	222,400	22.45 S	123.02 W				
12-A							Satellite/RTG/GGS(R)	Destroyed	223,900	Broken	219,700	Destroyed	191,200	33.20 S	123.43 W		
12-B	536	726,182	25,507	-1.75	16.13 N	121.36 W	Generator	Destroyed	251,600	Broken	235,300	Destroyed	215,600	33.46 S	123.44 W		
12-C							Fuel capsule			Destroyed	234,800	35.64 S	123.51 W				
13-A							Satellite/RTG/GGS(R)	Destroyed	232,000	Broken	210,000	Damaged	--	38.65 S	123.61 W		
13-B	537	725,357	25,591	-1.75	16.05 N	121.36 W	Generator	Destroyed	257,800	Broken	235,140	Destroyed	217,800	38.97 S	123.62 W		
14-A							Satellite/RTG/GGS(R)	Destroyed	244,600	Broken	208,600	Damaged	--	48.48 S	122.88 W		
14-B							Generator	Destroyed	267,300	Broken	230,700	Destroyed	210,300	48.97 S	123.89 W		
15-A	537.6	724,863	25,641	-1.744	16.02 N	121.36 W	Satellite/RTG/GGS(R)	Destroyed	270,000	Broken	234,000	Destroyed	217,000	64.45 S	123.91 W		
16-A	537.7	724,780	25,649	-1.743	16.01 N	121.36 W	Satellite/RTG/GGS(R)	Destroyed	281,000	Broken	246,000	Destroyed	229,000	71.79 S	123.43 W		
17-A	537.8	724,698	25,658	-1.7428	16.007 N	121.36 W	Satellite/RTG/GGS(R)	Destroyed	303,000	Broken	277,000	Destroyed	261,000	84.54 S	42.03 E		
18-A	537.9	724,615	25,666	-1.742	16.00 N	121.36 W	In orbit										
19-A	540	722,883	25,842	-1.73	15.86 N	121.37 W	Perigee, h _p = 72.24 naut mi; apogee, h _a = 367.4 naut mi										

(1) All abort points considered were during the first burn of Agena D. At 305.353 seconds, Atlas and Agena D separate.

(2) RTG--Radioisotope Thermoelectric Generator

GGs--Gravity Gradient System

R--RTG and GGS in their retracted position.

(3) The re-entry configuration at 80,000 feet.

Fig. 4.60. Abort Time: 305.353 Seconds (Agena D First Ignition) Case 1

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Fig. 4.61. Abort Time: 305.353 Seconds (Agena D First Ignition) Case 1

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Fig. 4.63. Abort Time: 305.353 Seconds (Agena D First Ignition) Case 2

Satellite/RTG/GGS (retracted).- This configuration was investigated for abort times beyond 400 seconds to orbital injection which occurs at 537.9 seconds after launch as illustrated by Cases 3A through 19A in Table 4.17. Additional abort times were considered to confirm orbital injection up to 540 seconds. Linear interpolation was used to determine the initial values of altitude, velocity, flight path angle, and azimuth angle for abort times of 536, 537, 537.6, 537.7, 537.8 and 537.9 seconds since the nominal trajectory did not present these data.

The partial burnup zone for this configuration exists between 12° south latitude and 123° west longitude and 64° south latitude and 124° west longitude. The far boundary for the partial burnup zone was for an abort time of 537.6 seconds; any abort after this time will result in a high altitude fuel release. The re-entry history of this configuration, altitude, velocity, stagnation enthalpy, stagnation pressure, stagnation heating, and integrated total heat from 300,000 feet for abort times of 500 and 537 seconds is presented in Figs. 4.64 through 4.67.

Generator. The generator was investigated from abort times of 400 to 537 seconds (Cases 3B through 14B) to determine its partial burnup zone. All abort times considered were during the first burn of the Agena D. This zone extends from the equator and 122° west longitude (Case 7B) to 21° south latitude and 123° west longitude (Case 11B). North of this zone, the fuel capsule would impact intact and south of it (abort times greater than 530 seconds), high altitude dispersion of the fuel would result. Curves of altitude, velocity, stagnation pressure, enthalpy, and heating rates, and integrated total heat are presented in Figs. 4.68 through 4.71 for two possible abort times, 400 and 535 seconds.

A heating distribution factor of 13.3% was used to determine the breakup of the generator for these cases.

Fuel capsule. The SNAP 17A fuel capsule was investigated with respect to ascent trajectory aborts occurring in the time span of 400 to 535 seconds after launch (Cases 3C through 12C) and between 520 and 535 seconds, the fuel was exposed to aerodynamic heating at altitudes above 200,000 feet. The partial burnup zone for the capsule re-entering initially from the nominal ascent trajectory was defined to lie between 8° north latitude and 122° west longitude, and 13° south latitude and 123° west longitude. These extremes were established by Cases 3C and 10C, respectively. Beyond an abort time of 520 seconds, high altitude dispersion of the fuel would result.

Typical histories for these abort times are presented in Figs. 4.72 through 4.75. It is shown in Fig. 4.72 that there is insufficient heating available to release the fuel during the re-entry from abort point of 400 seconds. For the abort time of 530 seconds, there is sufficient heating and the fuel was released at 220,000 feet as shown in Fig. 4.73.

Fig. 4.64. Abort Time: 500 Seconds Case 8-A

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Fig. 4.65. Abort Time: 500 Seconds Case 8-A

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Fig. 4.66. Abort Time: 537 Seconds Case 14-A-1 and -2

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Fig. 4.67. Abort Time: 537 Seconds Case 14-A-1 and -2

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Fig. 4.69. Abort Time: 400 Seconds Case 3-B

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Fig. 4.70. Abort Time: 535 Seconds Case 12-B

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Fig. 4.71. Abort Time: 535 Seconds Case 12-B

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Fig. 4.72. Abort Time: 400 Seconds Case 3-C

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Fig. 4.73. Abort Time: 400 Seconds Case 3-C

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Fig. 4.74. Abort Time: 530 Seconds Case 11-C

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Fig. 4.75. Abort Time: 530 Seconds Case 11-C

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4.3.5.2 Orbital Decay Study

The results from the orbital decay study (Table 4.18) indicate that the nominal criterion of fuel release by 200,000 feet was satisfied for all configurations except the dispenser/satellites. A heating distribution factor of 13.3% was used for the capsule assembly or capsule configurations while the generator factor was either 13.3 and 6.7% depending on the initial re-entry configuration.

Generator.- The SNAP 17A generator (Case 1) was investigated during an orbital decay trajectory to determine the fuel release altitude for this configuration. The generator was destroyed at 294,000 feet, the capsule assembly strap broke at 241,000 feet, and the fuel was released at 211,000 feet. Histories of altitude, velocity, stagnation enthalpy, pressure, and heating rate, and integrated total heat are shown in Fig. 4.76. The heating distribution factor for the generator was 13.3% of the stagnation value on a hemisphere.

Satellite/RTG/GGS(E).- Case 2 was investigated during an orbital decay trajectory and the results indicate that the strontium-90 fuel will be released at 210,000 feet. The generator was destroyed at 293,000 feet and the capsule assembly strap was broken at 239,000 feet. The histories are given in Figs. 4.78 and 4.79. The heating distribution factor of 13.3% was used in the investigation for generator breakup.

Satellite/RTG/GGS(R).- The satellite/RTG/GGS(R) (Case 3) was investigated during an orbital decay trajectory; and the generator was broken up at 267,000 feet, the capsule assembly strap was broken at 235,000 feet, and the fuel was released at 204,000 feet. Curves depicting the results are shown in Figs. 4.80 and 4.81. The heating distribution factor for the generator was 6.7%.

Agena D/dispenser.- The Agena D/dispenser (Cases 4A and 4B) were investigated during an orbital decay trajectory and the heating distribution factors for the generator breakup only were 13.3 and 6.7%, respectively, for these two cases. Using the 13.3% factor, the generator was destroyed at 299,000 feet, the capsule assembly strap was broken at 246,000 feet, and the fuel was released at 222,000 feet. For Case 4B, the 6.7% factor was used and the results are: generator destroyed at 272,000 feet; the strap was broken at 240,000 feet; and the fuel released at 209,000 feet. The curves for these cases are presented in Figs. 4.82 through 4.85.

Dispenser/satellites.- The dispenser/satellites configuration (Case 5) was studied during an orbital decay trajectory and the fuel was not released for this case. The generator was destroyed at 255,000 feet and the capsule assembly strap was broken by 198,000 feet. The heating distribution factor for the generator was 6.7% and the curves are presented in Figs. 4.86 and 4.87.

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TABLE 4.18

Summary of Results for Orbital Decay Study

Case Number	Initial Re-Entry Configuration	<u>Generator</u>		<u>Capsule Assembly</u>		<u>Fuel Capsule</u>	
		Fate of Generator	Burnup Altitude (ft)	Fate of Capsule Assembly Strap	Breakup Altitude (ft)	Fate of Capsule Wall	Release Altitude of Sr-90 Fuel (ft)
1	Generator	Destroyed	294,000	Broken	241,000	Destroyed	211,000
2	Satellite/RTG/GGS(E)	Destroyed	293,000	Broken	239,000	Destroyed	210,000
3	Satellite/RTG/GGS(R)	Destroyed	267,000	Broken	235,000	Destroyed	204,000
4-A	Agena D/Dispenser	Destroyed	299,000	Broken	246,000	Destroyed	222,000
4-B	Agena D/Dispenser	Destroyed	272,000	Broken	240,000	Destroyed	209,000
5	Dispenser/Satellite	Destroyed	255,000	Broken	198,000	Damaged	--

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Fig. 4.76. Orbital Decay Trajectory Case 1

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Fig. 4.77. Orbital Decay Trajectory Case 1

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Fig. 4.78. Orbital Decay Trajectory Case 2

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Fig. 4.79. Orbital Decay Trajectory Case 2

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Fig. 4.80. Orbital Decay Trajectory Case 3

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Fig. 4.81. Orbital Decay Trajectory Case 3

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Fig. 4.83. Orbital Decay Trajectory Case 4-A

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Fig. 4.8.4. Orbital Decay Trajectory Case 4-B

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Fig. 4.85. Orbital Decay Trajectory Case 4-B

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Fig. 4.86. Orbital Decay Trajectory Case 5

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Fig. 4.87. Orbital Decay Trajectory Case 5

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The conclusions obtained from the aerospace safety study of the SNAP 17A RTG for the MACS mission were:

- (1) The partial burnup region resulting from possible aborts occurring during the preorbital phase of the ascent trajectory will be over deep ocean, as illustrated in Figs. 4.58 and 4.59.
- (2) All aborts occurring after the far boundary of the partial burnup region will yield high altitude fuel releases above 200,000 feet.
- (3) For early aborts resulting in land impact, the conditions of velocity and temperature imposed upon the fuel capsule were found to be much more stringent for the single capsule design than the multicapsule (6) design, which would decrease the probability of impact survival.
- (4) The impact point of the Agena D and payload for an abort at the first ignition point of the Agena D would be at 10° north latitude and 122° west longitude.
- (5) The generator system will be aerothermodynamically consumed, exposing the radioactive fuel to aerodynamic heating at an altitude of 211,000 feet. In addition, the satellite/RTG/GGS(R and E) and Agena D/dispenser configurations also permitted exposure of the fuel above 200,000 feet for ultimate dispersal. However, the release altitude for the Dispenser/satellite configuration was found to be less than 200,000 feet. A thorough evaluation of this configuration must be performed both from an experimental and theoretical standpoint before its release altitude can be established. The evaluation would have to determine experimentally, the re-entry stability and heat distribution and its structural stability, in order that the re-entry breakup altitude could be predicted.
- (6) If the second burn of the Agena D cannot be achieved, the payload would re-enter the earth's atmosphere within approximately 4560 days. If the 5000-nautical mile circular polar orbit is achieved, the orbital lifetime of the generator would be greater than 1000 years. Therefore, for the successful mission, the Sr-90 would have decayed below a level that could constitute any radiological hazard.
- (7) The radioactive fuel release altitude or exposure to aerodynamic heating is very sensitive to shock patterns and heat distribution resulting from the complicated geometrical con-

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figurations to which the generator is attached during the re-entry heating period. Therefore, confirmation of the predicted release altitudes is dependent upon a thorough experimental program followed by a rigorous analytical evaluation.

From an aerospace standpoint, the SNAP 17A has been designed in accordance with safety design criteria as established by the Division of Reactor Development, Atomic Energy Commission.

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4.4 GENERAL SAFETY

The general safety section of the Nuclear Safety Study considers the SNAP 17A Radioisotope Thermoelectric Generator (RTG) for the MACS in its reciprocal relationship with its environment during operations and potential accident situations. The environments include the Naval Missile Facility Point Arguello (NMFPA), the surrounding land area and nearby ocean regions, the launch pad, earth burial, the location and recovery of a radioactive source after an abort, transportation and handling situations, and, as the final depository for the radioisotopic fuel, the earth's atmosphere, land surface, and ocean depths. Concern is for the entrance of the radioisotope into the biosphere in such a manner as to be inhaled by man, ingested in food or drink or as to produce a radiation field. Appraisal has been made of the probability and consequences of a radioactivity release, in case of prelaunch and launch accidents, to the ground and water supply, to the oceans and to the air, and (for re-entry burnup) to the upper atmosphere.

The incorporation of a SNAP device into a satellite system dictates the need for a carefully planned and implemented operational procedure in conjunction with a thorough hazards evaluation of the launch area environment. The operations involving radioactivity-bearing space vehicles at NMFPA may encounter certain accident conditions which might result in a release of the radioactive fuel. It should be pointed out, however, that a fuel release is highly improbable in light of launch system reliability and fuel containment design. Nevertheless, the conditions which affect fuel containment and a hypothetical release to the NMFPA environment and adjacent areas have been considered in this safety evaluation.

4.4.1 The Naval Missile Facility, Point Arguello

A brief description of the Point Arguello area, its land usage, and the main factors that determine the course of radioactivity through the ground, air, and ocean environments are presented in this section. It is largely an abstract of the United States Naval Radiological Defense Laboratory publication (USNRDL-TR-545), Ref. 4.17.

The facility is in western Santa Barbara county in southern California, about 20 miles north of Point Conception and 55 miles northwest of Santa Barbara. Comprising an area of approximately 33 square miles, the facility is bounded on the north by the Santa Ynez River Basin, and on the south by the crest of the Santa Ynez Mountains that extend about 10 miles eastward from the coast. An additional area, the Sudden Ranch, borders on the southern boundary of the facility and extends southward about four miles to the ocean.

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The passage of released radioactivity through the environment is primarily determined by topographic, geologic and hydrologic, meteorologic, and oceanographic conditions. The acceptance of a liquid by a ground formation, along with the rate, direction, and extent of underground movement of its constituents, is related to the porosity, directional permeability and ion-exchange capacity of the formation. Localized recharge from rainfall, and the slope of the ground water table are also important factors. In mountainous terrain, ground water can transport contaminants to surface streams by basal flow.

The characteristics of the subtropical inversion and the wind patterns are the major meteorological conditions that are expected to determine the spread of airborne activity released in the Point Arguello area.

An estimated 75% of the area consists of rugged, mountainous topography, with steep-walled canyons extending westward and southward from the Santa Ynez Mountains to the ocean. The remaining 25% consists of seaward-sloping hillsides and flood plains and Lompoc terrace, and the included Lompoc Canyon, which drains northward to the Santa Ynez River. The terrace is a generally westward-sloping, undulating plain that is bounded by the Santa Ynez River Valley on the north, Bear Canyon on the southwest, the earthquake fault on the south, and LaSalle Canyon on the east. Elevations in the Terrace range from 100 to 300 feet above the valley floor of the canyons.

The rugged, mountainous nature of the southwestern part of the facility and of the Sudden Ranch favors a partial containment of airborne and ground-deposited activity. The canyons will likely restrict the dispersal of activity by surface winds and thus tend to localize activity within the canyons. They will also determine surface water flow and directional permeability in the subsurface soil layers and rock formation fractures.

The Lompoc Terrace is vulnerable to the deposition of airborne activity released accidentally at nearby launch sites. The local topography favors the transport of deposited fallout to the canyon streams by surface runoff and underground seepage. There is considerable subsurface water movement due to soil porosity.

The dispersal of airborne radioactivity from ground and low altitude (up to about 5000 feet) releases will be strongly affected by the combination of topographic features of the NMFPA landscape, the characteristically low inversion layer and the prevailing on-shore winds. Somewhat large mechanical eddies may be expected to restrict the dispersal of radioactivity to local canyons and thereby favor more concentration on the canyon walls. Dispersal during rainfall will be restricted, perhaps by a factor of two or more. The latter restriction would tend to

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significantly increase the amount of radioactivity in the watershed runoff, streambeds, underground aquifers and possibly in the receiving coastal waters.

The topographic conditions also influence the degree of stability of the air masses over NMFA and thus determine important parameters used in the calculation of radiation doses, such as diffusion rate, settling rate and exposure time. Local variations in mechanical turbulence throughout the facility area are, expectedly, considerable because of the irregular topography. Likewise local variations in thermal turbulence are appreciable because of the relatively low stability of the low altitude air masses. Due to wind shear, the north slopes between the facility and Lampoc are likely to be a major factor in determining thermal turbulence in the marine and inversion layers.

Geologic conditions will affect the transport of ground-deposited radioactivity because of its physical and chemical interactions with soil substances and because of porosity factors that vary in different strata. Hydrologic conditions could provide a ready medium of transport of radioactivity in either particulate or soluble form and would influence soil uptake and dilution of the radioactivity concentration. The combined geologic and hydrologic conditions determine hydrologic continuity, a potentially important factor in determining dispersal and, hence, in assessing hazards and establishing test site criteria.

The geologic conditions pertinent to this study are those influencing the absorption of radioactivity by soil and its transport through soil to plants, animals and subterranean waters. Of particular significance to the transport of radioactivity is the fact that a more or less continuous terrace is formed by a relatively thin mantle of unconsolidated sediments between the steep slopes and the sea cliff.

Both the unconsolidated deposits and consolidated rocks contain openings for ground water storage. In the unconsolidated deposits, particularly beds of gravel and sand, pores occur between rock particles. In the consolidated rocks, the most common openings are fractures, but in general, they are not as continuous or as large as openings in gravel or sand.

The soil deposits present today in the flood plains of the Santa Ynez River and its tributaries and those on alluvial fans represent recent soil profiles that have coarse textures along the canyon streamways and finer textures on the fans and flood plains. Those soils are loose and highly permeable and favor the penetration of waterborne contaminants to the water table.

Also favoring downflow are the conditions of the higher terraces that have more rolling topography on the tops and steep side slopes. Some areas have underlying bedrock at depths of 2.5 to 5 feet near the

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valley rims that tends to channel water downward to the valley floors. There are known to be large underground inflows from the side hills along the north and, to a lesser extent, from the south sides of the Santa Ynez River.

The major watershed of the facility drains northward into the Santa Ynez River and includes Lompoc and LaSalle Canyons. In addition, there are three relatively minor watersheds that drain in a westerly direction to the ocean: Bear Canyon, Spring and Canada Honda. In Sudden Ranch, several small canyons extend southward from the Santa Ynez range to the coast.

The flow of surface water from the facility to the Santa Ynez River Valley is small. The largest contributor, Lompoc Canyon, has a watershed of 5.3 square miles and maintains a small flow during most of the year. Contamination of the watershed or stream could result in contamination of the Lompoc Valley ground water used for domestic and agricultural purposes. The degree of the resulting hazard would depend on the amount, area, and continuity of the deposited activity, its uptake by the soil, and its dilution by ground water. Because the alluvial is fairly thick and rests on a relatively impermeable substratum, the water table is high. The valley floor is characterized by dense vegetation (mostly phreatophytes) whose extraction of water directly from the ground appreciably reduces the amount of surface water that reaches the canyon mouth.

Bear Creek, a lesser, intermittent watershed of about three square miles, is ponded between the railroad and the main road. The pond drains to the ocean through dune sand, suggesting the possibility of beach contamination. However, the likelihood of hazardous contamination appears small due to dilution by coastal water and the amount of activity available to the area.

Canada Honda drains about 12 square miles of watershed in the southwestern part of the facility. Within three to four miles of its mouth, it contains a perennial stream where the water table is relatively near the surface. Most of the stream flow during the summer season originates from springs along the Canyon's steep walls.

Spring Canyon and an unnamed one within a mile south of it lie between Bear Canyon and Canada Honda. They drain the remainder of the facility.

In general, along the western slopes the water table is near the surface and surface seeps are common. Springs on the south slopes near Canada Aqua Vina show appreciable yields. Ground surface contamination in this area may be expected to show up in the waters of springs and seeps and eventually reach the canyon streams flowing toward the coastal beaches.

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Ground water provides an avenue of transport for waterborne radioactivity that penetrates the soil. The principal areas of available ground water are Santa Ynez River Valley, the Lompoc Terrace and Canada Honda Valley. Little information is available on the volume of water in the several underground basins.

The Lompoc Terrace ground water basin is a structural and hydrologic feature formed directly by downfaulting along the south side of the basin and possibly the north side. USCG studies have shown that the ground water is moving toward the sea and also northwestward toward the Santa Ynez River Valley, which has a well-developed ground water basin.

One of the principal conclusions from USGS geologic and hydrologic studies is that there is hydraulic continuity between the underground water basins. A reasonable assumption is that surface radioactive contamination could, by percolation into subsurface layers, be transported from the facility to the ocean and also to the well-developed Santa Ynez Valley ground water basin on which the agriculture of the area is largely dependent.

The ion-exchange capacity of the soil--the ability to remove and retain fission product cations from aqueous solution--is an important factor. Fission product cations, especially those of strontium and cesium, may be exchanged for natural cations in the soil. The amount of uptake by ion exchange will be dependent significantly on the relative concentrations of particular fission product cations and the exchangeable soil cations. Clays which are locally present may exchange some of their intercrystalline Na^+ , K^+ , Ca^+ , or Mg^{++} with isotope cations in solution.

Underground aquifers are the most important water sources for commercial and domestic use in the general facility area. They consist of porous materials generally of the alluvial type. The profile of the water table is, in general, a subdued replica of the surface profile. Studies have also indicated the presence of fissure water systems in rocks along fissures and bedding planes. These fissure aquifers, in general, are not necessarily filled with porous conglomerate so ion exchange is limited to exposed surfaces rather than throughout the aquifer volume. Flow rates in the rock channels may, therefore, be much larger than those through alluvial or conglomerate materials.

The Point Arguello-Point Conception area has changing meteorological patterns related to the continental climate and topography and to the ocean currents.

The growing season in the Lompoc Valley averages 270 days. About 70% of the annual precipitation occurs from December to March, the extremes being 6 to 41 inches with an annual average of 14.4 inches. The annual precipitation in the mountainous south central part of the area is about 25 inches.

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The magnitude of the diurnal fluctuations in relative humidity for nearby Santa Maria (30 miles north, 15 miles inland) characterizes, in a general way, the Lompoc area. The average mean monthly humidity in the daytime is about 60%; in the nighttime, about 85%. The mean number of days of cloudy and partly cloudy weather during a year is about 193. The mean number of days of heavy fog is 88, and about 50% are from July to October. The prevailing mean sky cover, sunrise to sunset, is in the lower range of the partly cloudy condition during June to November. The average monthly temperatures range from about 50° to 62° F. Temperatures below freezing or above 90° F seldom occur. The 1959 to 1960 average maximum and minimum temperatures at the facility were 65° and 48° F, respectively.

In general, winds of the Point Arguello-Point Conception area are influenced by two factors. There is a local, low-level alternation between a daytime sea breeze blowing toward the land and up the mountain canyons and a nighttime land breeze blowing down the canyons. Superimposed on these air movements are the effects of the prevailing northwesterly winds.

In summer, Point Arguello falls within the northern part of a belt of prevailing westerlies which extends southward to Mexico. At this latitude, these winds are considered light but are still persistent enough to be called prevailing. The pressure gradient responsible for them reinforces the daytime sea breeze and opposes the nighttime land breeze. A net transport of air from west to east results; however, there are many times during the summer when the net flow is reversed, especially at levels somewhat above the surface.

In winter, the belt of westerlies shifts southward, and therefore stronger northwest winds are expected for a larger part of the time. In 1959 to 1960, they predominated in February and March whereas east winds from a continental high prevailed in December and January.

Under both summer and winter conditions, deep vertical mixing is, at times, possible. When the inversion base is high, there is a deep marine layer and more favorable conditions for advection and, hence, dissipation of atmospheric contaminants. In general, with regard to the hazards being considered, summer is the season of greatest vulnerability.

The inversion is brought about by the subsiding motion associated with the diverging wind circulation that spirals outward from the semi-permanent northeastern Pacific anticyclone and has maximum divergence along the California coast. As this air subsides, it is subjected to adiabatic heating and thus it becomes warm and very dry. Beneath this subsiding layer is a surface stratum called the marine layer which is cooled by its contact with ocean water. Due to upwelling, the coastal

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Fig. 4.88. Average Monthly Temperature Variations with Altitude for Four Months of 1960 at Point Arguello

Fig. 4.89. Average Contours of Inversion Base Along Southern California Coast, September 1944

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waters are relatively cold in the Point Arguello area. The subtropical inversion is at the interface between the marine layer and the subsiding layer. The altitude, thickness and stability of the inversion layer are primary factors in the concentration and dispersal of released radio-activity.

Time that Temperature Inversion Existed at USWS,
Point Arguello (7/1/59 to 6/30/60)

<u>1959</u>	<u>(%)</u>	<u>1960</u>	<u>(%)</u>
July	96.8	January	77.4
August	100	February	65.5
September	100	March	88.7
October	100	April	86.7
November	100	May	98.6
December	95.2	June	100

Elevation of the station is 367 feet. Inversion records were taken daily at 400 and 1600 hours by the Meteorological Office, NMFPA.

Water vapor evaporated from the ocean is transported upward and uniformly distributed up to the inversion, which acts as an effective lid preventing further upward motion. A shallow layer of cool, moist air is then surmounted by one that is warm and often extremely dry. The inversion is usually present from 80 to 100% of the time in the Point Arguello area.

Figure 4.88 shows the average monthly temperature variations in 1960. The inversion layer is characterized by much greater stability than the layers in which the temperature decreases with altitude. It is more resistant to vertical motion and hence tends to limit the altitude to which activity may be lifted. The height of the inversion base varies considerably during any one day and from day to day. Thus, the concentration of the activity released on or near the ground will depend on the thickness of the marine layer at launch time. This layer is unstable most of the time, resulting in continuous stirring that tends to produce a homogeneous mixture of vapor air and any foreign particulates present. Because of its origin over the ocean, the water content of the marine layer is usually high near the coast.

Figure 4.89 shows a slight trough in the inversion that is parallel to the coast and slightly offshore. The upward slope toward land is caused, at least in part, by the higher surface temperatures inland.

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This slope is important because it allows a greater depth through which air contaminants may be dispersed. At present, it is believed that this dispersal would become significant in the event of large scale radioactivity releases under conditions favoring its transport more than 20 miles eastward by the mean flow wind. More important is the fact that the inversion is often wiped out in the eastern part of the area and near the mountains by the surface heating to a temperature greater than that of the inversion top. As a result, radioactivity released at or near the surface would be dispersed rapidly by convection through a thicker layer of air.

When the inversion remains at only a few tens of meters above the launch pad, released radioactivity would tend to be concentrated in the thin marine layer, and would be associated with surface fog as differentiated from stratus clouds or high fog. It is seen that the temperature differences throughout the inversion may vary from a few degrees to over 20° C. It is not uncommon for the inversion base to remain at ground level for several days. In January 1961, it was at ground level every morning of the entire month. The average thickness of the inversion layer is about 600 meters and ranges from 400 to 1000 meters. The thickness is less over the continental slope. The average temperature increase through the inversion is about 10° C, ranging from 12° C at the base to 22° C at the top.

The contours of relative humidity show an average decrease of 50 to 60% in passing upward through the inversion layer, indicating a relative humidity of about 90% for the marine layer. At times, the relative humidity above the inversion layer has been observed to be less than 1%, which would indicate an even greater overall decrease. Further studies have shown that the change in humidity takes place abruptly, usually occurring quite completely in the lowest part of the inversion layer. The monthly mean values for nighttime relative humidity in the marine layer are usually over 80% and from April to September, they average over 90%.

4.4.2 Ocean Environment Near Point Arguello

The Atlas-Agena vehicle carrying the SNAP 17A will be launched from the Port Arguello Launch Complex No. 2 (PALC-2) at north latitude 34° 38' and west longitude 120° 36'. The launch complex is located on a small plateau at about 400 feet elevation. The initial launch azimuth of 182 degrees carries the vehicle over rugged terrain for about 4.7 nautical miles, after which the trajectory is entirely over water until the Antarctic continent is reached.

The ocean floor near the shore slopes at a rate of about two feet per 100 feet. The sand is coarsest at the beach with a median diameter of about 300 microns. The size grades off rather rapidly becoming about

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140 microns at a depth of 60 feet. Wave action has little sorting effect beyond this depth, and the bottom is largely silt. Some near shore areas have rocks and boulders on the bottom (Ref. 4.18). Sand is found to migrate parallel to the shore even around such points as Arguello and Concepcion. Kelp grows in the shallow in-shore water and to several fathoms depth.

From the coastline the water depth increases rapidly and rather uniformly out to about 15 nautical miles from the launch site where it has reached a depth of about 250 fathoms (Fig. 4.90). At this distance, there is a minor shelf which continues for about 11 nautical miles with an average depth of 300 fathoms. After this, the increase in depth resumes, reaching 1100 fathoms at 44 nautical miles. Here the increase in depth is interrupted by an underwater ridge that extends out from the land and the top of which emerges as the San Miquel, Santa Rosa and Santa Cruz chain of islands. As the track traverses this spur, the water depth decreased to 700 fathoms at 54 nautical miles and continues at near this depth for about seven miles. The increase in depth resumes, and the 1000 fathom-line is reached again at 65 nautical miles. At about 70 miles, the slope increases sharply. This escarpment marks the edge of the continental shelf. By 95 nautical miles, the abyssal depth of 2150 fathoms has been reached. The floor of the ocean continues as a plain at near this depth for many miles.

The currents in the Pacific Ocean off Point Arguello are subject to diurnal and annual variation. From April to October, the California current prevails (Ref. 4.19). This current sets in a generally southeasterly direction, but shore off at Point Arguello is flowing almost due south. From October to April, the Davidson current, flowing northward, becomes established and has a velocity here of about 0.2 knot. These current directions correspond generally with the prevailing wind directions but there is no complete correlation in this area. During the summers, the prevailing winds are from the northwestern quadrant. In the winter the greater part of the winds are from the southeast, but they do not dominate as do the summer northwesterlys. In the transitional periods between the two current regimes, i. e., in February and October, the surface currents are generally on-shore and off-shore, respectively. The surface currents and winds are well presented in the U.S. Navy Hydrographic Office Pilot Charts (Ref. 4.20). Figures 4.91 through 4.94 have been prepared from these, and illustrate the conditions described. The wind roses are conventional; the detached arrows represent the direction of surface current flow.

The diurnal change in the tidal currents is superimposed on the general circulation and often mask it. The Tidal Current Tables (Ref. 4.21) state that off Point Arguello the current due to the flood tide sets five degrees and that due to the ebb tide sets 185 degrees. In either case, the average velocity is 0.5 knot.

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Fig. 4.90. Bottom Profile Along 182-Degree Azimuth from Point Arguello

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Fig. 4.91. Chart of Surface Currents and Winds near Point Arguello, February 1962

Fig. 4.92. Chart of Surface Currents and Winds near Point Arguello, April 1962

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Fig. 4.93. Chart of Surface Currents and Winds near Point Arguello, October 1962

Fig. 4.94. Chart of Surface Currents and Winds near Point Arguello, November 1962

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The track of the missile passes near the mouth of the Santa Barbara Channel so that current conditions therein are of some interest. The United States Coast Pilot 7 (Ref. 4.22) summarizes these:

"Currents in Santa Barbara Channel are variable, depending to a great extent upon the wind. It appears that a weak nontidal current sets eastward in the spring and summer and westward in autumn and winter"...

"A tidal current sets along the north shore of Santa Barbara Channel with velocities at strength of 1/2 to 1 knot. In heavy northwesterly weather, the current and heavy swells make into the southern side of the western entrance to the channel and along the northern shore of San Miguel Island."

In this part of the California coast, upwelling takes place during parts of the year, notably in October. This is a slow upward movement toward the surface of cold water that has come in from high latitudes. A velocity of about 100 in./day appears to be typical (Ref. 4.23). Its greatest significance lies in the fact that plankton proliferate in the nutrient rich water and thereby attract fish that feed on the plankton.

This coastal region is free from embayments and estuaries that limit flushing characteristics. Diffusion of any contamination introduced near shore can everywhere take place over arcs of at least 180 degrees. In addition to the natural diffusion, the process of dispersion would be everywhere, enhanced by the advection due to tidal and nontidal currents.

The area of greatest potential hazard connected with the use of the SNAP 17A MACS is release of the radioisotope into the sea. This can only come about as the result of an abort of the launch vehicle, or an early re-entry of the satellite. These are events of low probability.

For consideration of a release, three divisions of the ocean can be recognized: deep ocean water, shallow water near shore and the intermediate depths.

Release of radioactive material into the great ocean depths is considered to be acceptable, but there may be some limitation with regard to total quantity and kind of radionuclide. It is thought that at great depths, horizontal diffusion takes place quite freely but that vertical diffusion is very slow (Ref. 4.21). Deep ocean water is estimated to exchange with surface water only after 300 to 500 years.

It is considered to be almost imperative that recovery of a fuel container dropped into shallow water near shore be accomplished. It is thought that such recovery is highly probable in water to a depth of 100 feet. Beyond this, the probability decreases becoming practically zero at 200 feet.

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This leaves an indefinite zone of hazard extending from the recovery zone to the deep water zone in the intermediate depths. For impact in this zone, or for failure to recover the fuel container from shallow water, the eventual release of the radionuclide is almost certain. It is impractical to build a fuel container that will withstand seawater corrosion for a time sufficient to allow a significant reduction in the activity of the long lived radiostrontium.

The potential hazard for the release of the fuel in the ocean at shallow or intermediate depths arises principally not from the contamination of the water, per se, but from the possibility of the entrance of the radioactivity into the human food chain. Man does not drink seawater but he does eat ocean fish and other marine fauna and flora that can become contaminated by the radiostrontium. To fully assess the potential hazard, it is necessary to know as much as possible about the life cycle and food habits of the various organisms in the food chain and the prevalence of the food fishes, the number taken by commercial and sport fishermen and their disposition.

In some previous Martin reports (Refs. 4.25 and 4.26), it was assumed that an instantaneous release producing high concentrations for a short time gives the most hazardous situation. Some marine biologists now think that a slow release originating from a structure on the bottom may permit a benthic (bottom dwelling) community to be built up and result in the contamination of more fish (Ref. 4.27). It is well known that a few junk automobiles piled on the ocean bottom, creating an artificial reef, serve to increase the fish supply in the region. Bacteria, algae and barnacles successively become attached to the structure and become a food source for higher organisms in a chain that reaches the fish taken for human food. The structure also serves as an orientation device and haven for fish. If the structure is the wreckage of a launch vehicle containing a leaking radiostrontium fuel container, there is an opportunity for long term exposure and the ingestion of radioactivity. Since strontium is taken up by shell and bone, it will form a greater part of growing organisms than of adults and a long period of exposure is required for the higher forms of life to acquire an equilibrium body burden. At the same time, it is less likely to be ingested by man since the shells are not eaten and the bones usually are not.

It has also been generally assumed that soluble radioactive material presents a greater potential hazard than the relatively insoluble strontium, which may fall to the bottom in particulate form, but filter feeders take up the particulate material and are in turn eaten by higher forms so that the biological diffusion of the insoluble form may be fully as rapid as that of the soluble form.

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The lower boundary of the intermediate zone of potential hazard is not definitely established and is somewhat controversial. Commercial fishing, in some areas, is carried out to depths of 1000 feet and with the development of gear may be extended to 2000 feet. It is known that the benthic communities are more prevalent at shallow depths but benthic fish exist at all depths. The principal factor in establishing an upper boundary for deep ocean water is the extent to which pelagic fish (those living and moving freely in the upper layers of the ocean at some distance from shore) taken as food migrate vertically and, thereby, feed on benthic organisms which may also migrate through a vertical range. Many marine biologists feel that release of the radiostrontium fuel below 1000 feet is acceptable, but some insist that the intermediate zone should be considered to extend to 7200 feet.

The marine resources in the Point Arguello region are described in Appendix S. The information is taken largely from Refs. 4.28 and 4.29.

4.4.3 Potential Radioactive Releases

4.4.3.1 Land Release

In the event of an early launch abort of the vehicle carrying the SNAP 17A, there is the probability that the vehicle wreckage may impact in the vicinity of the NMFPA. The fuel containers have been designed to withstand impact from a free fall at the terminal velocity so containment of the radioisotopic fuel seems to be assured. But, if some combination of circumstances permits a release to the ground of the fuel that is not fully recovered, there is not only a local radiation hazard but also a potential hazard of contaminating the run-off and ground water.

Since the ground track of the missile leads south from PALC 2, impact in the southern part of the area is most likely. This area consists largely of rugged terrain with a thin soil and exposed rocks and is cut by steep-walled gullies. A land surface release here is most likely to be eventually carried away by the run-off following a heavy rain. This could produce some temporary contamination of the shallow water near the shore. This situation is examined in the next section.

There are several wells and springs in this area. They are fed by a shallow aquifer which is thought to have a quite limited capacity. Since it is shallow, it is susceptible to intrusion by material in solution released on the surface. In the worst situation, the loss of this aquifer because of radioactive contamination would result in a local economic loss, but not an extensive one. If a surface release of radioactive fuel were to take place, it would be known and there would be a continual monitoring of springs and wells in the area to prevent any hazard to health.

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Impact north of PALC 2 is much less probable but may be potentially more serious. While the underground hydrology of the region is not fully understood, Newcombe, et al., (Ref. 4.17) conclude that there is hydraulic continuity between the underground basins and there is a possibility of surface water percolating into subsurface layers through which it may be transported into the important aquifer that furnishes domestic and irrigation water to the Santa Ynez Valley.

There are several other factors that tend to reduce the potential hazard of a surface release to the point where it may be insignificant. First, the chemical compound of strontium used for the fuel is a slightly soluble material and, on account of the manner of preparation, it is likely to be in massive form rather than a fine powder. The solubility rate is, consequently, expected to be low. If in powder form, its transportation would be mechanical rather than in solution and it would be retained in the first few inches of soil rather than percolate into the water table. Second, strontium in soluble form tends to be fixed by ion exchange in many soil-forming minerals, including the clays usually present. Third, the movement of underground water through an aquifer is quite slow, usually a few feet per year. Thus, there is time for dilution and radioactive decay before the water reaches the wells that supply the Santa Ynez Valley. The effect of all of these factors may be reduced slightly by the fact that some of the underground water basins of the area are formed by channels along fissures and bedding planes.

While the investigation of the subsurface hydrology of the Point Arguello area, and of the exchange properties of its soils should be pursued, the general conclusion is that significant contamination of the aquifers by a surface release of radiostrontium is not possible.

4.4.3.2 Seawater Release

The Atlas-Agena launch vehicle has a high reliability but if an abort were to occur during the first two minutes after takeoff, there is a high probability of ocean impact in water of shallow or intermediate depth. The ground and ocean bottom profile along the missile track has been described. The first 4.7 nautical miles of the track are over land. The water depth reaches 200 feet at about two miles and the continental shelf is reached at about 70 nautical miles. The fuel container is designed to resist seawater corrosion for several months or a few years. After this time the radiostrontium would be released. It is expected that this release would be gradual since corrosion would probably first open only small holes in the container. and the radiostrontium fuel is in the form of a slightly soluble chemical compound. However, in the following study an instantaneous release of the entire payload is assumed, since this gives higher water concentrations and probably represents a worst case situation.

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Calculations have been made using a diffusion equation that has been developed (Refs. 4.31 through 4.34). It is

$$P = \frac{Q}{2 \pi h K^2 t^2} e^{-\frac{r}{Kt}}$$

where:

P = activity concentration of the nuclide in the sea (curie/m³)
(equivalent to $\mu\text{c/cc}$)

Q = activity of the released material (curies)

h = vertical thickness of the diffusion layer (meters)

K = diffusion velocity (m/sec)

r = distance from source (meters)

t = time after release (sec)

The quantity, h, is equal to the thickness of the mixed layer for deposition in shallow water. For deposition in the thermocline or below, it is determined by the vertical distribution produced by thermal currents from the hot isotope. In this study the value of 50 meters has been chosen. K is conservatively chosen as 5×10^{-3} m/sec (Refs. 4.32 and 4.35). Q varies with time according to the relation

$$Q = Q_0 e^{-\lambda t}$$

where:

Q_0 = activity at time of release (curies)

λ = disintegration constant (sec⁻¹)

Since Sr-90 is a long-lived isotope, the decay can be neglected ($\lambda = 7.91 \times 10^{-10}$ sec⁻¹).

The results of these calculations are shown in the graphs of Figs. 4.95 and 4.96. Figure 4.95 gives the activity concentration versus time for various radial distances from the source, and Fig. 4.96 the activity versus distance for various times after release. It should be recalled that the calculations have been made for the entire payload of

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Fig. 4.95. Ocean Activity Concentration Versus Time Since Release

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Fig. 4.96. Ocean Activity Concentration Versus Distance from Release

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724,000 curies. The release of this quantity at one time is scarcely credible. The most probable manner of release is of the contents of one capsule at random intervals. For the release of one generator loading, the concentrations should be sealed down by a factor of seven, and for one capsule by a factor of 42.

The ultimate hazard resulting from a sea release of radioactive isotope would be realized if the isotope were ingested directly or indirectly by the consumption of contaminated sea life. Two different approaches have been used in evaluating the potential hazard of the release of strontium in the waters of the Pacific Missile Range.

The first of these was used in the study of possible release from a nuclear rocket. It was developed in Refs. 4.36 and 4.37. It considers a single nonrecurring event and its effect on the sea environment. It evaluates the hazard by determining the activity which may be ingested by the consumption of fish assumed to have come into equilibrium with the sea environment. The following postulates are used:

- (1) Man ingests an average of $15,200 \text{ cm}^3$ of fresh water in one week.
- (2) If a man obtains almost all his entire protein requirements for one week by eating fish, he will consume about 1500 grams.
- (3) A factor S, relating the radiation exposure guide for the general population to that for radiation workers, is introduced; it is taken to be 1/10.
- (4) A single incident exposure factor, E_i , is introduced. It is assumed that one year exposure may be received in a single nonrecurring event. E_i is, therefore, taken as 50.

The criterion established is that the radioactivity in the fish consumed should not exceed that ingested by drinking water with the MPC_w for the isotope of interest.

$$\text{Thus, } 1500 P f_c f_d < 15,200 \times \text{MPC}_w \times E_i \times S$$

where

P = concentration of radioactivity in seawater ($\mu\text{c/cc}$)

f_c = fish concentration factor; the ratio of the concentration of the element in the fish body to that in the seawater

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f_d = isotope dilution factor; ratio of atomic percent of radioactive isotope in the seawater to atomic percent of the element

MPC_w = maximum permissible concentration (radiation protection guide) of the isotope for radiation workers ($\mu\text{c/cc}$)

A maximum permissible concentration of the seawater MPC_{sw} for a particular nuclide may be calculated by solving for P when the expression becomes an equality; i.e.,

$$MPC_{sw} = \frac{15,200 \times MPC_w \times E_i \times S}{1500 f_c f_d} \quad (1)$$

Since strontium is an element that occurs naturally in seawater in measurable amounts, f_d is a variable. It is given approximately by

$$f_d = \frac{PA}{C}$$

where

A = reciprocal activity of the nuclide ($\text{gm}/\mu\text{c}$)

C = natural abundance of the element in seawater (gm/cc)

Substituting in Eq. 1 gives

$$(MPC_{sw})^2 = P^2 = \frac{15,200 MPC_w E_i S C}{1500 f_c A} \quad (2)$$

For Sr-90, MPC_w is 10^{-6} , f_c is taken as 10, C is 8×10^{-6} gm/cc and A is 7.02×10^{-9} $\text{gm}/\mu\text{c}$. Then

$$(MPC_{sw})^2 = \frac{15,200 \times 10^6 \times 50 \times 0.1 \times 8.0 \times 10^{-6}}{1500 \times 10 \times 7.02 \times 10^{-9}}$$

and

$$MPC_{sw} = 7.6 \times 10^{-2}$$

This development of an expression for the MPC_{sw} is somewhat roundabout. A more direct development could be made in terms of the increase of body burden. Actually, the eating of 1500 grams of

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fish in equilibrium with water containing this MPC_{sw} of Sr-90 would result in an addition to the body burden in the bone of $6.84 \times 10^{-3} \mu c$. The resulting dose rate to the bone would be 1.33 mrem/wk. This would amount to about 70 millirem the first year, decreasing throughout life. The Federal Radiation Council suggests (Ref. 4.39) 170 mrem/yr as a maximum for the population with 500 millirem acceptable in an emergency situation.

The postulate in this model that the fish immediately come into equilibrium with the ambient water is highly conservative. Small organisms with short life cycles may come into equilibrium with the environment in a few hours but it is improbable that adult food fish would ever come into equilibrium with the strontium-90 contaminated water. Ophel (Ref. 4.38) found concentration factors for strontium-90 in fresh water perch of about 3000, but these were reached only after five years by fish that had spent their entire lives in the contaminated water.

The second approach (Ref. 4.40) examined an entirely different situation, the maximum permissible continuous concentration that is acceptable in seawater due to waste disposal therein. As in the foregoing analysis, they are concerned with ingestion of the radioactivity through the food chain. They have made an extensive study of the effect of the growth condition on the activity to be expected in the fish body.

They propose the following equation for calculating the maximum permissible continuous concentration, MPCC, for a nuclide when the limiting intake is determined by the body burden:

$$MPCC = \frac{Sq' I_{ne}}{I_{nb'}} \times \frac{K + B}{B}$$

where

- q' = activity of the radioactive isotope in the critical organ when the body burden has been acquired (μc)
- I_{ne} = mass concentration of the total element (or carrier) in seawater (gm/cc)
- $I_{nb'}$ = total mass of the element (or carrier) in the critical organ (gm)
- K = physical decay constant of the nuclide (day^{-1})
- B = biological decay constant of the element for man (day^{-1})
- $MPCC$ = maximum permissible continuous concentration for seawater ($\mu c/cc$)

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For strontium-90, $q' = 2 \mu\text{c}$, $I_{ne} = 8.2 \times 10^{-3} \text{ gm/kgm}$, $I_{nb'} = 0.13 \text{ gm}$, $K = 6.9 \times 10^{-5} \text{ day}^{-1}$, $B = 3.8 \times 10^{-5} \text{ day}^{-1}$, and S is taken as 0.1. Using these values the MPCC is found to be $3.4 \times 10^{-5} \mu\text{c/gm}$ (or $\mu\text{c/cc}$).

Lines indicating the MPC_{sw} and the MPCC have been drawn on Figs. 4.95 and 4.96. It is observed that the MPC_{sw} is exceeded over an area with a radius of 128 meters for 3.48×10 seconds, or 0.403 days. The MPCC is exceeded to a radius of 6.07×10^3 meters for 7.02 days.

These calculations have considered only the effect of turbulent diffusion. Tidal and nontidal currents will contribute to the dispersion of the radiostrontium, but it is not possible to make a quantitative estimate.

The results of this analysis indicate that the release of even an entire payload of the radiostrontium is not an intolerable accident. Hazardous levels of activity would exist for such short times and over such small areas that the chance of an individual ingesting a significant quantity of radioactivity is nonexistent or extremely remote.

If the aborted vehicle were to fall in shallow water near shore, efforts will be made to recover it. It is expected that recovery can be made to depths of 100 feet and with some probability to 200 feet. For impact in deeper water, the contamination would probably not reach the surface, but the opportunity for fish to receive some activity would remain. In this case, and if a generator in shallow water is not recovered, it may be desirable to make periodic examination of the suspected area for radioactivity. If unexpectedly high levels of activity are found it would be possible to restrict fishing until the activity is dispersed. Many areas in this region are subject to restriction during missile launches and for gunnery exercises, so the facilities for patrolling are available and the restriction should not be alarming to the public. Periodic inspections of the fish catch for radioactivity could be made. A difficulty in making analyses of the water and fish is that it is not possible to predict the time of release of the radioactivity so inspections would have to be carried out on a long term basis. Since the potential hazard is slight and a program of inspection might create a poor public image it may be unwarranted.

Slow release from a large number of fuel containers becoming opened at random times would result in the contamination of more fish, but the levels of activity would be so low that no appreciable hazard would result.

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An airborne release of the radiostrontium fuel of the RTG can occur only as the result of some combination of circumstances involving launch pad fire accompanied by propellant detonation (Section 4.4.2). The fuel container is designed to withstand impact from a height onto the launch pad, the temperatures of a standard fire for at least 20 minutes and the overpressure due to a propellant detonation. The fuel containers are further surrounded by the generator and satellite structure so that any release is extremely improbable.

Even if the fuel containment is violated, presenting some opportunity for release of the fuel, it is still very difficult to define a source term for any airborne diffusion. The fuel is pelletized, or has been compressed by step pressing, and sintered to some extent either in an oven, or by self-heating after pressing. It is not a powder easily subject to becoming airborne, and it will not have been subjected to continuous high temperatures sufficiently long to cause volatilization. In the following study of a hypothetical release, it has been postulated that 0.1% of the entire loading is released over a period of 20 minutes.

The diffusion of the radioactivity has been calculated by the use of Sutton's equation (Ref. 4.41) which, in its general form for a continuous point release, is:

$$X = \frac{2Q}{\pi \mu C_y C_z x^{(2-n)}} e^{-z^2/C_z^2 x^{(2-n)}} e^{-y^2/C_y^2 x^{(2-n)}} \quad (1)$$

where

X (chi) = activity concentration (curie/in.³, equivalent to $\mu\text{c/cc}$)

Q = release rate (curie/sec)

μ = wind velocity (in./sec)

C_y = lateral diffusion coefficient ($\text{m}^{n/2}$)

C_z = vertical diffusion coefficient ($\text{m}^{n/2}$)

x = distance from source (m)

n = stability index (dimensionless)

y = horizontal distance from centerline of plume (m)

z = vertical distance from centerline of plume (m)

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Calculations are customarily made for the points on the ground under the centerline of the plume; in this case the second exponential term becomes unity.

For the climatologic and meteorologic conditions at Point Arguello, diffusion conditions are dominated by the subsidence inversion that prevails about 80% of the time. The height of the base of this inversion varies with the season being highest in summer (July) and lowest in winter (December) (see Fig. 4.88). As shown in Fig. 4.89, the average height during 1960 for the region of the PALC 2 was 1400 feet. Within the marine layer beneath the inversion base, diffusion conditions are good but the inversion base places an effective lid on the diffusion.

PALC 2 is at an elevation of about 400 feet. The inversion base is often below this, sometimes at sea level. Diffusion within the inversion is quite limited. The inversion base serves as a boundary for diffusion from above as well as from below. When the inversion base is below the elevation of PALC 2 points on the ground below the elevation of the inversion base are effectively protected from the radioactive plume.

If the inversion base is at sea level, no ground points are protected in this way but vertical diffusion within the inversion layer is limited and the plume will move away from the source horizontally, producing slight concentrations at lower elevations.

On the basis of these conditions, two meteorologic models have been adopted for analysis. The first of these postulates that PALC 2 is within the marine layer with the inversion base at 300 meters elevation. At large distances, the radioactivity becomes uniformly distributed vertically through the marine layer. This requires a modification of Eq. (1) giving

$$X = \frac{Q}{\pi^{1/2} \mu C_y x^{(2-n)/2} h} \quad (2)$$

where h = thickness of diffusion layer (m). The lateral dispersion is postulated to be of the usual form, and for off-axis points can be found

by using the term $e^{-y^2/C_y^2 x^{(2-n)}}$.

The second model assumes that the inversion base is at sea level. The concentration at various points is calculated using appropriate values of the parameters in Eq. (1).

The cloud concentrations have been calculated at three distances, 12,000, 16,000 and 40,000 meters. The first of these is approximately the distance to Lompoc, elevation 93 feet, population about 12,000, the

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nearest town. A height of land with an elevation of more than 800 feet is interposed on the direct line from PALC 2 to Lompac; a plume of activity to reach Lompac would have to follow a sinuous course--generally northward into the Santa Ynez Valley and then eastward up the valley. The second distance, 16,000 meters, is that to Jalama Beach. On the direct line from PALC 2, the ground rises to 2170 feet in El Tranquillon, but it is perhaps credible that radioactivity could reach Jalama Beach by a sinuous course. The distance of 40,000 meters is that to Gaviota, a place name that represents the closest approach of Highway 101 to NMFP.

Reference 4.17 suggests the use of the meteorologic parameters as follows:

	<u>Marine Layer</u>	<u>Inversion Layer</u>
u (m/sec)	3.6	3.6
$C_g (m^{(n/2)})$	0.24	0.12
$C_z (m^{(n/2)})$	0.14	0.05
n	0.25	0.50

In the calculations made, these values were used: $Q = 0.6$ curie/sec, $h = 300$ meters. The elevation of the source was taken as 120 meters. The release was considered to take place in 20 minutes.

Cloud concentrations in themselves give little information concerning the hazard to the receptor. Of more interest is the activity of radionuclide inhaled, and the integrated lifetime dose received. In an airborne release of radiostrontium, the principal dose to a receptor in the cloud path is incurred by inhalation. The activity inhaled is calculated directly.

$$I = XBt$$

where

I = activity inhaled (μc)

B = breathing rate (cm^3/sec)

t = exposure time (sec).

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It is assumed that the "standard man" inhales 20,000 liters ($2.0 \times 10^7 \text{ cm}^3$) of air in 24 hours. The average breathing rate is consequently $232 \text{ cm}^3/\text{sec}$ (Ref. 4.42).

The most significant assessment of the potential radiation hazard from inhalation is obtained by a calculation of the integrated lifetime dose to the critical organ accruing from the activity inhaled. This may be calculated by the method proposed in Ref. 4.43. The applicable equation is:

$$D' = \frac{73.8 f_a \Sigma FE (RBE) n T_e}{m}$$

where

- D' = lifetime dose for activity inhaled (rem/ μC)
- f_a = fraction of activity inhaled that remains in the critical organ
- $\Sigma FE (RBE) n$ = energy per disintegration delivered to the critical organ, considering the relative biological effectiveness (RBE) of the radiation, and n the relative damage factor for nuclides deposited in the bone (Mev)
- T_e = effective half-life of the activity in the critical organ (days)
- m = mass of the critical organ (grams)

For the inhalation of strontium-90, a distinction should be made between soluble and insoluble forms. The bone is the critical organ for the soluble form and the effective half-life is long. For the insoluble form, the lung is the critical organ, and the residence time of the activity is relatively short. In the subsequent calculations, the values used for the parameters for strontium-90 with its daughter product, yttrium-90, are given below (from Ref. 4.43).

Parameter	Insoluble	Soluble
f_a	0.12	0.12
$\Sigma FE (RBE) n$	1.1	5.5

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<u>Parameter</u>	<u>Insoluble</u>	<u>Soluble</u>
T_e	120	6.4×10^3
Critical organ	Lung	Bone (including marrow)
Mass	1000	10,000
D' rem/ μ c	1.18	31.1

Results for computations using the analytical models described are given in the following tables.

First Model--Uniform Vertical Dispersion in the Marine Layer

<u>Place</u>	<u>Distance (meters)</u>	<u>Cloud Concentration (μc/cc)</u>	<u>Activity Inhaled (μc)</u>	<u>Lifetime Dose (millirem)</u>
Lompac	12,000	3.66×10^{-7}	0.102	120
Jalama Beach	16,000	2.83×10^{-7}	0.079	92.5
Gaviota	40,000	1.285×10^{-7}	0.036	42.1

Second Model--Ground-Based Inversion

<u>Place</u>	<u>Distance (meters)</u>	<u>Elevation (meters)</u>	<u>Concentration (μc/cc)</u>		<u>Lifetime Dose (millirem)</u>
			<u>Plume</u>	<u>Ground</u>	
Lompac	12,000	30	1.348 $\times 10^{-5}$	1.150 $\times 10^{-6}$	377
Jalama Beach	16,000	0	8.76 $\times 10^{-6}$	5.03 $\times 10^{-7}$	165
Gaviota	40,000	0	2.21 $\times 10^{-6}$	1.08 $\times 10^{-6}$	354
(maximum)	32,140	0	3.06 $\times 10^{-6}$	1.13 $\times 10^{-6}$	370

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Examination of the tabulated results shows that the integrated doses that might be received by receptors at these points is not excessive. The maximum permissible dose for the general public is 500 millirem/yr, and this is not exceeded in any case. The maximum exposure at sea level for the inversion case is found to occur at 32,140 meters, where it amounts to 370 millirems. The integrated lifetime doses have been calculated assuming that the radiostrontium is in an insoluble form. In this case, the lung is the critical organ, and the greater part of the so-called lifetime dose is received in the first few months. If the radiostrontium were in a soluble form, the critical organ would be the bone and the integrated lifetime dose would be larger by a factor of 31.1/1.18. However, the dose would now be spread over 50 years, with the dose rate for the first year (which would be greatest) not excessive.

4.4.4 SNAP 17A and Atmospheric Sr-90

In the earth-orbiting satellite mission, the plan calls for burnup of the payload, including the radiostrontium-fueled generator, upon re-entry. In a successful mission, this re-entry will not take place until after several hundred years, when the radioactivity will have decayed to low levels. In the improbable case of an unsuccessful mission terminated by an abort at near-orbital velocity, or the attainment of only a short-lived orbit, the re-entry will result in the insertion into the mesosphere of the total strontium-90 inventory of the satellite system.

In this chapter, the subsequent tropospheric distribution and ground deposition of the strontium-90 is calculated, using a modification of a dispersion model developed for the consideration of bomb debris. The resulting atmospheric concentration is compared to the MPC_a , and the atmospheric burden and ground deposition to that produced by bomb testing. It is found that the tropospheric concentration is several orders of magnitude below the MPC_a ; the contribution to the total atmospheric burden is of the order of magnitude of that now present (June 1, 1964) as the result of nuclear bomb testing.

It is concluded that the re-entry burnup of the SNAP 17A generators after a successful mission presents no significant hazard. The early re-entry burnup of the mission payload is acceptable on a scientific basis, but public relations implications must be considered.

The first insertion of fission products into the atmosphere from weapons testing occurred on July 16, 1945 at Alamogordo, New Mexico. The test had about a 19-kiloton yield (Ref. 4.44). Since then, a total of 193 megatons of fission yield has been added to the atmosphere. A yearly breakdown is shown in Table 4.19. In the period between

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1952 and 1954, US testing reached its maximum in terms of fission yield. All nations participated in a voluntary moratorium during the years of 1959 and 1960. The year of maximum testing for the USSR was in 1962. France began small tests in 1960, but the yields were considered negligible for this analysis. There have been no tests since December 1962 that have resulted in any significant atmospheric release.

TABLE 4.19
Approximate Fission Yields of Nuclear Weapons Tests
Conducted in Atmosphere by all Nations

<u>Inclusive Years</u>	<u>Fission Yield (megatons)</u>		
	<u>US and UK</u>	<u>USSR</u>	<u>Yearly Totals</u>
1945 to 1951	0.70	0.06	0.76
1952 to 1954	37.00	1.00	38.00
1955 to 1956	9.20	4.00	13.20
1957 to 1958	19.00	21.00	40.00
1959 to 1960	Test Moratorium		
1961	0	25.00	25.00
1962	<u>16.00</u>	<u>60.00</u>	<u>76.00</u>
Totals	81.90	111.06	192.96
	42.44%	57.56%	

Table 4.20 shows the amount of yield produced during air bursts, ground surface bursts, and water surface bursts, up to 1958, and the atmospheric injections, up to 1962.

The bomb tests resulted in the atmospheric inventories shown in Table 4.21. The first two readings (May 1960 and May 1961) were taken during the testing moratorium and show the inventory changes during a period of no further injections. The readings for April 1962 and January 1963 were taken after a large series of atmospheric tests. They show that large-magnitude testing increases the inventory of the stratosphere up to 70,000 feet most significantly. The marked increase in the inventory at the 70,000- to 100,000-foot altitude in January 1963

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is partly attributed to the high altitude detonations by the United States in late 1962. One of these was a 1.4-megaton bomb which was exploded at a height of 400 kilometers, or about 250 miles. The series of large detonations carried out by the USSR at this time also appears to have penetrated to high levels.

TABLE 4.20

All Nuclear Tests

<u>Inclusive Years</u>	<u>Fission Yield (megatons)</u>			<u>Total Yield (megatons)</u>	
	<u>Air Burst</u>	<u>Ground Surface Burst</u>	<u>Water Surface Burst</u>	<u>Air Burst</u>	<u>Surface Burst</u>
1945 to 1951	0.19	0.55	0.02	0.19	0.57
1952 to 1954	1.00	15.00	22.00	1.00	59.00
1955 to 1956	5.60	1.50	6.00	11.00	17.00
1957 to 1958	31.00	4.40	4.60	57.00	28.00
1959 to 1960	Test Moratorium				
	<u>Lower Atmosphere*</u>	<u>Upper Atmosphere*</u>		<u>Total Yield</u>	
1961	17.00	8.00		120.00	
1962	40.00	31.00		217.00	

*The lower atmosphere includes the first few tens of thousands of feet above the tropopause, and the upper stratosphere continues to 150,000 feet. The tropopause on the average is located at 30 to 40,000 feet in the temperate and polar zones and 50 to 55,000 feet in the tropical and equatorial zones.

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TABLE 4.21
Global Sr-90 Inventory (megacuries)

	<u>May 1960</u>	<u>May 1961</u>	<u>April 1962</u>	<u>January 1963</u>	<u>June 1964 Estimate</u>
Stratosphere					
Northern hemisphere to 70,000 feet	0.25	0.22	1.11	4.51	
70 to 100,000 feet	0.25	0.12	0.13	1.21	
Southern hemisphere to 70,000 feet	0.25	0.26	0.21	0.42	
70 to 100,000 feet	0.19	0.12	0.05	0.10	
Troposphere	0.02	0.03	0.16	0.32	
Total in atmosphere to 100,000 feet	1.0	0.8	1.7	6.6	3.0
World-wide deposition	4.3	4.2	4.9	5.8	9.0
Estimated local fallout	2.6	2.5	2.5	2.4	2.3
Total	7.9	7.5	9.1	14.8	14.3
Cumulative production	8.8	8.5	11.1	19.1	18.4

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Since there were no detonations during 1963 which released significant fission products to the atmosphere, the inventory at present will be lower than the figures for January 1963. Data from ground collections and air sampling since that time have not been adequately processed, but it is estimated that the atmospheric burden, as of June 1, 1964, is about three megacuries. This estimate and the corresponding ground deposition are also shown in Table 4.21. The other data presented are taken from the AEC Health and Safety Laboratory reports (Refs. 4.46 and 4.46). British reports (Ref. 4.47) substantially concur.

4.4.4.1 Dispersion Characteristics

The AEC Health and Safety Laboratory has carried out, over a period of several years, a world-wide study of dispersion from nuclear weapons. High altitude sampling has been carried out from a few locations, and ground level air sampling at more stations. Ground deposition can be determined more accurately than air sampling and with greater uniformity and reproducibility by different laboratories, so this has been done at a great many cooperating stations. The deposition of various nuclides has been determined, with special attention given to strontium-90. Since the amount of precipitation is an important factor in ground deposition, comparison between stations is facilitated by reporting the deposition in millicuries/mi²/in of rainfall. Figures 4.97 and 4.98 are graphs of the deposition of Sr-90 at Pittsburgh, Pennsylvania during the bomb test moratorium of 1959 to 1960. Pittsburgh is representative of a middle-latitude locality with precipitation extending through the year; and the data, taken by the Nuclear Science and Engineering Corporation under contract with HASL, is quite complete and appears to be well handled. It is seen from these figures that the deposition is a periodic function of time, with a distinct annual maximum in the spring (February to April) and a lesser maximum in the early winter (November and December). A large fraction of the total atmospheric inventory is deposited in the spring following a bomb detonation. The remainder disperses more slowly.

Various theoretical mechanisms of the atmospheric circulation have been proposed to account for the distribution of material through the atmosphere, its exchange between levels, and its deposition on the surface. These have been reviewed by Machta in Nuclear Safety (Ref. 4.48).

4.4.4.2 Fallout Estimation

Stebbins (Ref. 4.49) has proposed that the fallout from the injection of radioactive material into the atmosphere can be fairly well predicted by assuming a half-residence time of material injected of five years in the mesosphere, of two years in the stratosphere, and of 21 days in the

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Fig. 4.97. Fallout Deposition at Pittsburgh, Pennsylvania During Test Moratorium

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Fig. 4.98. Data Curves of the Sr-90 Fallout on Pittsburgh, Pennsylvania

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troposphere. Equations for this analytical model have been fully developed in the SNAP 9A report (Ref. 4.50).

Bombs exploded on or near the surface produce a great deal of local fallout and inject into the troposphere and stratosphere. Detonations far enough above ground that the fireball does not reach the earth's surface produce practically no local fallout. For detonations at higher altitudes and for high-yield detonations at any altitude, there is some injection into the mesosphere.

In this report, the result of injection of the fuel load of an earth-orbiting satellite mission into the stratosphere has been examined in a similar manner. The injection due to burnup on re-entry or near-orbital abort will actually be into the mesosphere, so the treatment overestimates the maximum ground deposition that will be produced.

4.4.4.3 Effect of Burnup Re-entry on Inventory

It can be shown that, for injection into the stratosphere, the following equations apply:

$$\begin{aligned}
 A_1 &= A_0 e^{-(k_1 + \lambda)t} \\
 A_2 &= \frac{k_1 A_0}{k_2 - k_1} e^{-(k_1 + \lambda)t} - e^{-(k_2 + \lambda)t} \\
 A_3 &= \frac{A_0}{k_2 - k_1} k_1 e^{-(k_2 + \lambda)t} - k_2 e^{-(k_1 + \lambda)t} \\
 &\quad + (k_2 - k_1) e^{-\lambda t}
 \end{aligned}$$

where

A_0 = initial activity (curies)

A_1 = activity in stratosphere (curies)

A_2 = activity in troposphere (curies)

A_3 = activity on ground (curies)

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k_1 = residence time constant for stratosphere (day^{-1})

k_2 = residence time constant for troposphere (day^{-1})

λ = radiological decay constant (day^{-1}).

Also

$$\frac{dA_2}{dt} = \frac{k_1 A_0}{k_2 - k_1} \left[(k_2 + \lambda) e^{-(k_2 + \lambda)t} - (k_1 + \lambda) e^{-(k_1 + \lambda)t} \right]$$

and

$$\begin{aligned} \frac{dA_3}{dt} = \frac{A_0}{k_1 - k_2} & \left[k_1 (k_2 + \lambda) e^{-(k_2 + \lambda)t} - k_2 (k_1 + \lambda) e^{-(k_1 + \lambda)t} \right. \\ & \left. + (k_2 - k_1) \lambda e^{-\lambda t} \right]. \end{aligned}$$

The parameters used are:

$A_0 = 7.24 \times 10^5$ curies (one-mission load)

$k_1 = 0.95 \times 10^{-3} \text{ day}^{-1}$

$k_2 = 3.3 \times 10^{-2} \text{ day}^{-1}$

$\lambda = 6.85 \times 10^{-5} \text{ day}^{-1}$.

It is found that the maximum tropospheric burden is 2.26×10^4 curies, occurring at 110 days. The maximum ground deposition is 6.63×10^5 , occurring at 2870 days.

For injection of radioactivity into the upper atmosphere, the fallout is distributed fairly uniformly in the hemisphere of injection between the 20th and 70th parallels of latitude. This is well known by Fig. 4.99, adapted from Refs. 4.51 and 4.52. The area of this zone is 5.4×10^{14} square meters. If it is assumed that, at the time of maximum ground activity, 80% of it is deposited in this zone, the average

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Fig. 4.99. Total Sr-90 Deposition During 1962 Versus Latitude Band

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ground concentration is 9.83×10^{-10} curies/ m^2 , equivalent to 2.55 millicuries/ mi^2 . While there is, technically, no maximum permissible concentration for ground deposition, this value may be compared with the deposition in the northern hemisphere during 1962, due to bomb testing, of 17 millicuries/ mi^2 (Fig. 4.99).

The troposphere extends to a height of 10,700 meters (standard atmosphere). The volume of the zone between 20° and 70° latitude is consequently 5.78×10^{18} cubic meters. If it is assumed that 80% of the tropospheric inventory is uniformly distributed through this volume, there is, at the time of maximum concentration, 3.12×10^{-15} curies/ m^3 . This may be compared with the maximum permissible concentration for air (MPC_a) for nonoccupational workers for a 168-hour week. For strontium-90 in the soluble form, this is 10^{-10} $\mu\text{c}/\text{cm}^3$, and for the insoluble form, 2×10^{-9} $\mu\text{c}/\text{cm}^3$. These values are seen to exceed, by several orders of magnitude, the predicted tropospheric concentration derived from the burnup of one-mission fuel load.

4.4.4.4 Orbital Lifetime

The orbital lifetime of a satellite depends upon the altitude of perigee, the eccentricity of the orbit, and the $W/C_D A$ of the body.

The relation is shown for relatively low orbital altitudes in Fig. 4.100. The Medium Altitude Communications Satellite is to be placed in an orbit at about 6000 nautical miles, where the seven functional satellites will be dispensed at intervals along the orbit in a manner to provide worldwide communications coverage. The lifetime of a satellite in this orbit will be measured in thousands of years. The re-entry after this time will be random, but probably some form of satellite scavenging will be in effect in that period. For a fuel load of strontium-90, the activity will have decreased by a factor of more than 1000 after 28 years. Consequently, re-entry after a truly long-lived orbital residence presents no significant radiological hazard. The problem of atmospheric contamination by MACS arises only if there is a launch thrust or guidance failure which results in an immediate re-entry at near-orbital velocity or in the achievement of only a short-lived orbit. Short-lived, in this case, should be interpreted as less than 300 years.

4.4.4.5 Burnup Characteristic

In the preceding discussion, the term "re-entry burnup" has been assumed to mean that the radioactive fuel is subject to mechanical

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Fig. 4.100. Orbital Lifetime Versus Orbital Altitude

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ablation and aerothermodynamic effects which reduce it, above 100,000 feet of altitude, to molecular form or submicron particles, as in the debris of nuclear bomb detonations. Aerothermodynamic studies underway indicate that this may not be possible and that the particles from the so-called burnup may range from 50 to 100 microns. If this is the case, the bomb fallout model would not be applicable. Particles in this size range would not become distributed worldwide, but would fall at velocities that may be calculated with some assurance by the application of Newtonian dynamics or Stoke's law. Their trajectories would, however, be very complex, depending on factors that include their size, density, altitude, velocity at time of formation, and the wind velocities encountered. The area in which deposition would take place would be limited, but would be determined by these factors and the point of origin. This topic will be investigated in the next phase of the study.

4. 4. 4. 6 Psychological and Political Considerations

It has been shown in the preceding discussion that the burnup of the radioisotopic fuel load of a single MACS mission into molecular and submicron form would produce an increase in the atmospheric concentration that is insignificant compared to the MPC_a . It has also been pointed out that the problem does not arise for a successful MACS mission, and the reliability of the launching system is high. However, not everyone will look at the situation in this way. It can be pointed out that, if all seven of the generators in one mission were to burn up in an early re-entry, the present atmospheric burden of strontium-90 (June 1, 1964) would be increased by 25%, and the fall-out rate would approach that at Pittsburgh in the months shortly after the conclusion of the last bomb tests. The increase in the atmospheric inventory would be about equivalent to that produced by the detonation of a nuclear bomb with a seven-megaton fission yield. These facts can be presented in an alarming way, and the psychological effect on the general population of this country and all over the world can be great. A bomb test ban having been agreed upon, it is scarcely conceivable that the deliberate introduction of large quantities of radioactive material into the atmosphere would be politically acceptable.

The principal point to be made is that, in the case of the MACS, any such introduction would not be deliberate but accidental, and highly improbable. There must be invoked the principle that there can be no technological progress without some risk.

The SNAP 17A generator and MACS system could probably be redesigned for intact re-entry at the cost of added weight. However, random intact re-entry also presents safety problems, not entirely nuclear in nature.

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The burnup of an occasional SNAP 17A generator is probably acceptable. The burnup of a large number of large radioisotopic-powered devices may be intolerable.

4.4.5 Launch Pad Incident

A potential safety problem of any missile launching is that of a launch pad abort, the magnitude of the problem becoming even more serious when radioactive material is aboard the missile. The integrity of the generator and fuel capsule must be assessed under a launch pad abort environment.

The most destructive launch pad accidents are: missile fuel tank rupture, due to overpressurization or destruct system failure; and missile fallback after liftoff, due to propulsion system failure. Either can result in a violent explosion, producing a strong thermal shock wave followed by a short-duration fireball of intense heat and burning of the residual fuel. The first of these aborts arises from fuel tank rupture prior to liftoff, the maximum effect occurring with the ignition and combustion of the fuels and oxidizers. The second, fallback after liftoff, occurs with the explosion of the first stage booster, causing fallback of the entire vehicle, the remaining booster stage exploding upon impact on the ground. An abort at altitude yielding wide dispersion of vehicle components over the launch complex is of lesser magnitude, due to depletion of propellants and poorer mixing.

The mixing of the propellant fuel and oxidizer takes place at random, so the overpressures produced by the detonation and the extent and temperature of the fireball can only be predicted within wide limits. When LOX is the oxidizer, as in the Atlas stage, the part not reacted in the initial explosion will be evaporated rapidly, certainly in 15 seconds and more likely in five seconds (Ref. 4.53). The subsequent fire will be due to combustion of the liquid fuel at its interface with the air.

4.4.5.1 Propellant Detonation

The shock overpressure produced by an exploding launch vehicle presents the most stringent dynamic conditions to which the generator may be subjected. The A. D. Little Company has carried out a number of scaled tests with LOX and RP-1, and the Space Technology Laboratories, using these data, have proposed the following empirical equations (Ref. 4.54).

The first equation is that predicting the average pressure

$$P = 593/Z^3 - 28.8/Z^2 + 20.7/Z$$

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and the second is an expression of the pressure at 98% confidence level, that is, 98% of the explosions will produce overpressures with less than this value:

$$P = 9862/Z^3 - 187.9/Z^2 + 52.8/Z$$

where

$$Z = R/W^{1/4}$$

P = average side-on overpressure (psi)

R = distance from explosion (feet)

W = total weight of propellants (pounds).

Using these equations, the overpressures versus distance expected from the detonation of the Atlas booster (244,500 pounds, total propellant) have been calculated and are presented in the graphs of Fig. 4.101. If the epicenter of the detonation is midway between the LOX and RP-1 tanks, the average overpressure at the nearest generator (distance, about 58 feet) (see Fig. 4.102) is about 37 psi; the pressure for the 98% confidence level is 530 psi. If the epicenter is at the engine (point A in Fig. 4.102), the distance is 72 feet and the corresponding overpressures are 21 and 270 psi, respectively.

If the Agena-D stage with IRFNA/UDMH propellants were to be detonated, the epicenter would be closer to the generators; but the loading of this stage is much less, and the hypergolic fuels not only have much less tendency to detonate but also have a lower TNT equivalence than the LOX/RP-1 mixture. The overpressure at the generator is consequently not expected to be as high in this case.

4.4.5.2 Effect on the Generator and Fuel Container

The strength of the hexagonal generator structure was considered. The first analysis considered an equivalent cylindrical generator of radius R (see Fig. 4.102) and calculated the maximum allowable external pressure on it. The second was concerned with the maximum load applied across the width and height of the generator face before collapse. The third analysis examined the structural strength of the fuel capsule alone. Very conservative calculations predict that the generator housing will collapse under pressures exceeding 87 psi. A pressure of 6750 psi is necessary to rupture the Haynes-25 fuel capsule, however.

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Fig. 4.101. Explosion Overpressure Versus Distance from Explosion
LOX RP-1 Fuels

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Fig. 4.102. Vehicle and Generator System

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The generators are somewhat protected by the nose cone fairing, but there is some probability that they may be collapsed by the shock wave. The capsule will survive the most severe shock.

4. 4. 5. 3 Thermal Effects of the Fireball

The temperatures and consequent thermal fluxes in the fireball, resulting from the explosion of a missile, are less well known than the detonation overpressures. Only a few large-scale tests have been carried out, and actual launch pad aborts have not been well instrumented for obtaining such data.

It has been estimated by experienced personnel of the Atlantic Missile Range Safety Office (Ref. 4. 53) that the temperature history of an Atlas fire would be as follows:

> 4000° F	< 1 second
3000° to 3500° F	< 5 seconds
1200° to 1400° F	300 to 600 seconds.

Thus, the true fireball would last for less than five seconds. Scaling down the results of a Saturn test on a $W^{1/3}$ basis, a duration of 11 seconds is found. The fireball starts to rise rapidly soon after its formation because of the buoyancy of the hot combustion products; it is also subject to drift. Therefore, objects on the launch pad will probably not be within the fireball for more than five seconds.

4. 4. 5. 4 Experimental Data

Data for an Agena-D fire is not available. Buna (Ref. 4. 55) has made a compilation and analysis of several fire tests and aborts, principally dealing with hypergolic propellants. The Martin Baltimore and Denver Divisions, assisted by the Denver Research Institute of the University of Denver and the United States Bureau of Mines, Explosives Research Laboratory, Pittsburgh, Pennsylvania, have carried out half-scale tests of Stage I and Stage II Titan II launch pad fires. The half-scale Stage II loaded with 10,000 pounds of nitrogen tetroxide and 5800 pounds of UDMH/hydrazine is considered, for the purpose of this study, to be equivalent to the Agena-D loaded with 14,100 pounds of IRFNA and UDMH. The half-scale Stage II test had about double the loading of the Stage I test.

In these tests, effort was directed toward obtaining the best possible mixing of the propellants in order to maximize thermal effects. In the

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Stage II test, the highest recorded temperature was 2400°F. The fireball reached a diameter of 148 feet at 2.3 seconds after destruct initiation; the bottom was 115 feet above the ground at 4.8 seconds. In the Stage I test, the maximum temperature recorded was 3000°F at 2.2 seconds. The fireball reached a diameter of 151 feet in two seconds and the bottom was 99 feet off the ground at 4.5 seconds.

Personnel of the Bureau of Mines made measurements of the thermal flux within the fireball (Refs. 4.56 and 4.57) in the Stage I test. They report a maximum of 380 Btu/ft²-sec and averages from 50 to 175 Btu/ft²-sec. These are much higher than the values of 12 to 15 Btu/ft²-sec found in fire tests at Aberdeen Proving Ground (Ref. 4.58).

4.4.5.5 SNAP 17A Analytical Study

An analytical study of the SNAP 17A fuel capsule was made to determine capsule integrity when exposed to initial heat fluxes of from 50 to 300 Btu/ft²-sec.

The analytical solution of the transient temperature distribution within the capsule was obtained using the FB090 heat transfer and ablation code (Ref. 4.59). This program, which is capable of handling three-dimensional heat transfer and one-dimensional ablation, requires that the structure be divided into elements to form a space network describing the problem. A heat balance equation in a finite difference form is set up for each element, and the resulting set of simultaneous equations is solved for temperatures for small, successive increments of time. Elements are defined by temperature-dependent material property curves. Equations of curves of enthalpy versus temperature are used in handling variable specific heat and phase changes. To increase accuracy, the heat balance equations are written as functions of the average temperature gradients over a time interval rather than the temperature gradient at the beginning of the time interval. The method used to solve the equations is an iteration procedure, where the first iteration is made by evaluating unknown terms on one side of the heat balance equation. This procedure is repeated to obtain successive iterations leading to a solution, provided the procedure is converging. 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. For the work done here, no blocking effects by ablated materials were considered. The emissivity of the fireball was conservatively taken as unity.

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Elements 1-3 Haynes

Elements 4-23 fuel compound

Fig. 4.103. Heat Transfer Model

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For the SNAP 17A fuel capsule engulfed in a fireball, the heat flux was assumed to be uniformly distributed about the capsule. This is a very conservative approach, since protection would be afforded by the structure on which the capsule would be supported. The heat transfer model developed for the fuel capsule is of the form shown in Fig. 4.103 which represents a cross section of the capsule. The element network consisted of three elements (Nos. 1 through 3) of Haynes and 20 elements of fuel compound. Two capsules were considered, with both having the same heat transfer model. The quantity of fuel contained by each was the same, but one capsule had a larger wall thickness, 100 mils, as opposed to 81 mils for the other. Factors considered in writing the heat balance equations were: heat flux to the elements (an input curve to the code), radiation heat loss from the elements, and heat conduction through the elements. The first two quantities were applicable to the outside element only. Heat fluxes used were 50, 100, 150, 200, 250, 300 Btu/ft²-sec.

The results obtained from this analysis are presented in Fig. 4.104, in which the initial average thermal flux is plotted against time to melt the capsule wall and thus expose the radioisotope fuel. Thus, it is seen that, according to this analysis, exposure of the fuel in six seconds would require an initial average flux of 230 Btu/ft²-sec for the 81-mil capsule wall and of 280 Btu/ft²-sec for the 100-mil capsule. For exposure in 10 seconds, the heat fluxes required would be 168 and 180 Btu/ft²-sec, respectively. Exposure in 20 seconds would take place with fluxes of 98 and 108 Btu/ft²-sec, respectively.

This analysis is highly conservative in many respects. For example, the fuel capsule is considered to be fully exposed and irradiated from all sides. No consideration is given to its protection by position nor by the generator structure.

Any combination of conditions that would permit exposure of the radioisotope is improbable.

4.4.6 Fuel Capsule Earth Burial

4.4.6.1 Terminal Velocity Impact of Capsule on Earth Surface

To determine the probability and conditions of earth burial for the SNAP 17A fuel capsules for free-fall terminal velocity impact on the earth's surface, a test was carried out at Aberdeen Proving Grounds. Eight capsules were dropped from a helicopter on the artillery range. The helicopter was at an altitude of 5000 feet, sufficient distance for the capsules to attain the free-fall terminal velocity of about 225 fps for the capsule and 350 fps for the single-capsule design.

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Fig. 4.104. SNAP 17A Design 4 Fuel Capsule Firetest Fuel Exposure Time Versus Average Heating Rate for 100 Mil Haynes Wall and 81 Mil Haynes Wall

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The impact surface was the artillery range. The resulting surface is designated as a sandy loam soil with, generally, the upper three inches loose or soft and rain-encrusted and the underlying subsoil harder. In some places, the harder base is at the surface.

The fuel capsules used in the test were formed of hollow, low-carbon steel, with end caps welded on. There were two sizes. The larger were 3.225 inches in diameter, 7.52 inches in length and weighed 11 pounds, 12 ounces (single-capsule RTG design). The smaller were 1.50 inches in diameter, 7.5 inches in length and weighed 2 pounds, 6 ounces; they duplicated in dimensions and weight the fuel capsules for the SNAP 17A generator. Two of the larger size and six of the smaller were dropped.

The results of the drop test are given in Table 4.22. Calling the orientation with the longitudinal axis of the cylindrical capsule perpendicular to the earth's surface the zero angle position, the impacted capsules were all found in near the 90-degree position. Typical impact crater formation with a lip of thrown-out earth was noted in all cases, except one. In the exceptional case, the capsule struck a concrete bunker and was found on the surface.

TABLE 4.22
Capsule Drop Tests

<u>Specimen No.</u>	<u>Impact Surface</u>	<u>Angle* (deg)</u>	<u>Crater Depth (in.)</u>	<u>Soil Cover (in.)</u>
1 (large)	Soft soil	90	8	3
2 (large)	Soft soil	90	8	3
1 (small)	Soft soil	60		Partial
2 (small)	Soft soil	90	4-3/4	1
3 (small)	Soft soil	90	4	3/4
4 (small)	Hard soil	80	3	Rebounded, not covered
5 (small)	Soft soil	90	3-1/8	3/8
6 (small)	Bunker			None

*Angle between ground surface and short axis of fuel capsule (measured after impact).

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Fig. 4.105. Aberdeen Proving Ground Artillery Range

Fig. 4.106. Large Capsule Showing Crater and Earth Covering

Fig. 4.107. Smaller Capsule Shown in Crater

The larger capsules formed craters eight inches deep and were covered with fallback soil to a depth of three inches. Three of the smaller capsules (Nos. 2, 3 and 5), found at the 90-degree angle, formed craters from 3 to 4-3/4 inches in depth and were covered with 3/8 to 1 inch of soil. One (No. 4) struck at an 80-degree angle and formed a 3-inch crater, but rebounded and was found on the surface. The remaining capsule (No. 1) was found at an angle of 60 degrees, partially buried.

Figure 4.105 shows the artillery range upon which the impacts took place. For Fig. 4.106, the earth was cut away diametrically across the crater formed by one of the larger capsules; the capsule position, crater depth, lip and fallback of earth is shown. Figure 4.107 is a similar picture for one of the smaller capsules; the fallback earth has been scraped away.

Some other drop tests have been conducted previously by the Martin Company and reported in Refs. 4.61 and 4.62. These were performed on normal and scaled-up specimens simulating those of the SNAP 9A generator at the Sandia Corporation's Drop Test Range at Tonapah, Nevada. The target area is at about 5300-feet altitude, and the drops were made from 10,000 and 15,000 feet above the terrain. Velocities were measured, and the impact velocities were found to be about 250 fps (terminal velocity). In none of these tests was there any burial in the soil. Craters of about five inches depth were produced in the desert caliche, but in all cases, the specimens rebounded and were found on the surface. These capsules were dropped from an airplane at low flying speed, and consequently had some horizontal component of velocity at impact.

It is apparent that probability of burial of SNAP 17A fuel capsules upon terminal velocity is largely dependent upon the soil type. The important points derived from the drop test were:

- (1) The depths of burial of the smaller fuel capsules (SNAP 17A) were less than the larger, single-capsule design.
- (2) The fallback earth from the crater on top of the fuel capsule was also much less for the smaller capsule.

These considerations are extremely important in terms of fuel capsule meltdown upon earth burial, because as the depth of burial and the amount of fall increases, the greater the chance of meltdown. A heat transfer analysis of a buried fuel capsule is presented in the following section. Other factors, such as a horizontal velocity component and the orientation at impact, may have some effect.

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4.4.6.2 Temperatures for Earth Burial

A study has been conducted to determine the time-temperature characteristic of a SNAP 17A fuel capsule which might be released during an aborted launching and became buried after an earth impact. Specifically, the purpose is to determine if and when the fuel cladding would melt after the capsule impacts the earth.

Both the steady-state and transient conditions depend on the position and depth of covering of the capsule with earth, as well as the physical properties, dimensions, and shape of the fuel capsule assembly and the soil with which it may be buried. The following postulates were made in determining the temperature characteristics:

- (1) The fuel capsule maintains its integrity and cylindrical shape after impact with the earth.
- (2) The initial temperature of the cladding after impact is 1600° F. Aerodynamic calculations (Appendix R) show that a clad temperature of 1600° F upon impact would be attained if the capsule fell from a height of 1000 feet. Falls from greater heights result in lower clad temperature at impact. The rise in temperature due to impact is negligible.
- (3) The ambient and earth temperatures are initially 100° F.
- (4) The earth with which the capsule impacts is a homogeneous mass with constant physical properties and bounded by a horizontal line at its surface.
- (5) The contact resistance between the soil and the capsule is negligible compared with the thermal resistance of the soil.
- (6) The physical properties of the cladding, fuel and soil, listed in Table 4.23, are independent of temperature. Since the thermal conductivity of the cladding shows a strong temperature dependence, the value at 1600° F was used. The physical properties of soil, particularly the density and the thermal conductivity, depend on both the moisture content and the type of soil. The figures for the physical properties of soil in Table 4.23 are based on values presented in the literature for sands, clay and gravel and extensive measurements on various types of soil and sand (Ref. 4.62).

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TABLE 4.23

Physical Properties of Fuel, Cladding and Soil

Material	Density (lb/in. ³)	Emissivity	Heat Capacity (Btu/lb-° F)	Thermal Conductivity (Btu/fr-° F-hr)	MP (° F)
Strontium fluoride	0.145	--	0.446	0.97	2170
Haynes alloy clad	0.3	0.5	0.092	14.0	*2425
Soil	0.074	0.9	0.15	0.1 to 0.3	

*Haynes-25 starts to melt at 2425° F. Two phases exist until the temperature of 2570° F is reached, where it is all in the liquid phase.

The following geometries are postulated to exist after impacts (Fig. 4.108).

- (1) Capsule lying on side after impact (little or no earth burial).
- (2) Capsule partially buried in earth in upright position.
- (3) Capsule fully buried in earth in upright position.

Of course, other geometries are possible. However, calculations based on the above geometries shall give results that are representative of the range of positions of the fuel capsule after impact. The fuel capsule model used in this study is shown in Fig. 4.109. The fuel capsule assembly is 7.27 inches in length and has an OD of 1.4 inches and an ID of 1.2 inches. The capsule contains six inches of strontium fluoride fuel, generating heat at a rate of 1.15 watts/cm³. For the purposes of the problem, the fuel capsule is assumed to be a seven-inch cylinder of SrF₂ with 0.1-inch cladding.

No exact analytic solutions exist for the geometries in these figures. However, equations have been developed for similar geometries and can be used in obtaining approximate solutions to determine those cases in Fig. 4.108 which require an exact analysis, using relaxation techniques.

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Fig. 4.108. Typical Geometries After Earth Impact

Fig. 4.109. Version of SNAP 17A Fuel Capsule Used for Earth Burial Study

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It can be shown (Ref. 4.63) that for a long cylinder of radius N_s and length L buried horizontally in a medium of conductivity k , the difference between the surface temperature of the cylinder and the temperature of the medium is given by

$$T_s - T = \frac{Q \cosh^{-1} (D/N_s)}{2\pi kL}$$

where Q is the heat generation rate and D is the distance from the boundary of the medium to the surface of the cylinder. Figure 4.110 shows the surface temperature of the cylinder (T_s) as a function of D , with k , the thermal conductivity of the earth, as a parameter. Inasmuch as the temperature at $D = 1$ inch is below the melting point of the cladding, it is not necessary to consider the case of the capsule assembly lying on or slightly imbedded in the earth.

The fact that the steady-state temperatures in Fig. 4.108 exceed the melting point of the clad at depths greater than two inches for a soil thermal conductivity of 0.1 and greater than six inches for a soil thermal conductivity of 0.2 indicates that the cases of partial and total upright burial must be considered further. Not only is the orientation of the capsule with respect to the earth's surface 90 degrees from that used in obtaining the source-sink solution, but the axial heat conduction from the bottom to the top of the cylinder along the high thermal conductivity cladding must be considered.

Neglecting for the moment the heat conduction by the soil, the temperature drop along the cladding can be calculated, assuming that all of the heat generated in the fuel is conducted radially or, in effect, assuming that all of the heat is generated in the cladding itself. For the case of total burial, the temperature drop along the seven-inch length is 3100° F. For the case in which the cylinder is half-buried in an upright position, the axial temperature drop along the buried half of the cylinder is approximately 800° F. Using an emissivity of 0.5 for the cladding, it can be shown that the surface temperature of the capsule is 2100° F. Therefore, the cladding of the half-buried capsule will not melt.

These calculations indicate the need for a two-dimensional analysis which will account for both axial and radial conduction in an upright buried cylinder. Several digital codes have been developed to carry out this type of calculation, using relaxation techniques. One such code, well-suited for this study, is TIGAMM, a heat conduction code that determines steady-state and transient temperature distributions in odd-shaped geometries. In addition, TIGAMM can handle heat flow by way of radiation and convection at the boundaries of the geometry

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Fig. 4.110. Surface Temperature of a Long Cylinder Buried in an Infinite Medium

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under consideration. The required input for a steady-state calculation consists of a complete specification of the geometry, the physical properties of the materials, heat generation rates, boundary temperatures, and parameters for radiation and convection heat loss. For a transient calculation, the initial temperature distributions and the variation of the boundary temperature and heat generation rates with time are required as additional input.

The geometry is specified by dividing each material into nodes and indicating the surrounding nodes with which each node is connected.

Figures 4.111 through 4.113 show the node diagram used for input to TIGAMM for the case of the top of the capsule assembly level with the surface of the earth. The temperature distribution in the capsule and the surrounding area is considered to be radially symmetrical; therefore, it suffices to take a pie-shaped slice of arbitrary angle, θ . Each internal node is bounded by arcs determined by the position of the node with respect to the centerline of the capsule and the angle θ (arc length = $r\theta$).

Since the region surrounding the fuel capsule is essentially unbounded in the N direction and in the -Z direction, some arbitrary limits must be placed on the size of this region. Ideally, the temperature at these boundaries would be about the same as the input boundary temperatures. However, there are limitations imposed by the code itself.

Because the maximum number of internal nodes allowable as input to TIGAMM is 640, the lengths in the N and -Z directions could not be extended beyond 6.7 and 12 inches, respectively, without increasing the size of the earth nodes. Although an increase in size permits a larger area to be included, it may introduce large errors into the temperature distributions determined by the code.

TIGAMM was used to determine the temperature distributions for various geometries to ascertain if and when the cladding would melt. A boundary temperature of 100° F was used for air, and heat loss by way of free convection and radiation were included in the code computations. A soil thermal conductivity of 0.1 Btu/hr-ft-°F was used.

It was found that, with the uppermost end of the capsule level with the surface of the earth (Fig. 4.111), the cladding reaches a maximum temperature of 2036° F. At a distance of three inches below the surface of the earth, the cladding reaches a maximum temperature of 2800° F. These figures are higher than would actually be experienced because, as pointed out earlier, there is a limitation on the size of the soil region that can be used in the heat conduction calculations. Figures 4.114 and 4.115 show temperature distribution maps for the two cases. Note

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Fuel	265	264	217	216	169	168	121	120	73	72	25	24
	266	263	218	215	170	167	122	119	74	71	26	23
	267	262	219	214	171	166	123	118	75	70	27	22
	268	261	220	213	172	165	124	117	76	69	28	21
	269	260	221	212	173	164	125	116	77	68	29	20
	270	259	222	211	174	163	126	115	78	67	30	19
	271	258	223	210	175	162	127	114	79	66	31	18
	272	257	224	209	176	161	128	113	80	65	32	17
	273	256	225	208	177	160	129	112	81	64	33	16
	274	255	226	207	178	159	130	111	82	63	34	15
	275	254	227	206	179	158	131	110	83	62	35	14
	276	253	228	205	180	157	132	109	84	61	36	13
	277	252	229	204	181	156	133	108	85	60	37	12
	278	251	230	203	182	155	134	107	86	59	38	11
Clad	279	250	231	202	183	154	135	106	87	58	39	10
	280	249	232	201	184	153	136	105	88	57	40	9
	281	248	233	200	185	152	137	104	89	56	41	8
	282	247	234	199	186	151	138	103	90	55	42	7
	283	246	235	198	187	150	139	102	91	54	43	6
	284	245	236	197	188	149	140	101	92	53	44	5
	285	244	237	196	189	148	141	100	93	52	45	4
	286	243	238	195	190	147	142	99	94	51	46	3
	287	242	239	194	191	146	143	98	95	50	47	2
	288	241	240	193	192	145	144	97	96	49	48	1

6 in.

12 in.

Fig. 4.111. Node Diagram for Soil Used as Input for TIGAMM Heat Conduction Code

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Fig. 4.112. Node Diagram for Fuel Capsule Assembly Used as Input for TIGAMM Heat Conduction Code

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Fig. 4.113. Radial Sectors Used as Input for TIGAMM Heat Conduction Code

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Clad			Soil						
1294	1305	1334	797	316	225	203	190	178	170
Fuel			1400						
			1470	1097	532	362	306	288	256
			1546						
			1615	1395	833	587	470	412	380
			1677						
			1739	1494	937	674	537	459	433
			1794						
			1841	1575	1021	747	661	545	481
			1887						
			1925	1641	1089	808	718	592	525
			1955						
			1985	1694	1142	858	765	634	565
			2006						
			2019	1733	1183	899	731	622	602
			2032						
			2036	1771	1228	953	790	683	635
			2032						
			2028	1768	1231	966	811	709	665
			2017						
			2010	1741	1217	969	827	731	691
1988	1989	1995							
			1441	1137	960	858	810	801	800

Fig. 4.114. Temperature Distribution Map for Buried Capsule Assembly--
Uppermost End Level With Surface of Earth (all numbers in °F)

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Soil									
383	382	382<	381	298	240	207	190	182	181
844	826	802	742	507	377	310	276	260	257
1709	1636	1517	1218	717	509	407	357	335	331
2644	2647	2647							
		2656							
		2674	1776	1059	629	498	434	406	400
		2702							
		2715							
		2733	1988	1059	732	580	504	472	466
		2757							
		2766							
		2778	2092	1165	815	650	568	532	525
		2796							
		2801							
		2809	2143	1232	879	708	623	585	578
		2808							
		2804							
		2800	2154	1265	922	755	670	632	626
		2799							
		2784							
		2772	2117	1264	946	790	709	673	666
		2764							
		2741							
		2725	1993	1228	953	814	741	707	701
2718	2718	2719							
2006	1947	1851	1611	1162	948	830	765	735	730
1416	1400	1378	1325	1090	935	839	784	758	753

Clad

Fuel

Fig. 4.115. Temperature Distribution Map for Buried Fuel Capsule--Uppermost End Three Inches Below Surface of Earth (all numbers in °F)

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that in Fig. 4.114, where heat is directly lost from the fuel capsule to the air by radiation and convection, the effect of the cladding is significant; that is, axial conduction cannot be neglected. However, in Fig. 4.115, there is little temperature differences along the cladding, which indicates that the role of the cladding is not important and that the capsule is effectively insulated by the three inches of earth. Note also that the temperatures in the most distant nodes are well above ambient, so all temperatures in the network are higher than they would be in the actual case.

The TIGAMM code was used to perform transient calculations in order to determine the time required for the capsule to reach its melting point (2425° F) for the case of the capsule three inches below the surface of the earth. Figure 4.116 shows the time-temperature variation for the hottest node in the clad. The melting point of the clad (2425° F) is reached at nine hours after impact.

The time-temperature study performed using TIGAMM was compared with an analytical expression for the time-temperature for a long cylinder of infinite conductance, initially at temperature t_e and imbedded in an infinite medium at the same initial temperature. At zero time, the capsule is supplied with heat at the rate of Q Btu/hr/unit length. The expression for the temperature of the cylinder is

$$T = \frac{2QR^2}{\pi^3 K} \int_0^\infty \frac{1 - e^{-\alpha t \mu^2 / u^2}}{\mu^3 \Delta(u)} du$$

where:

R = twice the ratio of heat capacity of the medium to that of the perfect conductor

K = the thermal conductivity of the medium

μ = the thermal diffusivity of the medium

a = radius of the cylinder

t = time

The term under the integral sign is an expression for the series that is characteristic of heat conduction problems of this type.

In Fig. 4.117, the temperature given by the equation is plotted as a function of time for the parameters of this study. For a soil thermal conductivity of 0.1, the melting temperature of the cladding is reached

Fig. 4.116. Transient Temperature Characteristic for Hottest Node in Fuel Capsule Buried in Earth with Uppermost End Three Inches Below Surface of Earth

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Fig. 4.117. Transient Temperature Characteristic of a Long Heated Cylinder of Infinite Conductance Buried in an Infinite Medium Initial Temperature-100° F Q - 860 Btu/hr/ft

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at 10 hours or about 7.5 hours after the clad reaches a temperature of 1600° F.

Basically, the conclusion that can be drawn from this experimental and theoretical analysis is that the SNAP 17A fuel capsule was not buried deep enough to permit sufficient earthfall to cause meltdown of the capsule upon earth impact. In order to confirm this, an air drop on the NMFPA would provide the best earth burial data.

4.4.7 Recovery of Radioactive Fuel After Missile Abort

A launch vehicle abort during the launch phase would result in impact of the vehicle debris in the area of the launch pad, either on land or in shallow water near the shore. Two emergency conditions are postulated; a missile collapse or fallback on the launch pad, and a down-range accident caused by loss of thrust or by command destruct. The associated radiation hazards which will result from these credible launch conditions and recovery operations are discussed in this section. The radioisotope might be in a large mass of vehicle debris or separated from it in the dispenser or as the individual generators, or as the individual fuel capsules. An analysis of the emergency conditions was performed to establish methods of location, neutralization, handling and recovery of the radioactive fuel which will be distributed as a result of the accident.

Information concerning the launch site terrain and recovery requirements has been obtained from the Aerospace Document 1983.80-018 and USNRDL-TR-545. Radiational exposure limits used in the analysis are those defined by AEC, Title 10 standards.

4.4.7.1 Procedural Requirements

In the event that an emergency does occur, the following procedural requirements must be satisfied:

Task 1--Locate all radioactive sources.

Task 2--Provide access to the radioactive sources.

Task 3--Neutralize the radioactive source by shielding in a manner suitable to permit handling.

Task 4--Removal of the radioactive source from the area to a suitable storage or shipping area for disposal or re-processing.

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4.4.7.2 Location of Radioactive Fuel

Missiles launched from the Pacific Missile Range are tracked by several radar and optical systems. The principal tracking capability is within the Vandenberg Tracking Station (VST-1). Available at the station are a 60-foot dish antenna capable of UAF/VHF receiving and doppler transmitting/receiving; a 60-foot VHF receiver; a manually operated tri-helix receiver; a three-axis angle track; and various tracking support equipment. Table 4.24 lists the available optical tracking equipment and its location. The optical systems can triangulate on the splash point; thus, it should be possible to localize and limit the search area both on land and in the water.

TABLE 4.24
Optical Equipment and Site Availability

<u>Equipment and Sites</u>		<u>Location and Quantity (operational)</u>				
		<u>Point Mugu</u>	<u>San Nicholas</u>	<u>NMFPA</u>	<u>VAFB</u>	<u>Santa Cruz Island</u>
Bowen and historical cameras	Units	5	--	2	--	--
	Sites	43	--	5	--	--
Theodolite stations	Units	6	6	3	4	1
	Sites	6	6	3	4	1
MOTU stations	Units	2	2	3	1	--
	Sites	2	7	4	2	--
Mitchel theodolite	Units	--	2	--	--	--
	Sites	--	2	--	--	--
Eyemo camera	Units	1	2	--	--	--
	Sites	1	2	--	--	--
ME-16	Units	--	--	1	--	--
	Sites	--	--	1	--	--
LA-24	Units	--	--	1	--	--
	Sites	--	--	1	--	--
Optical skyscreens	Units	--	--	3	--	--
	Sites	--	--	2	--	--
FPS-16 boresight camera	Units	3	1	2	--	--
	Sites	3	1	2	--	--

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At Point Mugu, trajectory information is collected by radars, theodolites, MOTU and acceleration cameras. The radar complex consists of four FPS-16 (C-Band), two MPS-26 mobile (C-Band), and two SCR-584 (S-Band) radars. Three FPS-16 radars are able to track through a range of 500 nautical miles.

The search will be conducted by the Missile Accident Emergency Team (MAET) under the direction of the Ground Safety Officer. The team occupies the fallback area during the launch period. Current operational orders state that the MAET Commander will deploy his forces so that the approach to the impact will be from upwind. The RADCON component of the team will be used to conduct a gross radiation survey, the remaining members staying upwind 1/2 mile until the survey is complete. Members of MAET include a medical group, a photographer, a missile expert and an explosive demolition expert.

Although the final step in every recovery procedure will involve a visual observation of the fuel component, detection of the gamma radiation will guide the recovery team to the recovery site in most cases.

For this reason, the radiational environments for the capsule, generator, and payload in air, water, earth and various combinations of these media were determined.

In addition to providing information for locating the source, it provides for an understanding of the possible radiational hazards to be encountered during the recovery operations.

It was assumed in these calculations that the dose rate at any given distance from the center of a source was the same in all directions. At short distances, this assumption will yield errors up to 25% in the rates for a single generator as the rates above the source are much lower than those to the side. However, as the distance increases, the source approaches a point source and the error correspondingly decreases.

The results of the environmental radiational analysis are illustrated in Figs. 4.118 through 4.126. The existing dose rates associated with the possible source configurations reveal the feasibility of precisely locating the source by monitoring instruments mounted aboard aircraft (helicopter) or boats. Table 4.25 summarizes much of the data contained in the figures and is useful in determining shielding requirements of recovery vehicles.

To indicate the altitude at which these sources can be detected if they are lying in water or buried in the earth, the dose rates are given as a function of distance in air after attenuation by various thicknesses of water and soil (Figs 4.121 through 4.126).

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Fig. 4.118. Dose Rates from Single Fuel Capsule, Single Generator, and Single Payload as Function of Distance in Air

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Fig. 4.119. Dose Rates from Single Fuel Capsule, Single Generator, and Single Payload as Function of Distance in Water

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Fig. 4.120. Dose Rates from Single Fuel Capsule, Single Generator, and Single Payload as Function of Distance in Earth

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Fig. 4.121. Dose Rates from Single Fuel Capsule as Function of Distance in Air After Attenuation by Thicknesses of Water Designated

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Fig. 4.122. Dose Rates from Single Generator as Function of Distance in Air After Attenuation by Thicknesses of Water Designated

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Fig. 4.123. Dose Rates from Single Payload as Function of Distance in Air After Attenuation by Thicknesses of Water Designated

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Fig. 4.124. Dose Rates from Single Fuel Capsule as Function of Distance in Air After Attenuation by Thicknesses of Earth Designated

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Fig. 4.125. Dose Rates from Single Generator as Function of Distance in Air After Attenuation by Thicknesses of Earth Designated

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Fig. 4.126. Dose Rate from Single Payload as Function of Distance in Air After Attenuation by Thicknesses of Earth Designated

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TABLE 4.25
Shield Thickness Required for Personnel Protection
from SNAP 17A Fuel

	<u>Condition of Fuel</u>		
	<u>Payload</u>	<u>Fuel Assembly</u>	<u>Capsule</u>
Indefinite Exposure = 0.02 mr/hr			
Air (ft)	2750	2100	1550
Water (ft)	8.8	8.4	7.4
Earth (ft)	5.9	5.7	5.3
100-Hour Week Exposure = 0.1 mr/hr			
Air (ft)	2200	1550	1100
Water (ft)	8	7.5	6.5
Earth (ft)	5.3	5.2	4.7
Lead (cm)	25	22	19
40-Hour Week Exposure = 2.5 mr/hr			
Air (ft)	1200	700	400
Water (ft)	6.2	5.8	5.0
Earth (ft)	4.2	4.1	3.6
Steel (cm)	35	30	26
Lead (cm)	19	16	14
Uranium (cm)	10.5	9	7.5
1-Hour Emergency Exposure = 1250 mr/hr			
Air (ft)	135	60	35
Water (ft)	3.2	3.0	2.4
Earth (ft)	2.2	2.2	1.8
Steel (cm)	18	14	10.5
Lead (cm)	9	7	4
Uranium (cm)	5.0	3.5	2.5
15-Minute Life Saving Emergency Maximum Allowable Exposure = 400,000 mr/hr			
Air (ft)	19	7	3

Shipping Cask = 10 mr/hr at 3 ft

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The fuel component location and accessibility after the emergency may vary considerably. The analysis is based on consideration of various landing conditions of the fuel component within the ground and local ocean area. The fuel may be visible and accessible on a firm surface such as the launch pad or rock; it may be entangled in missile wreckage in the case of the pad accident; it may be buried in mud or be submerged in water; the fuel could be caught in a tree or be deep at the bottom of a scrub tree-covered, steep-walled gully or canyon.

Where radiation reveals the approximate location of a fuel component neutron on the ground but vegetation or other features do not allow a visual siting it would be practicable to spray water into the suspect area. The elevated temperature of the fuel component should cause an initial burst of steam which may pinpoint the hidden source.

4.4.7.3 Recovery Equipment

The equipment recommendations made here for vehicle types should be considered preliminary and general. The search, neutralization and recovery analysis has been made on the basis of a number of parameters which may be subject to change. Conditions such as a large amount of ground water or mud may make search and recovery procedures very difficult as locating a fuel capsule buried in mud may be an impossible task. It is probable that a launch constraint based on local ground conditions due to wet weather may be required.

Another parameter greatly influencing equipment specification is topography. Detailed equipment requirements, for design purposes, cannot be completely defined without a thorough examination of the range hazard area. This effort will be one of considerable magnitude and will be conducted in Phase II of the program.

Recommendations for the auxiliary equipment such as tanks, manipulators, etc., as well as the recovery methods resulting from the analyses, are presented.

A shielded, manually operated rubber-tired recovery vehicle would be required. This vehicle would be implemented to neutralization and recovery of fuel components which are visible and easily accessible on firm ground having a grade no greater than 10%.

The vehicle would contain a manipulator and be capable of lifting an intact payload and of manipulating cutting devices, gripping devices, shearing devices and pry bars. It would be capable of operating in water up to five feet in depth.

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A vehicle will be required to affect fuel neutralization and recovery in difficult terrain having a greater than 10% grade or a sandy or muddy ground composition. A five-foot water depth capability will also be required.

This vehicle can be a manually operated type such as the AMF Handyman. These vehicles are adaptable to all types of terrain and are winch equipped to allow a descent down slopes too steep for normal vehicle operation. The vehicle manipulators are capable of dislodging fuel components from difficult positions and picking up an intact payload.

A hoist equipped helicopter will be required for use in recovery conditions occurring at the bottom of ravines or water. The helicopter will be used in conjunction with a ground vehicle as described in the recovery analysis. The only function of the helicopter will be to lift shielded containers holding recovered fuel components.

A recovery tank will be constructed to store and neutralize fuel components. The components may range in size from a capsule to an entire payload. This will require the tank to be large enough to contain an intact payload. The tank shall be 20 feet long by 10 feet wide by 7 feet deep. This size will ensure that even greatly distorted payloads can be safely stored. The tank will be installed so that the sides, up to within one foot of the top, are within a backfilled excavation. The purpose of this type of installation is to limit the tank size by using earth as a side shield, and to retain some shielding in the event of a tank rupture.

The tank will serve as a depository for recovered fuel components, as a safe storage area until a permanent disposal means is available; as a cooling basin to preclude meltdown; as a shielded work area for reduction of large components to approximately one cubic foot size for simpler removal from the site.

The tank shall be located outside the impact limit lines to ensure against damage as a result of missile fragment impact.

The tank will be equipped with a makeup water line and removable vented metal roof. A series of test point will be set around the tank to collect samples of water to ensure that no Sr-90 is out of containment. The vent will also be monitored after fuel has been placed in the tank.

A submersible radiation monitor will be provided so that as fuel recovery proceeds, an inventory of the number of capsules recovered may be kept. Visual observation will be allowed by installing submersible lights and using a plexiglass-bottomed box two feet on a side.

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Consideration has been given to two alternate approaches which would utilize expedient means in the event of an emergency. It might be possible to provide a temporary pool by damming the flame bucket at the launch pad, but this has the disadvantage of tying up that facility for some time and might require an excessive water demand. A portable pool for use at the impact location might be useful but could scarcely serve the purpose of a specially designated permanent pool.

A second expedient would be to scoop a hole of sufficient size and line it with concrete or asphalt after the emergency. This would be less costly but would not be available for several days after construction begins if a reasonably secure pool is desired.

An assortment of long handled tools such as grippers, spades, rakes, hoes, etc., will be required for use in recovery from on-site water. Firm design parameters for these tools cannot be established at this time.

A remotely controlled bulldozer, similar to the AMF Sandman, would be required for use in clearing and filling areas which would be too hazardous for the operator-controlled recovery vehicle to negotiate when close to a fuel component. A vehicle of this type is in existence at Fort Belvoir, Virginia, and should be brought to PMR for stand-by use.

A number of means may be made available to shield the fuel components as recovery proceeds in order to speed the process.

Earth or sand. Since some danger of a meltdown exists if the capsule is burned for too long in earth, it should not be piled atop a component unless continuous wetting is assured. A trench may be dug in which fuel components may be temporarily placed. This would provide a large area of safety even within the immediate recovery zone since a direct radiation field would exist only above the trench.

Fuel components may be placed behind a pile of earth or sand, creating a safe sector which unprotected personnel may occupy.

Water. Water, where it is available, is an ideal expedient shield material. Where danger of losing a fuel component does not exist, six feet of water will serve as an absolute shield. A portable tank might be carried to the recovery site in which to place components as they are located.

Sand or earth-filled bags. Where cutting work is required on a large missile component to enable removal of a payload, the shielded vehicle might construct a sand bag shield between the sources and the work site. This would enable men brought to the work site in the

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shielded vehicle to accomplish the necessary tasks without remote devices.

Concrete blocks. Prefabricated concrete blocks might be utilized to build a shield for isolating fuel components as recovery work proceeds. The most dense aggregate available should be utilized in fabricating the blocks.

The maximum block weight should consider the carrying and placing capabilities of the vehicle involved.

Slurry concrete. Where some danger exists that a capsule has been ruptured, slurry concrete may be sprayed from distances on the order of 50 feet to contain the shield the capsule.

4.4.7.4 Recovery Procedures

The general approach recommended for fuel component recovery consists of employing range personnel and search techniques as referenced in USNRDL-TR-545. The recovery procedure to be followed is:

- (1) Search to locate all fuel components.
- (2) Map hazard areas to establish personnel restriction areas.
- (3) Neutralize fuel component through shielding or establishing an exclusion area.
- (4) Recovery fuel from landing point and place fuel in water tank for storage prior to disposal.
- (5) Establish a recovery corridor along which the recovery vehicle will travel from the recovery area to the recovery tank.
- (6) Enclose fuel in shipping containers to be constructed on site after size requirements for that emergency are determined.

The following section presents detailed recovery procedures for the two cases of interest, missile fallover or collapse and post-launch destruct. In the former case, three fuel dispositions are considered: intact payload, partially intact payload with some fuel assemblies, and fuel assemblies and capsules. In the latter case, differentiation in procedure among impact points including flat terrain, steep-walled canyons, inland water, and the ocean are treated for the intact payload and fuel assemblies and capsules.

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Missile fallover or collapse. Visual and radiation means shall be utilized in attempting to locate fuel components. Assuming that the entire payload has remained intact, a standard radiation survey meter should indicate a dose rate dropoff of 75% if rotated 75 degrees and a 90% dropoff if rotated 85 degrees from the point of maximum reading. A collimator consisting of a lead tube placed before the survey meter window should be utilized before the recovery area is entered so that the presence of any loose fuel components may be discovered. Resolution to 10 degrees of arc is possible. The fallen payload should also be examined visually by use of a telescope.

If the payload is partially shielded by missile wreckage, it may be necessary to use a helicopter to make an initial radiation survey of the payload. While the initial portion of the survey is conducted from 1200 feet or more, the final unshielded surveillance will involve an approach to about 200 feet from the payload.

Where possible, three two-man teams will approach the payload in jeeps along three spokes of 120 degrees separation. Where this is not possible, a survey team on foot may be used but the length of stay in the recovery area will be shortened.

From the final close approach point, it should be possible to determine the problems which will be encountered by the recovery vehicle in removing the payload from the wreckage. Photographs of the wreckage may also be taken to assist in planning the removal operation.

In approaching the payload for recovery, the recovery vehicle operator should survey for radiation sources to each side and behind his vehicle. It is possible that a loose fuel component has fallen into an area where it is shielded from several directions and has not been detected in the initial ground or air survey. A stop and survey at 100-foot intervals on the path to the payload should ensure that no sources have been bypassed. Air sampling should also be conducted on the approach to the source.

The initial neutralization will be accomplished by establishing an exclusion area. The radius of the area should be approximately a 1200-foot circle centered on the payload and into which none but recovery personnel may enter. At this point, the dose rate is approximately 2.5 mr/hr. A wide circle of 3000-foot radius should also be established as a control area since nominal exposure will begin inside this area.

The vehicle will be equipped with cutting devices capable of separating the payload from the remainder of the missile if it is attached.

In approaching the payload, the vehicle operator will monitor the area continuously to ensure that he is not passing a separate fuel component.

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The vehicle will carry the payload to the recovery tank and deposit it in the tank. The payload will then be processed for safe removal from PMR. To facilitate removal of the fuel from PMR, it must be reduced to a size feasible to handle. This may involve cutting an intact payload while in the pool to remove a satellite or an RTG and finally removing the fuel assemblies.

If distortion due to impact or fire has not seriously altered the dimensions of the intact fuel assemblies, they will be reinserted in their original shipping casks.

When this is not possible, the fuel will be reduced to a size somewhat smaller than one foot by one foot by one foot and inserted into a removal cask.

It is not necessary to provide casks for fuel removal in advance of the launch. The recovery tank will provide the neutralization required for the cask fabrication period.

The casks will be designed according to ICC regulations, i.e., 200 mr/hr at the surface, 10 mr/hr at one meter, and will be able to hold fuel roughly one foot by one foot by one foot.

Cooling for the casks will be provided to preclude meltdown during shipping from the site.

If the payload is only partially intact, the location method is the same as for the intact payload with the addition of procedures for defining the location of the loose fuel assemblies.

The loose fuel assemblies must be located initially by radiation triangulation, being careful to differentiate between the partially intact payload and the smaller sources.

Neutralization is accomplished with the addition of a procedure to neutralize lost fuel assemblies. A loose fuel assembly will be isolated by establishing a 700-foot radius circle around the fuel assembly.

The recovery vehicle will first approach the fuel components in a direction which will keep the vehicle shield between the operator and the fuel component. When two fuel components can be safely approached, the one with the largest source strength will be recovered first.

A container will be provided on the front of the recovery vehicle so the fuel assemblies may be deposited while other fuel assemblies are sought and recovered. With fuel assemblies in the container, the vehicle will not be allowed to drive over rough terrain until the fuel has

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been deposited in the recovery tank. This is to preclude losing fuel as the result of an accident and irradiating the driver.

If it is known that the payload has broken up into capsules or fuel assemblies, radiation detectors will be used merely to define the hazard area and the general location of the components. The exact location will be determined by visual and radiation means from the recovery vehicle.

The monitoring team will define the exclusion area by the intensity of radiation, utilizing an in-out pattern of search.

Recovery will be accomplished as previously indicated except in the event of an explosion. If an explosion has followed the fallover, the fuel assembly or capsule may be located in the wreckage. In this event, the recovery vehicle will use its cutting apparatus to dismantle the missile to the extent required for fuel retrieval.

Post-launch destruct. For impact on flat terrain, all procedures will be similar to those proposed in Case 1.

For impact within a steep-walled canyon, the following procedures apply.

The trackers following the ascent of the missile are instructed to follow the payload as it ascends and descends in the case of an early abort or destruct. Triangulation will therefore yield the general location of the payload. A helicopter, equipped with radiation survey instruments, will be used to determine a more accurate location. The detector may be trailed beneath the helicopter which should fly at between 400 to 600 feet above the search area. A rough triangulation on the payload will be accomplished by searching for a maximum count rate from various directions.

In this case, the payload is neutralized by its location in a steep-walled canyon.

A pair of vehicles will be involved in the recovery. The recovery vehicle will be attached with a set of cables to a larger tracked vehicle or tree which will act as the anchor for the descent into the canyon. The anchor vehicle will be equipped with a pair of front winches to lower and raise the recovery vehicle and a back cable and winch which will be used to tie the anchor vehicle when the ground is unstable.

The recovery vehicle will descend into the canyon, find the payload and grasp it. The anchor vehicle will then assist the recovery in withdrawing. The anchor vehicle being unshielded, the withdrawal process will be accomplished so that the recovery vehicle is kept at a distance greater than 100 feet. The recovery vehicle will then carry the payload

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to the recovery tank. Vehicles should precede and follow the recovery vehicle to ensure that no personnel enter a 1200-foot radius circle drawn around the payload as it proceeds toward the recovery tank.

When trees and other obstacles block the approach of the recovery vehicle, a remote-controlled bulldozer would be utilized to clear a path.

In the case of impact of fuel assemblies and capsules within a steep-walled canyon, the trackers following the payload will determine the approximate landing point of the major components. The helicopter equipped for the radiation search will be used to search as low as 100 feet above the canyon floor to determine with the desired accuracy the approximate locations of the components.

Additional features are required to cope with the number of components in the fuel recovery for this case. The recovery vehicle will operate in conjunction with a helicopter to accomplish disposal. After the recovery vehicle has found and gathered some component, it will proceed to a convenient point for a helicopter rendezvous. The helicopter will be equipped with a wire net on a cable; a net will be lowered into the canyon; the recovery vehicle will place the collected components in the net. The helicopter will carry the net along the recovery corridor to the recovery tank into which the net and cable will be dropped. Personnel with grappling tools will then clear the net for use on another trip to the recovery site.

If the intact payload impacts on inland water, the trackers will indicate the approximate location by following the payload to its disappearance. The helicopter-borne radiation search procedures will reveal that the payload or its parts have been shielded and, therefore, cannot be detected, if the water is over four feet deep. The search procedure will require that men on foot survey the presumed impact area. Constant monitoring during the approach should ensure that the fuel components have not been bypassed. On finding a body of water, the searchers should try to find the missing sources either by sighting it or looking for convection currents at the surface of the water caused by the heat produced in the capsules. Submersible radiation detectors may also be used to probe the water. A relatively insensitive detector will indicate the presence of the source at six feet.

The source in this case is neutralized by the water in which it is immersed.

The recovery procedure will involve the use of grappling equipment. Before the payload is pulled from the water, an earth shield should be constructed behind which personnel may stand or lie while they assist in the withdrawal. Mirrors will be used to observe the progress of the withdrawal. The recovery vehicle will grasp the payload and the

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unshielded personnel will then assist in the withdrawal. The recovery vehicle will grasp the payload while it is still under water and the unshielded personnel will leave. The recovery vehicle will then proceed through the recovery corridor to the recovery tank.

The location of the fuel in the form of fuel assemblies and capsules will be the same as indicated in the preceding section except that fuel components will be harder to track as they fall.

Assuming that all fuel components lying on the ground have been recovered, missing fuel assemblies or capsules must be assumed to be in a shielded resting place.

Since a fuel capsule will be readily detected in water, if the detector is brought within five feet, a search by helicopter or boat will be undertaken. A detector suspended from the helicopter or boat will be dragged through each body of water in which a fuel component may have landed until they are located.

For the recovery procedure, finely meshed net will be anchored in one section of the body of water to act as a temporary storage point.

The grappling techniques previously described will be used to retrieve the components. Swimmers or divers may approach to within about eight feet of a fuel component without significant irradiation.

The grappled component will be placed by the recovery vehicle into the storage net until all the components have been recovered from the water. At this time, the recovery vehicle will remove the netted fuel components and carry them to the recovery tank. If some danger of a spill exists because of the ruggedness of the terrain, a helicopter pickup will be arranged.

Should the water be too deep for use of the recovery vehicle, miscellaneous remote tools will be used by personnel in a boat to retrieve and drop them into the net held underwater by the recovery vehicle grapppler. Swimmers or divers may also be used.

In the case of impact in the ocean, it is evident that the recovery probability diminishes with the size of the fuel configuration and with increasing depth of the ocean at the point of impact. Radiation detectors would be of little assistance in the search for a nuclear source under deep water. The shadow-graph (a device being developed by the Westinghouse Company) utilizes a sonar scan displayed on a cathode ray tube and may be adaptable to the search. It is towed about 25 feet above the bottom and has a resolution of a few inches. The incorporation in the vehicle of a small sonar transducer to be operated during the launch phase may be feasible as a means of increasing the probability of locating the point of impact.

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Recovery of the radioisotope from shallow water is highly probable. Recovery from water to a depth of 100 feet appears to have a high probability. Beyond 100 feet, the probability decreases and approaches zero at 200 feet. Diving by professionals is said to be limited to 120 feet and to periods of 20 minutes in these waters because of the strong currents. Naval diving units are available from PMR for underwater recovery operations.

4.4.8 Transportation Requirements

Safe handling of the fuel during shipment places definite requirements upon the design of the shipping cask.

The strontium-90 fuel is classified by the ICC as a Group I Class D Poison, denoting radioactive materials that emit gamma rays only or both gamma and electrically charged corpuscular rays. The design and shipping requirements which are to be applied to this equipment are as follows:

- (1) Radioactive materials, such as radioactive strontium, that present special hazards due to their tendency to remain fixed in the human body for long periods of time must be packed inside metal containers approved by the Bureau of Explosives, in addition to the prescribed Interstate Commerce Commission packing (Specification 2R) (Ref. 4.64).
- (2) All the radioactive materials must be so packed and shielded that the degree of fogging of undeveloped film under conditions normally incident to transportation (24 hours at 15 feet from the package) will not exceed that produced by 11.5 milliroentgens of penetrating gamma rays of radium filtered by 1/2 inch of lead (Ref. 4.64).
- (3) Containers for more than 4000 millicuries must have the words RADIOACTIVE MATERIAL and the permit number stamped, embossed or otherwise permanently applied so that they will not be obliterated by fire (Ref. 4.65).
- (4) Means must be provided for applying a seal so that the outer container cannot be opened without destroying the seal (Ref. 4.65).
- (5) The cask must be designed so that the gamma radiation will not exceed 200 mr/hr at the outside surface or 10 mr/hr at a distance of one meter perpendicular to the long axis of the source (Ref. 4.65).

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- (6) The cask must be able to withstand a standard one-hour fire (i. e. , temperature of 1700° F after 60 minutes as defined by the National Fire Protection Association) without radiating greater than 1 r/hr (Ref. 4.65).
- (7) Materials which might be damaged by a one-hour standard fire must be insulated from fire effects.
- (8) No material within the system must approach within 300° F of its failure temperature during transport (Ref. 4.66).
- (9) At all times during transport, the surface temperature of the cask must not exceed 180° F (Ref. 4.67).
- (10) Lead shielding, or other equally effective shielding material, must be encased in steel or other suitable material so that shielding will neither flow away nor lose its efficiency if in a fire. The casing material must be 1/8 inch thick, for 6 inches or less of shielding, or 1/4 inch thick, for more than 6 inches of shielding (Ref. 4.67).
- (11) The smallest dimension of any outside shipping container must not be less than 4 inches (Ref. 4.64).
- (12) The shielding must be supported within the outer container so that it can neither change position nor open under any ordinary conditions (Ref. 4.65).
- (13) Containers of more than 500 pounds must be fitted with skids or designed so as not to create excessive pressure on small areas of the carrier deck. Gross weight must be marked on containers destined for water shipment if the weight exceeds 500 pounds (Ref. 4.65).
- (14) Sections of the shield must be so designed that radiation cannot be beamed at joined points (Ref. 4.67).
- (15) Outer containers where practicable, must have joints 100% welded or brazed, with closure secured by a positive fastening device capable of withstanding severe impact without failure (Ref. 4.65).
- (16) The lid fastening must survive a force equivalent to 60 times the lid weight for 16 milliseconds without exceeding its ultimate tensile strength (Ref. 4.66).
- (17) The container must be designed to withstand any vibrations normally incident to transportation. This is defined by the

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Association of American Railroads to be equivalent to a four-foot fall (Ref. 4.66).

- (18) The container must withstand the forces generated in a 30-foot fall onto rigid target media without release of radioactive material or loss of shield integrity (Ref. 4.66).
- (19) The cask, as a single beam, must support 10 times its own weight without exceeding its ultimate tensile strength (Ref. 4.66).
- (20) Any lifting device must be of sufficient strength to lift 6 times the loaded cask weight without exceeding the yield strength of the material (Ref. 4.66).
- (21) Any device attached to the cask that may be used for transport tie-down must withstand a static force with components as follows: vertical component equal to 2 times the loaded cask weight; horizontal component equal to 10 times the loaded cask weight, without exceeding the material's ultimate tensile strength (Ref. 4.66).

A cask capable of meeting the same requirements as the shipping cask must be provided at the launch site as a standby measure for use in case of a launch pad accident or close-in impact from an abort. In such circumstances, the fuel containers will probably be entangled in wreckage which would have to be cut away until the fuel containers are separated or the accompanying material sufficiently reduced in size that it can be placed in the cask for shipment to the processing plant or to a waste disposal facility. It would be possible to avoid the use of a special cask for this purpose if it can be assured that the fuel containers can be isolated from the other material and returned to the original shipping cask.

In the improbable event that the fuel containment is violated, the material released will be recovered as fully as possible and mixed with a concrete slurry in standard waste drums for transportation to a waste disposal facility.

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5.0 DRAWING LISTS

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ENGINEERING DRAWINGS SUBMITTED

451	A	1000000	Generator Assembly
451	A	2000000	Prototype Generator Assembly
451	A	1100000	Generator, Thermoelectric
451	A	1100001	Housing Assembly
451	A	1100002	Lower Housing Weldment
451	A	1100003	Insulation, Lower Housing
451	A	1100004	Upper Housing Weldment
451	A	1100005	Insulation, Upper Housing
451	A	1100007	Transition Assembly
451	A	1100008	Transition Piece
451	A	1100009	Fuel Entry Tube
451	A	1100010	Mounting Pad
451	A	1100011	Base Plate
451	A	1100012	Stringer
451	A	1100013	Connector Plate
451	A	1100014	Feed-Through
451	A	1100015	Insulator, Corner
451	A	1200000	Fuel Core
451	A	1200001	Fuel Capsule
451	A	1200002	Capsule Cylinder
451	A	1200003	Capsule End Cap
451	A	1200004	Spacer
451	A	1200005	Latch Ring
451	A	1200006	Spacer Plate
451	A	1200007	Tie-Rod
451	A	1200008	Button, Spring Retainer
451	A	1200009	Band, Tension
451	A	1200010	Washer, Tension Band
451	A	1200011	Retainer, Latch Ring
451	A	1200012	Bolt, Tension Band

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451	A	1200013	Spacer-Tie Rod Assembly
451	A	1200014	End Cover
451	A	1200015	Latch Assembly
451	A	1200016	Fuel Core Subassembly
451	A	1200017	Insulation Assembly
451	A	1200018	Insulator
451	A	1300000	Thermoelectric Module
451	A	1300001	Module Plate
451	A	1500000	Simulated Fuel Core (elect. heated)
451	A	1500001	End Cap, Simulated Fuel Core
451	A	1500002	Cylinder, Simulated Fuel Core
451	A	1500003	Ceramic Insulator, Simulated Fuel Core
451	A	1500004	Heater Element, Simulated Fuel Core
451	A	1500005	End Cap Assembly, Simulated Fuel Core
451	A	1500006	End Cover, Simulated Fuel Core
451	A	1500007	Latch Assembly, Simulated Fuel Core
451	A	1500008	Simulated Fuel Core Subassembly
451	A	1500009	Insulation Assembly, Simulated Fuel Core
451	A	1500010	Insulator

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APPENDIX P

IMPACT TEST EQUIVALENCE JUSTIFICATION

One of the many types of tests required for SNAP 17A fuel capsules is a series of high velocity impact tests against a relatively massive stationary granite block. Any resultant capsule shell deformation is acceptable; however, the slightest fracture may represent a failure. As a means of better instrumenting the test, a procedure of impacting a high velocity granite block against the relatively small fuel capsule was conceived. The problem of resolving equivalence of these two methods became an issue.

The purpose of this investigation was to determine the equivalence of the two test techniques in accordance with a reasonable criteria for equivalent resultant damage.

A. THEORETICAL ANALYSIS

Fuel pellets may be impact tested by two methods (Fig. P-1); the fuel pellet may be shot into a fixed rigid wall simulating actual impact conditions, or the wall may be impacted on the fuel pellet. To have equivalence of the two methods of testing, the damage to the fuel pellet must be the same. It was assumed that the maximum deflection of the deformable body (fuel pellet) would be a valid measure of the damage. Therefore, the problem reduced to finding the relationship between the maximum deflection and impact velocity, and then by equating the maximum deflections, the relationship between the impact velocities of the two methods of testing was determined.

Consider an impact between a deformable body and a rigid wall (Fig. P-2). The deflection force (P) of the deformable body was considered to be a function (Fig. P-3) of the deflection distance (a).

When the impacting bodies contact, the compressive forces change the velocities of the bodies as follows:

$$M_1 \frac{dV_1}{dt} = -P_1, \quad M_2 \frac{dV_2}{dt} = P_1 \quad (1)$$

The time rate of deflection ($\dot{a}$) is equal to the difference between the velocities of the two impacting bodies during impact

$$\dot{a} = V_1 - V_2 \quad (2)$$

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Fig. P-1. Two Methods of Impact Testing

Fig. P-2. Generalized Impact

Fig. P-3. Generalized Force--Deflection Curve

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and

$$\dot{a} = \frac{dV_1}{dt} - \frac{dV_2}{dt} = -P_1 \left(\frac{M_1 + M_2}{M_1 M_2} \right) \quad (3)$$

Let:

$$M = \left(\frac{M_1 + M_2}{M_1 M_2} \right) \quad (4)$$

From Fig. N-2

$$P = f(a) = -P_1 \quad (5)$$

Substituting Eqs (4) and (5) into Eq (3) yields

$$\dot{a} = M f(a) \quad (6)$$

Multiplying Eq (6) by $\dot{a}$ gives

$$\dot{a} \ddot{a} = M f(a) \dot{a} \quad (7)$$

which can be written as

$$1/2 d(\dot{a})^2 = M f(a) da \quad (8)$$

Integrating both sides of Eq (8) yields

$$1/2 (\dot{a}^2 + C) = M \int f(a) da \quad (9)$$

Now at the instant of contact, $a = 0$, $f(a) = 0$, and the deflection velocity ($\dot{a}$) is equal to the impact velocity (V), (see Eq 10) and inserting these conditions in Eq (9) gives the value of C as being V^2 .

$$V' = V_1 - V_2 \text{ (at instant of contact)} \quad (10)$$

$$1/2 (V'^2 + C) = M \int (0) da \quad (11)$$

$$C = -V'^2 \quad (12)$$

Substituting Eq (12) into Eq (9) yields

$$1/2 (\dot{a}^2 - V'^2) = M \int f(a) da \quad (13)$$

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Now when $\dot{a} = 0$, the deflection (a) reaches its maximum value (a_m). Substituting these conditions into Eq (13) yields

$$1/2 (-V^{2'}) = M \int f(a_m) da \quad (14)$$

or

$$\int f(a_m) da = \frac{-1/2}{M} V^{2'} \quad (15)$$

Thus, it can be seen from Eq (15) that the maximum deflection distance is a function of the impact velocity and the mass ratio.

In order to have equivalence between the two methods of testing, the maximum deflections must be the same, and if this condition is satisfied then

$$\int f(a_{m_1}) da = \int f(a_{m_2}) da \quad (16)$$

or from Eq (15)

$$\frac{-1/2 V_1^{2'}}{M} = \frac{-1/2 V_2^{2'}}{M} \quad (17)$$

Case 1 Case 2

Letting V_1' be the impact velocity in Case 1 and V_2' the impact velocity in Case 2 allows Eq (17) to be rewritten as:

$$\left(\frac{V_1'}{V_2'} \right)^2 = \frac{M}{M} \begin{array}{l} \text{Case 1} \\ \text{Case 2} \end{array} \quad (18)$$

From Eq (18), it can be seen that if the mass ratio (M) of the impacting bodies are the same in both methods of testing, the impact velocities must be the same for equivalence. Now, if the mass of the deformable body (M_1) is the same in both methods, but the mass of the rigid wall (M_2) is not the same in both cases, the ratio of impact velocities is still approximately 1 if $M_2 \gg M_1$ in both cases; to illustrate

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Let

$$(M_1 = 1, M_2 = 1000) \text{ Case 1}$$

$$(M_1 = 1, M_2 = 100) \text{ Case 2}$$

$$\left(\frac{V'_1}{V'_2}\right)^2 = \frac{M}{M} \begin{array}{l} \text{Case 1} \\ \text{Case 2} \end{array} \quad (18)$$

$$\left(\frac{V'_1}{V'_2}\right)^2 = \frac{\frac{1001}{1000}}{\frac{101}{100}} = 0.991$$

$$\frac{V'_1}{V'_2} = 1$$

Symbols

a deflection distance

a_m maximum deflection distance

M mass ratio $\frac{M_1 + M_2}{M_1 M_2}$

M_1 mass of deformable body

M_2 mass of rigid wall

P deflection force

t time

V' impact velocity

V'_1 Case 1 impact velocity

V'_2 Case 2 impact velocity

V_1 velocity of deformable body

V_2 velocity of rigid wall

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B. EXPERIMENTAL SETUP

To provide a qualitative check on the theoretical analysis, a simplified experiment was performed. The experimental setup consisted of two pendulums attached to two parallel bars (see Fig. P-4) in a manner that tended to minimize the tip mass lateral rotation as the pendulums moved. One tip mass (Weight = 7.8 lb) was a lead rod partially encased by an aluminum tube simulating the fuel capsule. The second mass was a 105-pound block of aluminum, simulating the granite wall. The suspended masses were spaced so that in static equilibrium the exposed end of the lead rod was in close proximity ($< 1/4$ in.) to a ball bearing which was embedded in the aluminum block (see Figs. P-5 and P-6).

The test procedure consisted of impacting, at a predetermined velocity, the lead rod into the aluminum mass (Case 1), and then impacting the large aluminum mass into the lead rod (Case 2) at the same velocity. In both cases, the only surfaces of contact between the tip masses were the ball bearing and flat end of the lead rod (see Fig. P-7).

Upon impact, the ball bearing produced a measurable permanent depression in the end of the lead rod. This plastic deformation was used as the damage criteria. Since only four distinct impacts could be positioned on the end of the rod, it was necessary to provide a fresh surface after each four impacts. This was accomplished by removing a one-quarter inch thick slug from the end of the rod. The four impact depressions on each of the slugs were produced by two Case 1 and two Case 2 impacts.

To determine the effect of impact velocity change on the impact depression, the impact velocity was decreased from 4.3 to 2.3 fps for a Case 1 and a Case 2 impact on the last slug.

The diameters of the impact depressions were measured by means of an optical instrument. An average value of the depression diameters was obtained by measuring each one in three different directions.

C. EXPERIMENTAL RESULTS

Table P-1 presents the experimental results. As can be seen, the average diameters of the Case 1 and Case 2 impacts were 5.33 and 5.32 mm, respectively.

Reducing the impact velocity from 4.3 to 2.3 fps decreased the average depression diameter to 3.88 mm.

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Fig. P-4. Experimental Setup

Fig. P-5. Tip Masses

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Fig. P-6. Impact Point

Fig. P-7. Impact Depressions

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TABLE P-1

Semi-Elastic Impact Test Experimental Results

Impact Velocity (fps)	Slug	Impact	Case 1 Diameter (mm)				Case 2 Diameter (mm)			
			<u>1</u>	<u>2</u>	<u>3</u>	<u>Average</u>	<u>1</u>	<u>2</u>	<u>3</u>	<u>Average</u>
4.3	1	a	5.45	5.30	5.40	5.38	5.15	4.95	5.10	5.07
4.3		b	5.40	5.30	5.35	5.35	5.35	5.20	5.30	5.30
4.3	2	a	5.20	5.15	5.20	5.18	5.20	5.35	5.25	5.27
4.3		b	5.30	5.15	5.30	5.25	5.40	5.35	5.40	5.38
4.3	3	a	5.30	5.20	5.25	5.25	5.40	5.50	5.40	5.43
4.3		b	5.35	5.45	5.30	5.35	5.30	5.40	5.30	5.33
4.3	4	a	5.50	5.45	5.50	5.48	5.40	5.40	5.30	5.37
4.3		b	5.35	5.35	5.40	5.37	5.35	5.45	5.40	5.40
						Average = 5.33				
4.3	5	a	5.35	5.40	5.30	5.35	5.25	5.20	5.35	5.27
2.3		b	3.90	3.85	3.95	3.90	3.90	3.85	3.80	3.85

Average = 5.33

Average = 5.32

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D. DISCUSSION OF RESULTS

The theoretical analysis predicted equal impact velocities would produce equal impact depressions. The experimental results showed a difference of less than 1% between the average diameters of Case 1 and Case 2 depressions, thereby checking with the theoretical analysis.

Reducing the impact velocity by 47% reduced the diameter of the impact depressions by approximately 27%, displaying a qualitative check with the assumed functional relationship between impact velocity and impact depression.

E. CONCLUSIONS

- (1) Experimental results verified the theoretical analysis.
- (2) Impact velocities in Cases 1 and 2 should be identical for equivalence of resultant damage.

F. REFERENCES

1. Timoshenko, S. and Goodier, J. N., Theory of Elasticity, p 383, McGraw-Hill Book Company, Inc., New York, 1951.

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APPENDIX Q

IMPACT TESTS

A. TEST EQUIPMENT

The ballastic research track is a dual-rail type, 2448 feet long (see Fig. Q-1). The rocket sled is an aluminum structure designed to carry various boosters over the velocity range shown in Table Q-1. Angle iron frames, located in front of the sled, rigidly support the granite block targets. Two grid plates are welded to the angle iron frames as the background for the two on-board photosonic cameras (see Fig. Q-2). The rocket sled is locked to the track by replaceable aluminum shoes.

Velocities along the track are measured by a magnet and coil system. As the magnet on the sled passes over coils along the track, electrical impulses are sent to the control blockhouse. The signal is recorded on a millisecond time base on teledelto tape and oscilloscope. A 16-mm film is made of the impulses on the oscilloscope.

In previous capsule impact tests, furnace heaters were employed to bring the test specimen to the proper temperature. Because the expected temperature will be quite high, rapid cooling of the specimen will occur between time of removal from such a furnace and actual time of impact. To minimize such cooling, it was necessary to design an automated heating device. The heater was designed to maintain the proper capsule temperature until just prior to impact, and then deploy itself to permit rocket sled impact with the test specimen. Only a small temperature drop occurred before impact, approximately 40° F for the maximum temperature case of 1600° F. The fuel capsules were heated to above impact temperature to account for this temperature drop.

The heater box assembly was a sheet metal rectangular box with thermally insulated sides, a heated cavity, and an opening large enough to accept the largest capsule under consideration (Figs. Q-3 and Q-4). The specimen, in the test position, is located deep in the box or well below the box centerline. An array of heaters is nested between the specimen and the insulation. The heaters protrude through the insulation on both ends of the box and through the box itself. The heating elements, which must operate in air at temperatures ranging from 1700° to 1900° F, are quartz lamps, 3/8 inch in diameter, with a heated length of 9 inches and an overall length of 12 inches. Four of these heaters are located under the specimen in a semicircular pattern, and four additional heaters extend up each side of the box toward the open top. The bottom heaters radiate directly to the specimen with little

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Fig. Q-1. Ballistic Research Track

Fig. Q-2. Photosonic Cameras and Background Grid Plates

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Fig. Q-3. Capsule Preheater Design

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Fig. Q-4. Test Specimen Heaters

Fig. Q-5. Heater Assembly After Free Fall

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heat loss, while those near the open top lose considerable heat by direct radiation from this opening. The effective heating area is 9.4 in.² and the required flux from the heaters was found to be approximately 46.5 watts/in.². The recommended maximum heating flux from the particular heater selected is 90 watts/in.²; thus, the elements are safely derated. The insulation selected for this application was Fiberfrax ceramic fiber FC-25, a material capable of being cast in place.

This insulation has a density of 20 to 28 lb/ft³ and can operate continuously at 2300° F. Although the thermal conductivity is higher than the familiar Min-K insulation, it has better resilience, and hence was chosen to help dampen the shock load on the silicon carbide heaters. Aluminum electrical leads are attached to the heaters by a metallized end which protrudes through the box assembly. A wire mesh guard then covers the wiring installation at each end.

The heater box assembly, which surrounds the specimen prior to impact, was mounted on a mechanism which allows the heaters to escape the path of the rocket sled with a minimum time delay between deployment and impact. The mounting arrangement permits positioning of the heater box, and hence the specimen, anywhere on a 360-degree horizontal plane. The rod to which the heater box assembly was attached has two sets of roller bearings which ride in a set of channel guide rails. The guide rails are assembled and vertically attached with brackets directly to the concrete test facility at APG. At the installation, the heater box was attached to the rod, then inserted in the set of guide rails and raised into position above and slightly to the outside of the rocket sled track. The assembly was held in this position by a solenoid-driven pin mounted to the guide rails, the tongue of which protrudes through a bearing block and into a slot in the heater mounting pipe. To actuate the deployment mechanism, the solenoid is tripped, retracting the pin, and the heater assembly free falls in the guide rails. The rails were designed with a ramp so that when the heater assembly clears the test specimen, the ramp imparts an outward motion to the heater assembly. The assembly then continues to fall free until stopped by a foam rubber cushion above ground level (see Fig. Q-5). Travel to clear the specimen was approximately 11 inches, and estimated time for complete deployment was approximately one second. To facilitate testing of two specimens with one rocket firing, an identical assembly was used on the opposite side of the rocket sled tracks. Power to the heaters was furnished by a set of variacs housed in a metal cabinet. The variacs control the heater input to maintain proper specimen temperatures. Each specimen was instrumented with a chromel-alumel thermocouple to monitor temperature (see Fig. Q-6).

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Fig. Q-6. Instrumented Fuel Capsule

Fig. Q-7. Impact Area and Recovery Box

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Located 10 feet downtrack from the impact point was the recovery box, which consisted of sand bags, plywood, and Cellotex sheets, as shown in Fig. Q-7. There were two additional recovery boxes, fabricated from Cellotex sheets, located 60 feet and 110 feet from the impact area.

The rocket sled was brought to a stop approximately 800 feet from the impact area by a retrorocket carried aboard the sled. The retrorocket firing was initiated when two screens with an electrical potential between them, positioned on each side of the tracks, came into contact with the knife blades carried underneath the sled, thereby completing the firing circuit (see Fig. Q-8). As an emergency measure, an arresting cable was set up near the end of the track with sufficient drag to stop the sled in the event the retrorocket malfunctions (see Fig. Q-9).

Attitude control of the test specimen at impact was maintained by a rotating plate which can be locked into position every 15 degrees (see Fig. Q-10). Two nichrome wires (31 gauge) with a ceramic loop at one end support the fuel capsule; the other ends of the support wires were attached to the rotating plate.

The firing sequence was initiated when the second warning whistle was sounded; four seconds later, the heaters dropped away. The microswitches on the heaters were closed, so the rockets fired 0.5 second later. As a built-in safeguard, both heaters had to be in the down position with the microswitches closed in order for the rockets to fire.

After the fuel capsules impacted, the capsule flight trajectories were unpredictable, due to the attitude of the capsule as it passed through the recovery box and to the effects of secondary impact. If the recovery box did not stop the capsules, a search of the surrounding area was made. If the capsules were still not located, probable flight paths were determined from the point where the capsules passed through the recovery box and/or the secondary impact point; then a search of the indicated area was made.

Photographic documentation of the impact test program was made by the Martin Company, with backup coverage provided by APG. Two photosonic cameras were mounted on the sled to show the attitude of the capsule throughout the impact event.

B. ROCKET SLED FIRING SEQUENCE

Prior to any test run on the ballastic track, the booster rockets were installed at the assembly plant, and the sled was weighed and delivered to the track. The targets were mounted on the front of the sled, and the onboard cameras were installed. While a continuity check was made of the sled, the Martin test personnel made a final check of all test equipment, including temperature recorders. The

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Fig. Q-8. Retrorocket Firing Mechanism

Fig. Q-9. Arresting Cable

Fig. Q-10. Test Specimen Positioning Plate

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track area was then cleared of all personnel. After all personnel were under cover, two warning whistles were sounded and the firing sequence was initiated. Four seconds after the second whistle was blown, the heaters dropped away and the onboard cameras were started. The rockets were ignited 1/2 second after the heaters fell away. The targets impacted the test specimen, and the sled continued down the track until the retrorockets fired, stopping the sled. The heaters were left in the down position until the sled was pushed back up the track and taken to the assembly plant. A search for the test specimens was made while the sled was being pushed up the track. After the capsules were located, a complete description of the test was made covering all events of the test. The test specimens were then returned to the test laboratory for data reduction.

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TABLE Q-1
Velocity Range

<u>Velocity Level (fps)</u>	<u>Total Weight (lb)</u>	<u>Boosters</u>	<u>Calculated Velocity (fps)</u>	<u>Braking</u>	<u>Remarks</u>
221	700	1 HVAR	220	1 HVAR	
250	840	1 HVAR + 2 2.75-inch FFAR	249	1 HVAR	514 + hardware (326)
300	700	1 HVAR + 2 2.75-inch FFAR	301	1 HVAR	514 + hardware (186)
350	780	1 HVAR + 4 2.75-inch FFAR	352	1 HVAR	536 + hardware (244)
400	685	1 HVAR + 4 2.75-inch FFAR	401	1 HVAR	536 + hardware (149)
450	680	2 HVAR	452	1 HVAR	572 + hardware (103)

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APPENDIX R

AERODYNAMIC STUDIES

A. AERODYNAMIC TRAJECTORY AND ABLATION

In the Phase I aerothermal and trajectory analysis, three separate and distinct digital computer codes were employed. For the determination of the orbital decay trajectory, the two-dimensional trajectory program UB003 was used. For the abort and impact analysis, the three-dimensional trajectory program UB024 was used. Both of these programs also yield aerodynamic heating data. These data were used in the three-dimensional heat transfer, one-dimensional ablation structural heating program FB090 to determine the effects of aerodynamic heating on the bodies under study. A brief description of the three programs follows.

UB003 is an N-phase, two-dimensional, two-degree of freedom program. The program will continuously compute a vehicle trajectory which has been broken into any number (N) of parts or phases. This is accomplished automatically by starting each successive phase at the condition existing at the end of the previous phase. One of two solutions may be selected as desired in any given phase (1) integration, or (2) free-flight. The solution integrates the equations of motion as a function of time, using prescribed aerodynamic thrust and control data inputs while assuming a rotating oblate earth and the 1959 ARDC standard atmosphere. The free-flight computation gives 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 aeroheating data. These data include velocity, altitude, flight path angle, dynamic pressure, Mach number, altitude pressure, heat fluxes for both convections and convection plus radiation and total integrated heat for both convection and convection plus radiation.

The equations of motion are:

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

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

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

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where

$\ddot{\bar{x}}$ = acceleration in $\bar{x}$ direction (fps²)

$\ddot{\bar{y}}$ = acceleration in $\bar{y}$ direction (fps²)

m = mass (slugs)

T = thrust (lb)

L = lift (lb)

D = drag (lb)

g = gravitational acceleration (fps²) and the angles are defined in Fig. R-1.

The heat fluxes and total heats are obtained from

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

$$\dot{q}_R = 26.8 R_N^{\frac{E}{2}} \frac{\delta}{R_N}$$

$$\dot{q}_{c+R} = \dot{q}_c + \dot{q}_R$$

$$q_{c+R} = \int \dot{q}_{c+R} dt$$

where

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

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

$\dot{q}_{c+R}$ = 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)

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V = velocity (fps)

μ = earth's gravitational constant ($1.4076 \times 10^{16} \text{ ft}^3/\text{sec}^2$)

R = earth's mean radius ($20.9256 \times 10^6 \text{ ft}$)

δ = shock standoff distance (ft)

E_2 = one-half of the emitted radiation energy per unit volume from the stagnation region (watts/cm^3)

UB024 is an N-phase, three-dimensional, three-degree of freedom program. The program assumes a rotating oblate earth in an inertial reference frame. 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. The data supplied are the same as for UB003 with the exception of the addition of latitude and longitudes, thereby allowing a precise determination of impact location following an abort. The equations used in the solution are similar to those in UB003, differing, in the case of the equations of motion by the addition of a third dimension and third degree of freedom.

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 result are solved for temperatures for small, successive increments of time, when boundary and initial condition 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 ($^{\circ}\text{R}$)

ρ = density ($\text{lb}/\text{in.}^3$)

C_p = specific heat ($\text{Btu}/\text{lb}^{\circ}\text{R}$)

t = time (sec)

x, y, z = distance (in.)

k = thermal conductivity ($\text{Btu}/\text{in.} \cdot \text{sec} \cdot ^{\circ}\text{R}$)

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This equation is solved numerically by the mid-point finite difference technique and in this finite difference form, the heat balance equation is

$$\begin{aligned} \frac{\rho_{E_f} V_E}{\Delta t} J_{E_f} = & \frac{\rho_{E_i} V_E}{\Delta t} J_{E_i} + \frac{1}{2} \left[-F_{R_E} \sigma \epsilon_{E_i} A_T T_{E_i}^4 \right. \\ & + F_{ab} F_q A_T \dot{q}_{K_i} + A_L U_{L_i} (T_{L_i} - T_{E_i}) \\ & + A_R U_{R_i} (T_{R_i} - T_{E_i}) + A_T U_{T_i} (T_{T_i} - T_{E_i}) \\ & + A_U U_{U_i} (T_{U_i} - T_{E_i}) + A_F U_{F_i} (T_{F_i} - T_{E_i}) \\ & \left. + A_B U_{B_i} (T_{B_i} - T_{E_i}) \right] + \frac{1}{2} \left[-F_{R_E} \sigma \epsilon_{E_f} A_T T_{E_f}^4 \right. \\ & + F_{ab} F_q A_T \dot{q}_{K_f} + A_L U_{L_f} (T_{L_f} - T_{E_f}) \\ & + A_R U_{R_f} (T_{R_f} - T_{E_f}) + A_T U_{T_f} (T_{T_f} - T_{E_f}) \\ & + A_U U_{U_f} (T_{U_f} - T_{E_f}) + A_F U_{F_f} (T_{F_f} - T_{E_f}) \\ & \left. + A_B U_{B_f} (T_{B_f} - T_{E_f}) \right] \end{aligned}$$

where

ρ = density (lb/in.³)

V = volume (in.³)

t = time increment (sec)

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)

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A = area (in.²)

ε = emissivity

σ = Stefan-Boltzmann constant (0.33×10^{-14} Btu/in.²-sec-°R)

T = temperature (°R)

q_{xk} = hot wall external heating (Btu/in.²-sec), i.e.,

$$\dot{q}_K = \dot{q}_{c+R} \left[\frac{h_s - h_w}{h_s - (h_w)_{300^\circ K}} \right]$$

q_{c+R} = total heating rate obtained from trajectory data (Btu/in.²-sec)

h_s = h_o + V²/2g_cJ stagnation enthalpy of air (Btu/lb)

h_o = ambient enthalpy of air (Btu/lb)

V = velocity (fps)

J = mechanical equivalent of heat (778 ft/lb/Btu)

h_w = enthalpy of air at the wall temperature (Btu/lb)

(h_w)_{300° K} = enthalpy of air at 300° K (130 Btu/lb)

Subscripts

E = element in question

i = initial time of calculating interval

f = final time of calculating interval

T = top of element

U = under side of element

L = left side of element

R = right side of element

F = front of element

B = back of element

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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 temperature can be determined.

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 equation 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 give 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 Phase I, no blocking was considered during ablation, and all radiating elements were considered to radiate to infinity.

B. PARAMETRIC FUEL CAPSULE BURNUP STUDY

The re-entry burnup characteristics of various fuel capsule configurations were investigated. The investigation considered two basic design approaches: (1) a single source configuration; and, (2) a distributed source configuration. The parametric study considered the number of fuel capsules, different geometrical location, diameter, lengths and wall thickness to determine an optimum re-entry fuel capsule design.

The re-entry heat transfer model utilized in the analyses considered the cylindrical cross section of the fuel capsule divided into concentric elements, the internal heat source and a nominal re-entry trajectory. The re-entry characteristics of the fuel capsule were then determined by applying this model to the transient FB090 heat transfer code. The complete ablation of an element was considered to be the point in the trajectory where its enthalpy was equal to or greater than the sum of the melting enthalpy plus the enthalpy of transformation (fusion, etc.). All fuel capsules were assumed to be released at an altitude of 270,000 feet, a nominal release altitude.

The single source configurations were studied to determine the feasibility of the design in terms of satisfying the safety criteria of

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Fig. R-2. Fuel Capsule Designs

Fig. R-3. Fuel Release Altitude as Function of Number of Distributed Capsules, Based on Constant Fuel Volume of 600 Cubic Centimeters

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re-entry burnup. If a single configuration could satisfy the criteria, a weight reduction might be realized in the RTG, provided the earth impact containment requirement could also be satisfied by a large single capsule design. The single source configurations that were investigated are illustrated in Fig. R-2.

The results of the study indicate that re-entry burnup is extremely marginal, if not impossible, in terms of permitting a fuel release above 200,000 feet for the single source configuration (see tables). All single source configurations investigated did not completely ablate. Therefore, fuel release and subsequent ablation of the fuel to submicron particles at altitudes required to permit world-wide distribution do not appear feasible with a single source configuration equivalent to or larger than the size required for SNAP 17A.

Distribution source configurations, multiple full length capsules, were investigated with respect to re-entry burnup. The number of distributed sources (fuel capsules) was varied from two to six. An upper limit of six capsules was fixed because of fabrication, fueling and weight limitations. The multicapsule design approach is inherently better for a re-entry burnup criteria, because the aerothermodynamic heating increases as the radius of the capsule decreases. The results of the study are presented in Table R-1. The fuel release altitude as a function of the number of capsules in the RTG is illustrated in Fig. R-3. It shows that as the number of fuel capsules increases, the fuel release altitude becomes higher. Therefore, from an aerospace safety consideration, that of compliance to re-entry burnup and dispersion criteria, the higher the number of capsules in the RTG, the larger the safety factor.

C. FUEL CAPSULE IMPACT VELOCITY AND TEMPERATURE ANALYSIS

1. Generator and Vehicle Impact Velocities

The earth impact velocities of the generator and Agena-D with dispensers were determined. A detailed fuel capsule impact study was also conducted. The maximum possible free-fall impact velocity occurs when the re-entry body has attained terminal velocity. Three different re-entry modes (orientations) were investigated: tumbling, zero degree angle of attack, and 90-degree angle of attack. The angle of attack, α , is defined as the angle between the velocity vector and the longitudinal axis of the body. The most probable re-entry mode for the various systems, based on available experimental data (SNAP 9A tests), is a tumbling mode.

TABLE R-1

Case	Capsules (No.)	Total Weight per Capsule ² (lb)	Length (in.)	Diameter (in.)	Wall Thickness (in.)	Ballistic Coefficient W/C _o A (lb/ft ²)	Capsule Elements (No.)	Results Capsule Element (No.)		Fuel Release Altitude (ft)
		Melted						Ablated		
Single source capsules										
1	1	11.69	6.5	3.44	0.21	70	3	3	2	
2	2	6.65	3.25	3.61	0.15	53	4	4	3	
3	3	4.96	2.17	3.81	0.15	42		1	0	
4	1	11.79	6.5	3.44	0.21	70		4	3	
5	1	10.8		3.34	0.15	67			3	
6	1	7.98		3.11	0.16	55			3	
Distributed source capsules										
7	2	4.03		2.21	0.13	43			4	161,000
8	3	2.92		1.85	0.13	39				192,000
9	3	3.81		1.97	0.125	47				197,000
10	4	2.15		1.6	0.11	35				203,000
11	5	1.81		1.45	0.11	33				208,000
12	6	1.64	6.5	1.35	0.11	32	4	4	4	215,000

1. Capsules were stacked.

2. Cases 1 through 5: $P_{\text{fuel}} = 0.155 \text{ lb/in.}^3$, $(V_{\text{fuel}})_{\text{total}} = 40 \text{ in.}^3$.

Cases 6 through 12: $P_{\text{fuel}} = 0.112 \text{ lb/in.}^3$, $(V_{\text{fuel}})_{\text{total}} = 34.3 \text{ in.}^3$.

Case 1: Waspalloy used as capsulation material.

Cases 2 through 12: Rene' 41 used as capsulation material.

Case 1 had smaller end cap design than Case 4.

3. Capsules were released at 270,000 feet in tumbling orientation on an orbital decay trajectory.

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The terminal velocity of a body is the velocity at which the drag force, D_F , is equal to the weight of the body, W_B . Applying the boundary conditions $D_F = W_B$, the drag force, expressed as a function of velocity, is

$$D_F = 1/2 \rho C_D A V^2$$

where

ρ = density of atmospheres (slugs/ft³)

C_D = drag coefficient

A = reference area of body (ft²)

V = velocity (fps)

This equation can be solved for the terminal velocity, V_T , for any altitude from the following equation:

$$V_T = \sqrt{\frac{2}{\rho} \frac{W_B}{C_D A}}$$

Terminal velocities at sea level, 3000 and 5000 feet for the bodies investigated are presented in Table R-2.

2. Impact Temperature Study

A major factor in assessing the overall safety of the SNAP 17A RTG is the post-impact integrity of the fuel capsules. Since the integrity of the capsule depends to a large extent upon its temperature at the time of earth impact, a study was conducted to determine impact temperature as a function of launch vehicle abort altitude. The fuel capsules were assumed to be released at various points along the ascent trajectory. An evaluation of the fuel capsule aerodynamic stability showed that the capsule was unstable and would therefore re-enter in a tumbling mode. A total of five abort points were considered along the trajectory occurring at 10, 20, 30, 50 and 180 seconds after liftoff. The time range represents the maximum possible time elapse from liftoff because any greater time would result in partial burnup of the fuel capsule prior to impact. Both a single and multi-capsule design was considered in the analysis.

The heat transfer model utilized considered the internal heat source, aerothermodynamic heating, and convection and radiation cooling of the capsule in the nonaeroheating portion of the trajectory. The operating

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TABLE R-2
SNAP 17A Terminal Velocity Study

Body	Weight (lb)	Length (in.)	Diameter (in.)	Area (ft ²)	C _D *	Orientation	Terminal Velocity		
							Sea Level	3000 ft	5000 ft
Generator without fins	30	12	7.5 ^{avg}	0.295	1.15	Tumbling**	273	285	294
					1.4	$\alpha = 90^\circ$	248	259	267
					0.9	$\alpha = 0^\circ$	308	322	332
Generator with fins	30	12	7.5 ^{avg}	0.295	1.83	Tumbling**	216	226	233
					2.76	$\alpha = 90^\circ$	176	183	190
					0.9	$\alpha = 0^\circ$	308	320	332
Agena with payload and fuel (no fairing)	16,300	427	60	19.6	3.86	Tumbling**	426	443	459
					6.82	$\alpha = 90^\circ$	320	333	345
					0.9	$\alpha = 0^\circ$	883	915	949

*Theoretical drag coefficients

**Most probable re-entry mode

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temperature of the capsule (1700° F) was assumed to exist at the time of abort. The fuel capsule heat transfer coefficient for convection was determined by the empirical equation:

$$\frac{h_e D_o}{K} = 0.664 \left(\frac{D_o G}{\mu} \right)^{1/2} \left(\frac{C_p \mu}{K} \right)^{1/3}$$

where

h_e = coefficient of heat transfer (convection)

D_o = outside diameter of fuel capsule

K = thermal conductivity

G = fluid mass velocity

μ = fluid viscosity

C_p = specific heat of fluid

The cylindrical wall of the fuel capsule was divided into concentric cylindrical elements. A constant heat rate, representing the rate of heat generated by the radioisotope, was applied at the external surface of the capsule according to the re-entry trajectory.

The results of the study are presented in Table R-3. Fuel capsule impact velocity and temperature for various impact altitudes as a function of abort altitudes is illustrated in Fig. R-4. The impact temperature of the fuel capsule was found to decrease as the abort altitude increased, as illustrated in Fig. R-4.

In addition, the multicapsule RTG exhibits lower impact temperatures than the single capsule design. Therefore, the strength of the multicapsule will be greater than the strength of the single capsule, since the strength of the material is inversely proportional to its temperature.

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TABLE R-3

Time From Launch (sec)	Altitude (ft)	Velocity (fps)	Velocity (fps)	Temperature (° F)	Velocity (fps)	Temperature (°F)	Velocity (fps)	Temperature (°F)	Velocity (fps)	Temperature (°F)	Capsule	
											Small	Large
10	420	121	--	--	--	--	--	--	168*	1580	X	
20	3,028	335	--	--	192	1520	239	1402	239**	1360	X	
30	7,424	555	257	1350	251	1258	246	1210	241**	1150	X	
50	23,370	1,059	262	970	252	930	248	900	241**	870	X	
50	23,370	1,059	378	1437	367	1420	357	1407	348**	1400		X
180	416,718	13,358	--	--	--	--	--	--	--	--	X	

*Terminal velocity not yet achieved.

**Terminal velocity achieved.

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Fig. R-4. $T_0 = 1700^{\circ}F$, Capsule Impact Temperature Study ($^{\circ}F$)

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Fig. R-5. Atlas-Agena D Configuration

D. DESCRIPTION OF LAUNCH VEHICLE AND SEQUENCE OF EVENTS

1. Atlas

The two-stage launch vehicle (Fig. R-5) for the MACS program is an Atlas/Agena D, used primarily for space programs. The Atlas (Ref. R-1), noted as SLV-3B, is comprised of three sections: the booster section, the sustainer or tank section and the interstage adapter. The booster section, which is jettisonable, consists of two booster engines, an aft engine fairing assembly, a fire shield assembly, two forward nacelle door assemblies and thrust longerons. The sustainer, or tank section, supplies fuel to the booster, sustainer, and vernier engines during the flight. It is retained for the full duration of the Atlas flight; at staging, only the two booster engines are jettisoned. The interstage adapter is only a transition section between the Atlas and Agena D vehicles.

The Atlas standardized space launch vehicle (SLV-3B) receives its thrust from two 165,000-pound thrust booster engines, one 57,000-pound thrust sustainer engine, and two vernier engines which add a total of 1500 pounds of thrust. At sea level, the total thrust is 385,500 pounds. The two booster engines are independently gimbal-mounted to provide directional control and stability during the first-stage powered flight. During the sustainer stage, the sustainer engine provides directional control of the vehicle by gimbaling in any direction about the pitch and yaw axes. This engine is locked out of the control system during the booster portion of the flight. The function of the two gimballed vernier engines is to assist in providing roll and attitude control about all axes and to provide fine control of the velocity vector. These engines, prior to launch, are started before the booster and sustainer engines; and they continue to provide thrust after sustainer engine cutoff.

2. Propellants

The propellants (Table R-4) used for the Atlas space launch vehicles are liquid oxygen (approximately 171,000 pounds) and RP-1 hydrocarbon fuel (approximately 76,000 pounds). The propellants are applied to the combustion chambers under pressure from centrifugal pumps (turbopumps). Liquid oxygen and RP-1 are burned in two gas generators, and the resulting hot gases drive the turbines of the propellant pumps.

3. Guidance System

The Atlas (SLV-3B) space launch vehicle utilizes the General Electric Guidance System, which consists of two subsystems. One subsystem

TABLE R-4
Propellant Data

<u>Vehicle</u>	<u>Engine</u>	<u>Fuel</u>	<u>Oxidizer</u>	<u>Thrust at Sea Level (lb)</u>	<u>Specific Impulse at Sea Level (sec)</u>	<u>Fuel Flow (lb/sec)</u>	<u>Oxidizer Flow (lb/sec)</u>	<u>Fuel Density (lb/ft³)</u>	<u>Oxidizer Density (lb/ft³)</u>
Atlas	Booster (2)	RP-1	Liquid oxygen	330,000	251	397	904	50.45	71.38
	Sustainer (1)	RP-1	Liquid oxygen	57,000	215	81	184	50.45	71.38
	Vernier (2)	RP-1	Liquid oxygen	1050* 1500**	-- --	4 --	2.0* 2.5**	50.45 --	71.38 --
Agena D	Main	UDMH	IRFNA	1600 (vac.)	--	--	--	--	--

*Tank fed,
**Pump fed.

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measures the position of the vehicle and provides a command link with the ground, and the second measures the components of the velocity by continuous wave radar.

The components of the airborne guidance system consist primarily of three canisters. One canister contains a continuous wave (cw) radar beacon, the second one contains a monopulse radar beacon, and the third contains the decoder, which operates in conjunction with the pulse beacon. Operation of this guidance system is as follows:

The pulse beacon receives a pulse coded signal from the ground station. This signal contains discrete command information and steering commands. The pulse beacon sends a return signal to the ground station for measurement of the vehicle's position. The decoder decodes the pulse message from the ground station and distributes this information to the various vehicle systems. The continuous wave beacon receives a double side-band suppressed carrier signal from the ground station and generates a return signal which lies between the frequencies of the two side-bands received.

The ground-based components of the GE guidance system include: a monopulse radar system capable of measuring the position of the vehicle and of transmitting a pulse-coded message to the vehicle-borne guidance system; a rate-measuring device (cw radar) which employs doppler-shift techniques to measure the vehicle's velocity; and a computer which accepts position and velocity coordinates of the vehicle and computes real-time steering and control commands.

4. Autopilot

The Atlas vehicle, like all missiles and space boosters having no stabilizing fins or movable air surfaces, is aerodynamically unstable and incapable of flying a predetermined course without an autopilot. This autopilot incorporates three main functions:

- (1) It senses the attitude and any changes in attitude about the pitch, yaw, and roll axes by means of displacement gyros.
- (2) It changes the relationship of the thrust vector to the center of gravity by causing gimbaling of any of the five engines.
- (3) It selects the engine or engines to be gimbaled for attitude control during a specific flight phase, and it provides for programmed maneuvers.

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Fig. R-6. Agena D

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The principal components of the Atlas autopilot consist of five separate packages: the programmer assembly, the servo amplifier assembly, and the displacement gyro assembly (one rate gyro for roll control is also included with the displacement gyros), the adapter-mounted autopilot package (containing the pitch and yaw rate gyros), mounted inside the Agena adapter, and ten actuator assemblies located in the aft portion of the sustainer section.

The following is a brief description of the operation of the autopilot system.

The displacement gyros sense the attitude and changes in attitude from an initial reference. The changes and variations in attitude are then transmitted to the engines' servomechanisms, which gimbal the applicable engine or engines to correct the vehicle's attitude and to realign it with the initial reference. Damping is provided, as necessary, by the rate gyros; and an integrator, included in the system, compensates for steady-state errors. The programmer, through the autopilot, rolls the vehicle to a predetermined attitude, pitches it into a predetermined trajectory, and sequences timed commands during flight.

5. Agena D

The Agena D vehicle (Ref. 2), shown in Fig. R-6, consists of the following four major sections: forward, tank, aft and booster adapter. The spaceframe provides the aerodynamic and structural shape of the Agena D vehicle and houses and supports the various vehicle system components and modules.

The Agena D forward section carries guidance, flight control electronics, telemetry, command, tracking, electrical power and propellant pressurization equipment. The forward section also has mounting provisions for the payload and program optional equipment.

Fuel and oxidizer necessary for operation of the main rocket engine are stored in the Agena D tank section. This section also provides the aerodynamic surface and supporting structure between the forward and aft sections. Fuel tank capacity is 553.31 gallons, while oxidizer tank capacity is set at 738.0 gallons.

The aft section is the structural portion of the Agena D vehicle to which the rocket engine, ullage rockets, and pneumatic attitude control thrust valves are attached. Because of the tension loading design, the aft section is a lightweight structure with a high load capability.

The booster adapter section is the interconnecting structure between the Agena D vehicle and the first-stage booster. Prior to separation of

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the Agena D vehicle from the first-stage booster during flight, the adapter section encloses the vehicle aft section. Two retrograde rockets, which effect separation of the Agena D vehicle and the first-stage booster, are mounted in the adapter section and are enclosed by exterior fairings. A vehicle self-destruct system is also installed in the adapter section.

6. Propulsion System

The propulsion system provides the final thrust necessary for the Agena D vehicle to perform missions as an intermediate stage booster or as an orbital vehicle. After launching and upon completion of the thrust phase by the Atlas first-stage booster, the Agena D and its first-stage booster separate. Following separation, the Agena D vehicle continues its programmed space mission with thrust being provided by the Agena D propulsion system.

The propulsion system consists principally of a rocket engine, with its propellant-flow and electrical-control equipment, and the propellant subsystem and equipment that are necessary to support the rocket engine operation.

A USAF Model XLR 81-BA-9 (Bell Aerosystem Company, Model 8096) liquid bipropellant rocket engine system with a single combustion chamber powers the Agena D. The propellants utilized for engine operation are unsymmetrical dimethylhydrazine (UDMH) as the fuel and inhibited red fuming nitric acid (IRFNA) as the oxidizer. This engine develops a rated thrust of 16,000 pounds in a vacuum for a total duration of 240 seconds.

7. Guidance and Control System

Agena D guidance and control system functions include: vehicle flight altitude control; vehicle ascent, orbital, or spatial trajectory control; vehicle velocity control; and timing and sequence control of the vehicle's programmed operations. The guidance and control system can be programmed to achieve a vehicle circular orbit, to correct the launch trajectory to modify the vehicle's orbit, and to effect payload recoveries, using rocket engine thrust for braking. The system can be programmed to accomplish altitude maneuvers, perform active or semiactive vehicle control, and to stabilize the Agena D vehicle vertically or horizontally in orbit.

8. Destruct System

No information describing the destruct system on board the Atlas launch vehicle was available; therefore, this system is not discussed

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in this document. The destruct system located in the Atlas-Agena D adapter section and in the Agena D vehicle itself are described.

The self-destruct system provides a means of destroying the program satellite during the orbital boost phase of flight, in the event an uncontrollable condition occurs wherein continued flight would constitute a hazard to property and personnel. The system consists principally of a shaped explosive destruct charge, a destruct charge initiator, four auxiliary destruct batteries, two premature separation switches (also known as destruct lockout switches), and related destruct system circuitry. All system components are installed in the booster adapter section. The destruct charge initiator and batteries are adjacent to each other on the outside of the adapter, just aft of the vehicle separation plane. The two premature separation (destruct lockout) switches are inside the adapter.

The self-destruct system is capable of being actuated either by a command signal from the Range Safety Officer or automatically upon premature separation of the Agena D vehicle and booster. The system is electrically connected with the first-stage booster destruct system to provide the capability for simultaneous destruction of both vehicles by the ground command signal transmitted to the booster destruct system. Destruction may be effected any time between lift-off and booster thrust cutoff. Safety features are incorporated into the system to prevent accidental detonation of the destruct charge during prelaunch checkout on the launch pad and until the normal separation of the Agena D and booster occurs during flight.

An optional command destruct module may be installed in the Agena D vehicle to provide the additional capability of the vehicle destruct after separation of the Agena D and first-stage booster. The command destruct module also provides capability for performing functions of the self-destruct system. The self-destruct system hardware may therefore be removed from the vehicle whenever the command destruct module is installed. The command destruct module is installed on the side of the propellant tank assembly and destroys the vehicle by means of an explosive charge that penetrates the propellant tanks. The command destruct module includes a receiver and antenna which receives the fire signal from the Range Safety Officer.

9. Separation

Two separation operations are accomplished by the Atlas SLV-3B: separation of the booster section from the sustainer sections, and separations of the sustainer section from the upper stage or payload section.

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The booster section separates on command from the flight control subsystem, whereas the upper stage can be separated by a command initiated in the upper stage itself. At the end of the predetermined booster flight period, a staging command from the ground guidance system initiates a programmer subroutine which locks the sustainer engine. The booster engines then shut down and a pyrotechnic-activated device is ignited which enables pressurized helium gas to release 10 separation fittings. Fluid and pneumatic lines uncouple, and the booster, booster engines, turbopumps, and associated equipment, together with the skirt structure, move away from the vehicle along the jettison guide rails, thus lightening the load by some 7000 pounds.

The mechanism that provides for separation of the SLV-3B from the Agena upper stage includes an attachment and release device which secures the Agena to the forward end of the Atlas vehicle during powered flight. After vernier engine cutoff, the Atlas SLV-3B flight control subsystem, in response to a signal originated by the Agena upper stage, detonates three pyrotechnic devices, which actuate a mechanism that separates the Atlas vehicle from the upper stage adapter (Atlas/Agena adapter). The adapter remains attached to the forward end of the Atlas, and rollers installed on the Agena equipment rack guide the upper stage away from the sustainer along channels incorporated in the adapter.

After mechanical separation has taken place, two solid-propellant retarding rockets are fired to give the Atlas a velocity different from that of the Agena, to allow for complete, unhindered escape of the Agena upper stage. Complete disengagement takes 1.5 seconds.

10. Launch Sequence

During a typical launch sequence (Table R-5), all Atlas engines are fired on the ground, and when sufficient thrust has been obtained, the vehicle rises from the launcher. There are six principal milestones in the powered portions of an Atlas-Agena D flight. These are: vertical rise, pitchover, staging, sustainer cutoff, vernier cutoff, and upper-stage separation. However, staging is the only milestone that will be discussed at length, since it is the most pertinent.

The staging operation prepares for and accomplishes the jettisoning of the booster engine package. It is initiated by a guidance system command from the ground as a function of pre-established guidance equations, and controlled by the flight programmer. After staging, the vehicle flight attitude in pitch and yaw are maintained through thrust vector control of the sustainer engine, and the roll attitude is maintained by differential gimbaling of the vernier engines. The flight path is adjusted by ground guidance correction signals, which torque the auto-

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pilot pitch and yaw displacement gyros. A sustainer stage pitch program, if required, originates in the flight programmer. Sustainer engine cutoff discrete signal (SECO), vernier engine cutoff discrete (VECO), start Agena D timer discrete, and initiate Agena separation discrete, all initiated by guidance, are enabled by the flight programmer at about Guidance Staging Discrete (GSD) + 56 seconds.

TABLE R-5
Launch Trajectory Sequence of Events

<u>Time (sec)</u>	<u>Event</u>
0	Atlas engine ignition
2.25	Liftoff
~65	Max q
133.43	Radio command to stage
133.73	BECO (201,640 ft, $V_I = 8970$ ft/sec) (booster engine cutoff)
136.73	Booster package jettisoned
200.0	Nose fairing is jettisoned by radio signal
280.7	Command for SECO
280.8	SECO (h = 618,170 ft, $V_I = 17,074$ ft/sec) (sustainer engine cutoff)
300.35	VECO (vernier engine cutoff)
302.9	Staging begins (retrorockets fire)
305.4	Complete separation
349.8	Pitch program initiated
349.8	Ullage rockets ignited

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<u>Time (sec)</u>	<u>Event</u>
361.8	Agena D main engine ignited
363.8	Steady-state thrust obtained ($h = 755,187$ ft, $V_I = 16,883$ ft/sec)
581.5	First burn cutoff
6425.7	Ullage rockets ignited
6437.7	Agena D main engine reignited
6439.7	Steady-state thrust obtained ($h = 30,359,249$ ft, $V_I = 12,901$ ft/sec)
6461.7	Second burn cutoff
6462.7	$h = 30,359,205$ ft, $V_I = 16,568$ ft/sec $V_I = 0.0$ deg (Longitude = 34.0° E) (Latitude = 9.0° S) Final orbit established $h_a = 5002$ naut mi $h_p = 4998$ naut mi $t = 5.4$ hr $i = 89.4$ deg.

E. HEAT TRANSFER AND ABLATION MODELS

1. Generator

The heat transfer and ablation code, FB090, was used to determine the effect of aerodynamic heating on the generator, fuel capsule as-

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sembly and the fuel capsule. From a typical pie section of the generator (Fig. R-7), a heat transfer model representing a portion of this section is shown in Fig. R-8. A model optimization with respect to heat transfer was performed to minimize the computing time required, and the result of this study is the heat transfer model of the generator shown in Fig. R-8. It was discovered that some elements remained approximately constant during the aerodynamic heating of the generator and, therefore, the elements below them could be ignored. Elements 1 through 3 represent the aluminum skin of the generator; Elements 4 through 10 and 20 through 27 represent the insulation, Min-K; and Elements 11 through 19 represent a portion of the thermal electric element.

The following assumptions and considerations were used for this model:

- (1) External heating and radiation losses to infinity were only considered for Elements 1 and 2.
- (2) No heat transfer losses were considered in longitudinal direction of the generator. The model was assumed to be perfectly insulated on all external surfaces, except the top surfaces of Elements 1 and 2.
- (3) Heat transfer by conduction (no gaps) was considered between elements of aluminum, silicon-germanium and Min-K.
- (4) A linear temperature distribution was considered through the various composite areas using the beginning-of-life temperatures for the hot junction (1550° F) and the cold junction (458° F).
- (5) A radius of 5.4 inches (from centerline to tip of the stringer) was used in the heating equation.
- (6) The aerodynamic heating was assumed to be equally distributed over the generator by a factor of 13.3% (Ref. R-3) of the stagnation heating rate on a hemisphere of equal radius. For the Agena D/dispenser, dispenser/satellites, and the satellite/RTG/GGS(R) configurations only, an additional factor of 1/2 was used to account for the time the generator was hidden from the flow by the Agena D, dispenser and satellite.
- (7) No effects from the generator fins with respect to hot spots due to shock interaction were considered in the aerodynamic heating calculations.

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Fig. R-7. Typical Pie Section from Generator

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NOTE: All dimensions in inches.

Elements 1 through 3	Aluminum alloy
Elements 20 through 27	Min-K
Elements 4 through 10	Min-K
Elements 11 through 19	Germanium-silicon

Fig. R-8. Heat Transfer Models for the Generator

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Fig. R-9. Heat Transfer Model of Capsule Assembly

NOTE: All dimensions in inches.

Fig. R-10. Heat Transfer Model for the Fuel Capsule

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- (8) The generator was assumed destroyed when either one of the two top elements were ablated. An element was considered ablated when its enthalpy was equal to or greater than the melting enthalpy plus the heat of fusion of aluminum at its melting temperature.

2. Capsule Assembly

The heat transfer model for the capsule assembly, including the strap, is shown in Fig. R-9, and it represents a typical symmetric section from the capsule assembly. Elements 1 through 6 represent the Haynes 25 strap; Elements 7 through 18 represent the Haynes capsule; and Elements 19 through 48 represent the fuel. For this model, the following assumptions were used:

- (1) Heat conduction was only considered between Strap Element 6 and Capsule Element 7 and between elements representing the capsule's wall and the fuel. Parallel plate radiation was considered between Elements 5 and 8, 4 and 9, 3 and 10, 2 and 11, and 1 and 12.
- (2) External heating and radiation to infinity were only considered for Elements 1 through 6. Therefore, all other external surfaces were assumed to be perfectly insulated from their surroundings. No heat transfer was considered in the longitudinal direction of the capsule.
- (3) An initial temperature of 1640° F was assumed for all elements of the heat transfer model for the capsule.
- (4) The strap was considered a portion of a solid cylindrical body for aerodynamic heating distribution; therefore, the tumbling-surface averaged heating factor (0.133) was used over the top surface of the strap. This is a conservative approach, since, during some portion of this tumbling mode, a shock wave will be formed around the edge of this strap, and it will experience higher heating rates.
- (5) The strap under a load was assumed to be broken when any one of the six strap elements reached a temperature of 2425° F. This is the temperature where Haynes 25 starts to melt.

3. Fuel Capsule

The heat transfer model for the SNAP 17A fuel capsule is shown in Fig. R-10. The first three elements represents the Haynes wall of

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the capsule, and the remaining elements (20) represent the fuel. The following assumptions were considered in the heat transfer analysis of the fuel capsule:

- (1) The initial temperatures for the Haynes 25 and fuel were determined by averaging the temperatures of the 12 capsule elements of Haynes and the 30 elements of fuel, respectively, in the heat transfer model of the capsule assembly at the time the strap was broken.
- (2) Conduction was the only mode of heat transmission between the elements of Haynes and fuel.
- (3) Heating distribution over the capsule was considered to be 13.3% of the stagnation heating on a hemisphere of equal radius.
- (4) The fuel was exposed when the three elements of Haynes were destroyed by ablation. Haynes was considered ablated when its enthalpy was equal to its melting enthalpy plus 110 Btu/lb. This representation of Haynes ablation agrees very favorably with measured ablation in plasmajet tests reported in Ref. R-4.

F. DRAG CURVES

The drag curves for the Agena D/payload, dispenser/satellites, satellite/RTG/GGS(R), satellite/RTG/GGS(E), generator, capsule assembly, and the fuel capsule are presented in Figs. R-11 through R-17. These curves are for tumbling configurations and were used in their trajectory analyses. The analytical technique used to determine these curves, except Agena D/payload, is presented in Section 4.0. The Agena D/payload curve was taken from Ref. R-5.

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Fig. R-12. Variation of Drag Coefficient with Mach Number of a Tumbling Dispenser

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Fig. R-13. Variation of Drag Coefficient with Mach Number of a Tumbling Satellite/RTG/GGS (retracted)

Fig. R-14. Variation of Drag Coefficient with Mach Number of a Tumbling Satellite/RTG/GGS (extended)

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Fig. R-15. Variation of Drag Coefficient with Mach Number of a Tumbling Generator (with fins)

Fig. R-16. Variation of Drag Coefficient with Mach Number of a Tumbling Capsule Assembly

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Fig. R-17. Variation of Drag Coefficient with Mach Number of a Tumbling Fuel Capsule

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APPENDIX S

MARINE LIFE IN NMFPA VICINITY

The following lists and describes the more important marine resources in the NMFPA area. If a species that inhabits the area is omitted from the discussion, it is because the species is not frequently caught (possible due to legal restrictions) or is not frequently eaten by humans or by marine life that humans are likely to eat. The intent of the study is, therefore, to describe the species of marine life that are most often caught and eaten. Among the mollusks, the pink and red abalone and pismo clams constitute the majority south of Morro Bay. The California spiny lobster and ocean shrimp are the principal crustacean resources. Kelp is the most important California marine plant.

A. KELP

Kelp harvesting has been centered in Southern California in the past, but more recently it has been centered in Central California. It requires about a year for a young plant to develop and become established. Young plants double in size about every three weeks under favorable conditions. Giant kelp is a perennial, living and sending up new stipes for a period of five to ten years, individual stipes living about six months.

Food is not obtained from the sea bottom, but is taken from the surrounding water by the pigment (chlorophyll) of the plant in the presence of sunlight (photosynthesis).

The presence of kelp greatly increases the number of fish an area can support. It provides habitat for small animals important in the food chains, it allows fish to hide from their predators, and it gives predators hiding places from which they can pounce on their prey.

Among the many factors adversely affecting kelp are pollution; storms; grazers, such as sea urchins, abalones, and opaleye; and a condition known as black rot which occurs during periods of high water temperature and is thought to be caused by bacterial action.

At present, two kelp products are important: meal as stock food and algin. A few of the more than 100 items of which algin is an important component are pharmaceuticals, dairy products, soda fountain drinks, cosmetics, salad dressings, candies, jellies, natural and synthetic rubber, textiles, paper products, paints, boiler compounds and adhesives.

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B. CRUSTACEANS

1. California Spiny Lobsters

California landing figures indicate that the bulk of spiny lobsters is taken in the northern part of the range at Santa Barbara. Sport fishermen may take a legal limit of ten lobsters in season. The average yearly catch is roughly 475,000 pounds which, at approximately 3.3 pounds per lobster, is 144,000 lobsters.

The lobster is sexually mature at a body length of about 8.9 inches. The bulk of the diet consists of marine worms, smaller crustacea, and mollusks.

Lobsters are sold only as fresh fish in the market (alive, cooked, or frozen).

2. Ocean Shrimp

Ocean shrimp are distributed along the Pacific coast from Unalaska to San Diego. They occur at depths from as shallow as 25 to as deep as 200 fathoms. Little is known about the food habits of this species; however, it is believed that ocean shrimp prefer the microscopic material associated with green mud bottoms. Sole, skates, hake, sablefish, sharks, and rockfish are the principal predators.

Most shrimp mature as males at about one year, after which they undergo transition to become mature spawning females at about 2-1/2 years of age.

The shrimp season is from May 1 to October 15 or until the poundage quota for the area is caught. The quota for the Pt. Conception area (Pigeon Pt. to Rincon Pt.) is 250,000 pounds.

C. MOLLUSKS

1. Pink Abalone

Pink abalone are found from Pt. Conception south to Magdalena Bay, among the Channel Islands off Southern California and have been taken from Cortez Bank. They are found from the intertidal zone along rocky shores out to 180 feet, but the majority are located within depths of 20 to 80 feet. The greatest numbers are found among the Channel Islands, especially Santa Barbara and San Clemente.

The young of this species feed on algae which they scrape from the substrate with their file-like tongues. After one or two years, the

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abalone begins to feed on giant kelp, but also continues to feed on various algae. As with other species of abalone, they are found only where the giant kelps occur; but the presence of kelp does not ensure that pink abalone will be present.

At present, about 1/3 to 1/2 of the total abalone catch are pinks. In sport fishery, a bag limit of five is allowed.

Almost the entire catch is processed into frozen steaks and sold to the restaurant trade. The remainder is sold to local fresh fish markets.

2. Red Abalone

The center of red abalone population is in central California from Cape San Martin to Pt. Buchon, which is the center of the commercial fishery for this species. In its central range, it is found in greatest concentrations in waters from 35 to 50 feet in depth. It occurs among all the Channel Islands. South of Pt. Conception, it is rarely taken along the shore, but is more abundant in water from 60 to 80 feet deep.

The red abalone reaches maturity at about four or five years when about four inches in diameter.

The young red abalone feeds on the various algae of the substrate for about one year, then begins to feed on the brown kelps.

The commercial fishery is centered in Morro Bay, where the catch is taken from Pt. Estero north to Cape San Martin, an area approximately 25 miles long. The annual landings average between 1.5 and 2.5 million pounds, being limited by the number of young abalone which grow to marketable size. The red abalone is caught, processed, and sold similarly to the pink abalone.

3. Pismo Clams

Pismo clams occur from Halfmoon Bay south to Magdalena Bay and are most common in the intertidal zone on flat sandy beaches.

The Pismo clam is unisexual with the proportion of males to females about equal. Nearly all become sexually mature after they have lived through one winter. Being a scavenger, the clam buries itself in the water-covered sand, extends its siphons and extracts particles from the water. It has been estimated that a three-inch clam filters about 16 gallons per day or 5800 gallons per year. Their food includes dino-flagelates, diatoms, bacteria, algae, zooplankton, eggs, sperm and detritus from the disintegration of plants and animals.

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The Pismo clam in California is reserved for the sportsman (bag limit is 10); commercial digging has been prohibited since 1947. The areas open to clam digging alternate to preserve the population. No annual bag figures are available; however, due to unfavorable environmental conditions, the Pismo clam population has declined to the extent that it will be at least 1966 before any appreciable number grow to legal size.

4. Squid

The market squid is found from San Diego to Puget Sound. The squid fishery is based on spawning individuals or upon schools that are moving inshore to spawn. Spawning squid tend to congregate in semi-protected bays, usually over a sandy bottom.

Squid feed on small fish, shrimp, and smaller squid. Evidence indicates that the market squid is mature at the age of one year.

Annually, at least two million pounds of squid are sold fresh or frozen for bait. Though the catch is largely centered in Northern California, the squid live and travel all along the California coast.

D. FISH RESOURCES

Information pertaining to the annual landings both by commercial and sport fishermen is limited. The following study will assume that those species which dwell and/or are caught in the kelp beds are of the greatest importance. With respect to the possible contamination of pelagic fishes, it is felt that a lesser hazard exists by virtue of their being pelagic, i.e., offshore, surface dwellers.

1. Kelp Bass

The range of the kelp bass brands it as a Southern California resident. It is caught from Santa Barbara south to and including Los Coronados Islands, the average catch weighing about two pounds.

Bass do not move about to any great extent, as demonstrated by a tagging program. The catch of bass in or around the kelp beds is unrelated to the kelp harvest.

Although the kelp bass is a most popular sport fish, it no doubt takes second place when pelagic species are abundant. Party boats reported a maximum of about 800,000 bass in 1954, and a minimum of 470,000 in 1956.

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2. Rockfish

In California there are nearly 50 species of rockfish, or rock cod which, as a group, rank high both in the market catch and in the sport catch. Some species attain a length of only 10 to 12 inches, but most are larger, and a few reach 30 to 36 inches. The adults of some species are found only in shallow water, around rocks, while others are found in water as deep as 300 fathoms. The young of the deep-water species are often found in shallow water, shifting into deeper water with increasing size. South of Pt. Conception, the olive, whitebelly, and vermilion rockfish are the most important rockfish sport catches. Commercially, the bacaccio, chilipepper, canary, and vermilion rockfish compose the greater catch of the annual landings in California. No size or bag limits apply to the commercial taking of rockfish, but sport fishermen are restricted to 20 per day.

Among the diet of most varieties of rockfish are small plants, small fish, shrimp, and squid.

Since 1916, annual commercial landings of rockfish have been as low as two million pounds (1942) and as high as 17 million pounds (1958). During the five years, 1955 to 1959, about 45% of the total number of fish caught by party-boat fishermen were rockfish.

3. Jack Mackerel

The distribution of jack mackerel is extensive, from British Columbia to at least Acapulco. The main fishery is from Monterey to San Diego, extending offshore to about 120 miles.

The adults feed on minute shrimp-like crustaceans, pelagic mollusks, and, at times, anchovies, latern fish, and young squid.

Since 1952, the annual catch has fluctuated between 22 and 82 million pounds. In general, landings have tended to vary inversely with the successes and failures of the sardine and Pacific mackerel fisheries. Although the jack mackerel is primarily a commercial fish, as many as 200,000 have been taken in a season by sport fishermen.

Most of the catch is canned for human consumption, though small amounts are sold in fresh fish markets and canned for animal food.

4. Pacific Mackerel

Pacific mackerel are found along the west coast from Alaska to Banderas Bay. The main concentration occurs from Pt. Conception south and are most intensively fished of Southern California.

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Pacific mackerel feed on small fish, tiny shrimp-like crustaceans, and nearly all forms of plankton to some degree.

A tagging program has shown a considerable mixing of the fish throughout the mackerel range. Fish tagged off central Baja California were later caught off Southern and Central California.

Average commercial landings average between 20 and 60 million pounds. Sport fishermen take upward of 500,000 Pacific mackerel annually.

The catch is processed and utilized much like the jack mackerel.

5. White Sea Bass

White Sea Bass range from Juneau to Magdalena Bay and congregate offshore in Southern California during spawning.

The major foods of the white bass are squid, sardines, anchovies, and red crabs when available.

They are the most valuable croaker found in California waters. They are used only as fresh fish, never canned. In 1958, the white sea bass ranked sixth in poundage for those species sold exclusively as fresh fish.

Major catches are made in the coastal waters from Pt. Conception to San Diego. The average annual commercial catch is 953,000 pounds. Since 1946, the annual sport fish catch has been 32,105 fish.

6. Barred Surfperch

Bodega Bay to Playa Maria Bay constitutes the range of the barred surfperch.

This specie is solely a sport fish by law south of Pt. Conception, constituting about 73% of the Southern California sport fish bag, and an excellent pan fish.

Ninety percent of the food of the barred surfperch is sand crabs, the remainder being bean clams and small crustaceans. This perch is generally found in the surf and occasionally in water as deep as 240 feet.

7. Swordfish

The swordfish is most plentiful south of Pt. Conception, usually seen lazing along at the surface; but some have been caught as deep as 200 fathoms.

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Young swordfish feed almost entirely upon fish they capture near the surface; but with age, they forage at greater and greater depths. Various deep sea fishes have been noted in their stomachs, so it appears they spend considerable time at depths of 1000 feet or more. They also eat vast quantities of squid and octopi.

Commercially the annual landings approach 500,000 pounds. The catch largely is filleted and sold both fresh and frozen.

8. Cabezon

The Cabezon is found from Pt. Abreojos to Queen Charlotte Island and is a subtidal bottom dweller. When about one and one-half to two inches in length, the young take up a bottom dwelling habit, eating small tide pool fish and crustaceans. Adult cabezon are usually found in deeper rocky areas (20 to 60 feet) but will often move into shallow water with the incoming tide to feed. There they eat mostly crab and small fish.

The cabezon is essentially a sport species. The ratio of sport to commercial catch is greater than five to one. Although no landing figures are available, the Cabezon sport catch is thought to be high.

9. Bluefin Tuna

California bluefin tuna have been recorded from Cape San Lucas to Wide Bay. They are generally caught from Pt. Conception to the Mexican border.

This tuna feeds largely on northern anchovies and, to a lesser extent, on smelt, sanddab, mackerel, white croaker, pompano, and squid. Indications are that tuna migrate large distances away from the shore.

Though a sought sport fish, few are landed by sport fishermen. Commercially between 280 tons and 12,587 tons are landed annually. A vast majority of the catch is landed around the Terminal Island canneries.

Most of the catch is canned but a small amount is sold fresh.

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APPENDIX T

SHIPPING CASK THERMAL ANALYSIS

This appendix summarizes the calculations performed to predict the temperature distribution of the shipping cask. Based upon ICC regulations for transporting radioactive materials, the surface temperature of the shipping cask must be limited to a maximum temperature of 180° F when the cask is subjected to an environment of 120° F.

To limit the cask surface temperature as specified above, the cask is designed with 43 rectangular steel fins 1/8 inch thick. The fins were sized using an iterative technique. The following is a typical calculation. Figure 3.26 summarizes the cask design.

The heat generated by the strontium-90 fuel is nominally 650 watts (2218 Btu/hr) at fueling. The heat transferred from the surface of the cask is described by:

$$q = h A_s (T_1 - T_a) \quad (T-1)$$

where

q = heat transferred (2218 Btu/hr)

h = natural convection heat transfer coefficient (Btu/hr-ft²-°F)

A = effective heat transfer area (ft²)

T_1 = fin root temperature (180° F, maximum)

T_a = ambient temperature (120° F)

The correlation specifying the natural convection heat transfer coefficient for a body in air is given by McAdams (pg 173) as:

$$h = 0.29 \left(\frac{T_1 - T_a}{l} \right)^{1/4} \quad (T-2)$$

where

l = characteristic length, 3.83 feet (mean circumference for cylindrical fins)

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For this design, substituting in Eq (L-2).

$$h = 0.29 \left(\frac{60}{3.83} \right)^{1/4} = 0.577 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}$$

Revising Eq (L-1), the effective heat transfer area required is:

$$A = \frac{q}{h(T - T_a)} = \frac{2218}{0.577(60)} = 64.07 \text{ ft}^2 \quad (\text{L-3})$$

To achieve this effective area, we must surround the cask with a sufficient number of fins so that the effective area (including fin inefficiency) is at least that specified above. Assume now that 43 rectangular steel fins 1/8 inch thick and 3 inches wide are mounted to the cask as illustrated by Fig. 3.25. The effective fin length for this design is 46 inches. This effective length is the perimeter of each fin taken at a mean between the root and the outer radii of the circumferential fins.

To calculate the efficiency of the fins, Fig. 2-19 of Reference T-1 is used. Here fin efficiency is plotted as a function of the following fin parameters:

$$\left(r_o + \frac{t}{2} - r_1 \right)^{3/2} \sqrt{2h/k t (r_o - r_1)} \quad (\text{T-4})$$

and

$$\frac{\left(r_o + \frac{t}{2} \right)}{r_1} \quad (\text{T-5})$$

where

r_o = outer radius of cask including fins [0.8875 ft (10.65 in.)]

r_1 = outer radius of cask excluding fins [0.72 ft (8.65 in.)]

t = fin thickness [0.0104 ft (0.125 in.)]

k = thermal conductivity of fin (30 Btu/hr-ft- $^\circ\text{F}$)

Substituting the above values into Eqs (T-1) and (T-5) and referring to Fig. 2-19 of Reference T-1, we obtain a fin efficiency, η , of 0.911.

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The effective heat transfer area is then:

$$A = 2N \eta WL/144 \quad (T-6)$$

where

N = number of fins (43)

η = fin efficiency (0.911)

W = fin width (3 in.)

L = effective fin length (46 in.)

A = heat transfer surface area (ft²)

Substituting the values specified above into Eq (T-6), we calculate an effective heat transfer area of 75.08 ft². The minimum surface area required, as specified by Eq (T-3), is 64.07 ft². Thus, the cask is slightly oversized with the assumed 3-inch fins. This means that when the cask is subjected to an environment of 120° F, the maximum surface temperature of the cask will be less than 180° F. Due to the uncertainty associated with the convective heat transfer coefficient correlation, oversizing is desirable; thus the 3-inch fin was selected.

The temperature distribution through the cask was calculated using a rather conservative approach. It was assumed that all the heat dissipated by the fuel is transferred through the cylindrical sides. The temperature drop through the lead shield is calculated with the following equation.

$$q = \frac{2\pi kL (T_2 - T_1)}{\ln (r_1/r_2)} \quad (T-7)$$

where

q = heat transferred (2218 Btu/hr)

k = thermal conductivity of the lead (18 Btu/hr-ft-°F)

L = length (1.58 ft)

T_1 = surface temperature of cask (180° F)

T_2 = temperature of lead at inner surface (°F)

r_2 = radius at inner surface (0.25 ft)

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Solving for T_2 we get:

$$T_2 = \frac{T_1 + q \ln(r_1/r_2)}{2\pi kL} \quad (T-8)$$

Substituting into Eq (T-8), we find that T_2 equals 193° F .

The heat transferred from the fuel capsule to the cask is by radiation since no contact exists.

Thus:

$$q = \sigma \epsilon A_2 (T_3^4 - T_2^4)$$

or

$$T_3 = (T_2^4 + q/\sigma \epsilon A_2)^{1/4} \quad (T-9)$$

where

σ = Stefan-Boltzman ($0.173 \times 10^{-8} \text{ Btu/hr-ft}^2\text{-}^\circ\text{R}^4$)

ϵ = assumed effective emissivity between parallel surfaces (0.428)

T_3 = surface temperature of fuel capsules ($^\circ\text{R}$)

A_2 = radiating surface area (ft^2)

Substituting these values into Eq (T-9), we find that the average surface temperature of the fuel capsule is 748° F .

REFERENCES

T-1 Kreith, Frank, "Principles of Heat Transfer."

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APPENDIX U

STRONTIUM-90 FUEL FORM PROPERTIES

The following fuel form properties were assumed during the Phase I engineering effort for the SNAP 17A. These properties have been used throughout the program except where otherwise noted in this report. Selection of these properties was based on the assumption that the fuel chemistry would be primarily strontium fluoride.

A. Isotopic Properties

Half Life

Sr-90 (yr) 27.7

Y-90 (hr) 64.2

Sr-89 (days) 31

Maximum Beta Energy (Mev)

Sr-90 0.57

Y-90 2.19

Specific Activity

142 curies of Sr-90/gm Sr-90

Specific Power

6.68 watts/kc Sr-90

Ratio of Sr-90 to total strontium

0.5 to 0.6 (assuming negligible Sr-89)

B. Chemical Impurities

Ce-144 = 0.15 curie/gm Sr-90

Stable cations = 25 wt% excluding stable strontium

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Power Density--thermal

Theoretical specific power (watts/gm)	0.353
Theoretical power density (watts/cm ³)	1.51
Practical power density (watts/cm ³)	1.00

Physical Properties

Molecular weight, SrF ₂	127
Density (gm/cm ³)	
Theoretical	4.28
Practical	3.43
Melting Point (°C)	1360 ± 20
Boiling Point (°C)	2380 ± 20
Thermal conductivity	See Fig. U-1
Heat capacity	See Fig. U-2
Surface tension	See Fig. U-3
Emissivity	See Fig. U-4
Vapor pressure	See Fig. U-5

C. Compatibility with containment materials

The maximum depth of reaction detected in several materials after exposure to SrF₂ at 1000° C for 200 hours in nitrogen were as follows:

<u>Material</u>	<u>Depth of Reaction (in.)</u>
Type 321 SS	0.0015
René 41	0.0025
Hastelloy C	0.001
Haynes -25	0.001

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U-3

Fig. U-1. Thermal Conductivity

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Fig. U-2. Heat Capacity

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U-5

Fig. U-3. Surface Tension

Fig. U-4. Emissivity

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Fig. U-5. Vapor Pressure

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APPENDIX V

RTG FUEL CAPSULE TEMPERATURE DISTRIBUTION

An accurate knowledge of the fuel capsule temperature distribution during launch is of great importance to:

- (1) Evaluate the structural stresses imposed on the system during launch.
- (2) Help predict the fuel capsule temperature at impact due to a launch abort.
- (3) To help establish the generator operating characteristics.

Figure V-1 is a layout showing the relation of the six fuel capsules to the silicon-germanium thermoelement heat collector plates. The heat generated by the fuel capsules is transferred to the collector plates by thermal radiation. Although the heat is generated uniformly throughout the fuel, only about one-half of the capsule surface can reject heat (the inner half can be considered insulated since it exchanges heat with a surface of equal temperature). This leads to a variation in temperature around the fuel capsule. Such a two dimensional problem with a radiation boundary condition can be readily analyzed by a numerical technique. An IBM computer program (Tiger II) was employed for this purpose. The program handles internal heat generation, radiation type boundaries and multidimension heat conduction.

To simplify the problem somewhat, the conduction of heat along the axial direction (less than 10%) was neglected. Two conditions were analyzed.

- (1) Beginning of life

Hot junction temperature = 1550° F

Heat generated at a rate of 1 watt/cc

- (2) End of life

Hot junction temperature = 1415° F

Heat generated at a rate of 0.885 watt/cc.

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Fig. V-1. Fuel Capsule Layout

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The material properties and other assumptions used in the analysis are given in Table V-1. The total heat generated by the six fuel capsules was assumed to be 652 watts at beginning of life.

The results of the analysis (beginning of life) are presented in Figs. V-2 and V-3. The hottest point within the fuel was found to be 1731° F. Strontium fluoride has a melting point of 2490° F; therefore, the fuel remains in the solid form at all times. Note that the maximum temperature of the Haynes 25 is 1702° F. This is also well below the clad material melting point and in the region where considerable short term strength is available. At end of life, the temperatures are reduced considerably. The results are shown in Table V-2.

All indicated temperatures are for the center point of the incremental columns shown. A sufficiently small grid was employed to assure accurate results.

TABLE V-1
Analytical Data

Thermal conductivity of Haynes-25 (Btu/hr-ft-°F)	14.8
Thermal conductivity of strontium fluoride (Btu/hr-ft-°F)	1.21
Emissivity of capsule surface	0.60
Capsule wall thickness (in.)	0.08
Fuel diameter (in.)	1.20

TABLE V-2
Generator Temperature Profile

<u>Location</u>	<u>Temperatures (°F)</u>	
	<u>Beginning of Life</u>	<u>End of Life</u>
Hot junction	1550	1415
Clad (maximum)	1702	1563
Fue (maximum)	1731	1588

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Fig. V-2. Fuel Capsule Temperature Distribution (beginning of life)

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Fig. V-3. Fuel Capsule Temperature Distribution (five years after launch)

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