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APOLLO LUNAR RADIOISOTOPIC HEATER SUMMARY REPORT

D. P. Kelly and V. L. Avona

AEC Research and Development REPORT

MONSANTO RESEARCH CORPORATION

A SUBSIDIARY OF MONSANTO COMPANY

M O U N D L A B O R A T O R Y

MIAMISBURG, OHIO

OPERATED FOR

UNITED STATES ATOMIC ENERGY COMMISSION

U.S. GOVERNMENT CONTRACT NO. AT-33-1-GEN-53

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Printed in the United States of America
Available from
Clearinghouse for Federal Scientific and Technical Information
National Bureau of Standards, U. S. Department of Commerce
Springfield, Virginia 22151
Price: Printed Copy \$3.00; Microfiche \$0.65

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MLM-1637
TID-4500
UC-23 Radioisotope
and Radiation
Applications

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Issued: April 30, 1969

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MONSANTO RESEARCH CORPORATION

A Subsidiary of Monsanto Company

MOUND LABORATORY

Miamisburg, Ohio

operated for

UNITED STATES ATOMIC ENERGY COMMISSION

U.S. GOVERNMENT CONTRACT NO. AT-33-1-GEN-53

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ABSTRACT

Three Apollo Lunar Radioisotopic Heaters were designed and fabricated for environmental protection of seismic instrumentation on the moon. The heater will be part of the Early Apollo Scientific Experiments Package for the first lunar landing. Each heater was fueled with 37.6 g of plutonium-238 dioxide microspheres to produce 15 thermal watts. The fuel was encapsulated in multiple containers of Ta-10 wt % W alloy, Pt-10 wt % Rh alloy, titanium, graphite, and stainless steel to ensure safety. The safety of the design was confirmed by a series of tests which simulated all possible accidental conditions surrounding the Saturn V launch and flight. The three sources were shipped to Kennedy Space Center on April 2, 1969.

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INTRODUCTION AND CONCLUSION

In October 1968 NASA management substituted the Early Apollo Scientific Experiments Package (EASEP) in place of the Apollo Lunar Surface Experiments Package (ALSEP) for the first lunar landing. Included as part of the EASEP design were two radioisotopic heaters to protect electronic seismic instrumentation from cold during the lunar night. The Apollo Lunar Radioisotopic Heaters (ALRH) (Figure 1) were designed and fabricated at Mound Laboratory.

The Early Apollo Scientific Experiments Package (EASEP) comprises two instrumentation units: the Passive Seismic Experiment Package (PSEP) and the Laser Ranging Retro-Reflector (LRRR). The two radioisotopic heaters are mounted on the PSEP.

The Passive Seismic Experiment Package (PSEP) shown in Figure 2 will monitor lunar seismic activity. It will detect

FIGURE 2 - Practice deployment of the Passive Seismic Experiment Package (PSEP) on a simulated lunar surface. One of the two heaters mounted on the PSEP is circled. The heater is covered with similarly shaped thermal insulation with a mirror finish exterior. The insulation directs the heat downward toward the instrumentation. (Bendix Aerospace Division photograph)

FIGURE 1 - The Apollo Lunar Radioisotopic Heater (ALRH) produces 15 watts of thermal power with plutonium-238 dioxide microsphere fuel. The height of the heater is slightly greater than 3 in. (7.6 cm).

meteoroid impact and free oscillations in lunar rotation. It may also detect surface tilt tidal deformations resulting, in part, from periodic variations in the strength and direction of external gravitational fields acting on the moon. Powered by solar cells, the package will transmit data only during the lunar day-time.

Portions of the seismic detector would be damaged by the extreme cold of the lunar night, when the temperature drops as low as -300°F (-184°C). Without heat the experiment would be limited to a maximum operating time of about 14 days. However, two of the Apollo Lunar Radioisotopic Heaters (ALRH) will maintain the detector above -65°F (-54°C) during the night. During the lunar daytime, insulation and a reflective coating will protect the package from heat, maintaining the temperature in the range 0 - 140°F (-18 to 60°C) for reliable operation. The heated PSEP will have a useful life-

time of as much as 2 yr. The greater cost effectiveness and the increased scientific returns are obvious.

Each ALRH is fueled with 37.6 g plutonium-238 dioxide microspheres (~ 450 Ci of plutonium-238) to produce 15 thermal watts $[\text{W(t)}]$. The half-life of plutonium-238 is 87.4 yr; it decays predominantly by alpha particle emission, with slight gamma and neutron radiation. The resultant power decay for the ALRH will be less than 1% per yr.

Due to the limited time available for development of the ALRH (about 6 mo) a philosophy of overdesign and overtesting was adopted to ensure safety. Existing AEC laboratory facilities were used whenever possible for fabrication and testing.

Ultimately, two fueled heaters were fabricated for use on the PSEP; a third fueled heater was fabricated as backup.

An exploded view of the ALRH is shown in Figure 3. The microspheres were en-

FIGURE 3 - Exploded view of the ALRH showing the multiple encapsulation.

capsulated initially in an inner liner of Ta-10 wt % W refractory alloy. An outer liner of the same metal was used to obtain a capsule free of radioactive surface contamination. Cladding of Pt-10 wt % Rh alloy provided an oxidation barrier to protect the refractory alloy. The thick titanium fragmentation shield provided the major protection against a possible launch pad explosion. As protection against the temperature and heat of reentry in the case of an abort from space, a graphite insulator covered by an ablative graphite heat shield were used. The outer container of stainless steel was riveted to an aluminum base plate for attachment to the aluminum mounting plate of the PSEP. The outer insulation was to be added later.

The testing program included a series of mechanical tests and radiation measurements. Capsule components were also exposed to all possible accidental conditions of impact, explosion, and heat that might be encountered before, during, or after the launch of the Saturn V space vehicle.

The favorable results of the tests were reported by Lt. Col. W. S. Holman, Project Safety Officer, in the "Safety Analysis Summary for Apollo Lunar Radioisotopic Heater (ALRH)" on March 1, 1969:

The results of these tests and analyses indicated that the ALRH presents no undue hazard to the general populace under any accident condition provided within the framework of a Saturn V mission.

Two fueled heaters were fabricated for use on the PSEP; a third fueled heater was fabricated as backup. The three heaters were shipped, ahead of schedule, to the Kennedy Space Center on April 2, 1969.

DESIGN CRITERIA

The design criteria for the Apollo Lunar Radioisotopic Heater were established jointly by representatives of Bendix, NASA, AEC and Mound Laboratory. The finished heaters met or exceeded all requirements.

Program Requirements: Three heaters are to be delivered to Kennedy Space Center by May 1, 1969.

Thermal Power: The total thermal power of each heater shall be 15 ± 0.25 W(t) on July 1, 1969. The thermal out-

put shall not decrease more than 1% per yr.

External Radiation: The total nuclear radiation at 1 m from the heater shall be less than 10 millirems per hour (mrem/hr).

Dynamic Environment: The heaters shall withstand, without degradation, the following dynamic environments:

1. **Vibration:** The heater shall withstand, without degradation, both sinusoidal and random vibration. Sinusoidal vibration will range from 5 to 30 Hz at 0.25 in. (0.64 cm) double amplitude and 30 to 100 Hz at 10 g (g = acceleration due to gravity). The random vibration will range from 10 to 2000 Hz for 15 min.
2. **Shock:** The heater shall withstand, without degradation, three mechanical shocks along each major axis.
3. **Acceleration:** The heater shall withstand, without degradation, steady-state acceleration of 14 g .

Weight: The maximum weight of the individual heaters shall be 3 lb (1.4 kg).

Capsule Dimensions: The external heater diameter, exclusive of the flange, shall be 3 in. (7.6 cm) maximum. The external height of the heaters shall be 3.2 in. (8.1 cm) maximum. The aluminum flange shall have a maximum diam of 4.25 in. (10.80 cm) and a minimum thickness of 0.180 in. (0.457 cm). The bolt hole circle shall be 3.625 in. (9.208 cm) in diam.

Outer Container Material: The outer container, exclusive of the flange, shall be fabricated from 304 stainless steel, titanium, titanium alloy, or aluminum.

Flange: The flange shall be fabricated from 6061 aluminum and shall have a surface finish of 63 μ in. (1.6 μ m) and a flatness of 0.003 in. (0.008 cm).

Center of Gravity: The center of gravity shall be no more than 2.0 in. (5.1 cm) from the bottom of the flange.

Fuel: The fuel shall be plutonium-238 dioxide microspheres.

Mounting Holes: Six holes shall be placed in the mounting flange for securing the heater to the PSEP.

APOLLO LUNAR RADIOISOTOPIC

HEATER PROCESS FLOW DIAGRAM

TITANIUM BAR

GRAPHITE INSULATION

STAINLESS STEEL BAR-TUBE-SHEET

ALUMINUM BAR

FIGURE 4 - Cross section of the ALRH.

DESCRIPTION OF HEATER

Figure 4 is a cross-sectional drawing of the ALRH as it was fabricated to meet the design criteria.

Fuel: The thermal power requirement of 15 ± 0.25 W(t) was achieved using 50-250- μ m diam plutonium-238 dioxide microspheres prepared by fusion of oxide particles in a plasma torch. The actual fuel used for the flight hardware had the following characteristics:

Apparent density	10.14 g/cc
Total impurities	<0.44 wt %
Stoichiometry	2.00
Plutonium-238 content	70.7 wt %
Melting point	$2370 \pm 80^\circ\text{C}$
Fuel per capsule	~ 37.6 g
	~ 450 Ci

Shim: In order to prevent blowout of heated gases through the molten metal during the welding of the inner liner, a Ta-10 wt % W shim was placed over the fuel. This alloy is compatible with the fuel at the operating temperature of the heat source. The shim is shown in Figure 5 as one of the components of the fragmentation shield assembly.

Inner Liner: The fuel was first encapsulated in a 20-mil (0.051-cm) thick Ta-10 wt % W refractory alloy container (Figure 5) having the following nominal dimensions: i.d. 0.785 in. (1.994 cm); o.d. 0.825 in. (2.096 cm); and overall

length 0.822 in. (2.088 cm). Because of its compatibility with the fuel, Ta-10 wt % W alloy was chosen for this application. The thickness of 20 mils (0.051 cm) was chosen for ease of fabrication. Thicker material is difficult to TIG (tungsten-inert gas) weld.

Outer Liner: The inner liner was next TIG welded (in an argon atmosphere) in another 20-mil (0.051-cm) thick Ta-10 wt % W container (Figure 5) having the following nominal dimensions: i.d. 0.835 in. (2.121 cm); o.d. 0.875 in. (2.222 cm); and overall length 0.886 in. (2.250 cm). This secondary Ta-10 wt %

FIGURE 5 - Components of the fragmentation shield assembly of the ALRH.

W container was used to provide a capsule free of surface radioactive contamination.

Clad: To provide an oxidation barrier for the refractory metal, the outer liner was TIG welded inside a 10-mil (0.025-cm) thick Pt-10 wt % Rh alloy container (Figure 5) with the following nominal dimensions: i.d. 0.885 in. (2.250 cm); o.d. 0.905 in. (2.299 cm); and overall length ~0.950 in. (~2.413 cm).

Fragmentation Shield: In order to provide the mechanical protection for the heat source should it be exposed to a launch pad explosion, or terminal velocity impact, the clad assembly was welded inside a 0.25-in. (0.64-cm) thick titanium body (Figure 5) having the following nominal dimensions: i.d. 0.919 in. (2.334 cm); o.d. 1.419 in. (3.604 cm); overall length 1.445 in. (3.670 cm). Titanium was chosen for its relatively high strength and low density.

Insulator: In order to prevent the high temperature associated with the heat of reentry (in case of an abort from space) from reaching the titanium, the shield was surrounded by approximately 0.150 in. (0.381 cm) of fibrous graphite insulating material supplied by Oak Ridge National Laboratory. The insulator is shown in Figure 6 as one of the components of the heat shield assembly.

Heat Shield: As protection from possible heat of reentry, the insulator was encased in a 0.6-in. (1.52-cm) thick graphite heat shield with the following nominal dimensions: i.d. 1.723 in. (4.376 cm); o.d. 2.929 in. (7.440 cm); overall length 2.878 in. (7.310 cm). The graphite heat shield assembly (shown in Figure 6) was made of Poco graphite, grade AXF-5Q (Poco Graphite, Inc., Garland, Tex.), which was chosen for its relatively high tensile strength and product uniformity.

Outer Container: The graphite heat shield was next welded into a 304 stainless steel container (Figure 7) approximately 30 mils (0.076 cm) thick with nominal dimensions as follows: i.d. 2.94 in. (7.47 cm); o.d. 2.999 in. (7.617 cm); overall length 3.020 in. (7.671 cm).

Base Plate: The 304 stainless steel container was fastened with 12 rivets to

FIGURE 6 - Components of the heat shield assembly of the ALRH.

a 6061 aluminum base plate (Figure 7). The 6061 aluminum was chosen to assure compatibility with the PSEP mounting plate of the same material. To ensure good thermal contact between the outer container and the base plate, Dow-Corning silicone grease was applied to the outer container at the interface with the base plate.

FIGURE 7 - Components of the ALRH.

Capsule Fabrication: The fabrication of the heater assembly was carried out in accordance with the Mound Laboratory procedures developed for the fabrication of heat sources. The flow diagram on pages 10 and 11 summarizes this fabrication procedure.

Nineteen complete capsules, 24 fragmentation shield assemblies, and 4 heat shield assemblies were fabricated with a fuel simulant for testing.

Tests of heaters with and without fuel ensured that all design criteria were met. The units withstood the dynamic environments without degradation. Calorimetric analysis indicated that the fueled ALRH produced the desired amount of heat. Each heater weighed 2.1 lb (0.95 kg).

SAFETY EVALUATION

The safety evaluation of the ALRH was performed by Sandia Laboratories in Albuquerque, New Mex. A summary of this safety evaluation is presented below. The system of overtests was planned to ensure that there would be no release of radioactivity under any conceivable accident condition. Potential accidental conditions were simulated for all phases of the program before, during, and after launching of the Saturn V vehicle. All tests were performed with capsules containing a simulated fuel.

Transportation and Handling The fueled heaters may encounter accidental shock, impact, or fire during handling

or transportation. In no case, however, would they encounter conditions so severe as those to be described in later accident modes. It is worth noting that although the carrying container (Figure 8) for the individual heaters is of a rugged construction and surpasses Department of Transportation requirements, tests showed that the heater itself is far stronger. No credible case exists for the release of fuel due to handling or transportation accidents.

Prelaunch and Launch Phase The Saturn V/Apollo vehicle contains the largest propellant load of any U. S. space vehicle. This fuel, if ignited on or near the launch pad could produce a severely trying combination of blast, heat, and fragments. Tests simulated the effect of each of these singly or in combination on the ALRH:

1. **Blast and Impact - Shock Tube Tests:** To simulate the immediate and secondary effects of the blast wave produced by detonating propellants, the heaters were subjected to shock tube tests at pressures as high as 1100 psi (7.6×10^8 dynes/cm²). Since this yield is about three times the maximum which can be realistically predicted, it represents a substantial overtest. In this test a mock-up of the seismic detector with ALRH units attached was propelled at 608 ft/sec (185 m/sec) through aluminum U-beams representing spacecraft structure. The fragmentation shields

FIGURE 8 - Shipping container for the ALRH.

FIGURE 9 - The fragmentation shield was impelled from a shock tube at 608 ft/sec through aluminum U-beams, which simulated structural members of the space vehicle.

were located some distance away, the farthest traveling approximately a half mile from the shock tube. Figures 9 and 10 show the aluminum U-beams after impact by the mockup of the seismic detector with the ALRH.

Figure 11 is a cross section of the titanium fragmentation shield after this test. As a result of the blast, the outer container and graphite layers were lost, but there was

no discernible loss of integrity of the titanium fragmentation shield.

2. Secondary Blast Effects - Heavy Equipment Test: A metal box weighing 24 lb (10.9 kg) and simulating heavy electronic equipment was fired at 290 ft/sec (88 m/sec) into a mockup of a seismic detector on which two heaters were mounted. This test simulated

FIGURE 10 - The imprint of the fragmentation shield can be seen on one of the U-beams used in the shock tube test.

FIGURE 11 - Cross section of the titanium fragmentation shield assembly after it was blasted in the shock tube test. Although there was no apparent deformation of the fragmentation shield, the liners were dented.

the objects that might hit the ALRH as a result of a blast. As a result of this test, one heater was torn loose from its aluminum mounting, but the outer container maintained its integrity. The other heater remained mounted and intact.

3. Secondary Blast Effects - Fragmentation Tests: A variety of fragmentation tests were run on the titanium shield, including impact with 0.060-in. (0.152-cm) thick aluminum sheets edge-on (Figure 12), impact with irregular fragments of aluminum, and an inadvertent impact (Figure 13) at high velocity into the end of a piece of 3/8-in. thick steel pipe. Tests were conducted with both heated and unheated fragmentation shields in the velocity range of 1000-2750 ft/sec (305-839 m/sec).

FIGURE 12 - Test setup for impacting the fragmentation shield (mounted at left) edge-on into a sheet of aluminum (right). (Sandia photograph)

In no case was the fragmentation shield breached. In all planned tests there was either no apparent damage or only superficial nicking and scarring of the shield. In the inadvertent impact, the titanium shield was nicked deeply but not breached; this case far exceeded even the overtest conditions. Figure 14 is a cross-sectional photograph of the shield inadvertently impacted into the steel pipe. The containers maintained their integrity.

FIGURE 13 - This fragmentation shield was inadvertently impacted into a steel pipe, far exceeding even the requirements for overtesting. (Sandia photograph)

4. Thermal Effects - Analysis: Several fireball models (i.e., profile of temperature as a function of time) were considered, the most severe of which was extended to include all other proposed fireball models. In some cases, the selection may have been unrealistically severe, again with the objective of attempting to

FIGURE 14 - This is a cross section of the fragmentation shield shown in Figure 13. Even under the extraordinary condition, the shield was not breached. (Sandia photograph)

establish the limits of the design. All analyses were performed on the bare fragmentation shield, assuming instant removal of the stainless steel canister, graphite, and insulation. The most severe fireball flux removed only the titanium, leaving the Ta-10 wt % W fuel containers with their oxidation-protective coating of Pt-10 wt % Rh intact.

5. Thermal Effects - Titanium Oxidation Test: A titanium fragmentation shield was heated in oxygen at 900°C for approximately 3 hr. Only minimal surface oxidation was noted.
6. Thermal Effects - Titanium Burn Test: To simulate the effect on titanium of a fireball environment and to determine if a titanium burn in oxygen will sustain itself, the titanium fragmentation shield was heated to the ignition point in oxygen. No burning occurred at the ignition point. When the temperature was raised further to the melting point of titanium, burning began; but removal of either the heat or the oxygen extinguished the flame. It was impossible to produce conditions for a self-sustaining burn either in air or in 100% oxygen. Regardless of the extent of burning of the titanium the Ta-10 wt % W would survive intact.

Early Ascent Phase This phase covers the flight up to the point at which aerodynamic heating becomes significant. All circumstances which occur on the launch pad could also occur during early abort. No case during early ascent would be more severe than the accidental condition that might occur on the launch pad; the fireball model would, if anything, be less severe. Two new conditions must, however, be considered:

1. ALRH Land Impact Test: Based upon the overtest concept, a terminal velocity of 430 ft/sec (131 m/sec) for impaction into granite or steel was initially selected to test the bare fragmentation shield. This velocity is about two and a half times the actual terminal velocity that might be expected if the ALRH fell during this phase of flight. Soil was impacted at 1000 ft/sec (305 m/sec).

Concrete was impacted at 600 ft/sec (183 m/sec). In no case did the fragmentation shield lose its integrity. Figures 15 and 16 are cross-sectional photographs of two specimens impacted into steel targets.

FIGURE 15 - The bare fragmentation shield was tested in the land impact test by impacting against granite, steel, and concrete. This cross section shows an assembly that was impacted against steel. Only the inner liners were deformed. The terminal velocity for the bare fragmentation shield in these land impact tests was 430 ft/sec (131 m/sec). (Sandia photograph)

FIGURE 16 - This fragmentation shield was also impacted into steel. Although the corner was deformed, the capsule did not lose its integrity. (Sandia photograph)

Figure 17 is a photograph of a titanium fragmentation shield assembly after impact into a concrete target at 595 ft/sec (181 m/sec). Figure 18 shows the concrete target after impact.

FIGURE 17 - This titanium fragmentation shield was impacted into concrete. The shield maintained its integrity. (Sandia photograph)

2. ALRH Terminal Velocity Test: Terminal velocity drop tests were conducted on the fragmentation shield, a simulated ablated unit, and a complete unit. The terminal velocity of the ablated unit was determined to be about 175 ft/sec (53 m/sec). The complete unit tended to sail because of the mounting plate, but probably did not exceed 175 ft/sec (53 m/sec). The fragmentation shield alone was too small to allow satisfactory velocity measurement, but it probably did not greatly exceed the measured velocity of the ablated unit.
3. ALRH Impact - Water: Impact on water due to early abort would be less severe than on land (or granite). No loss of integrity of the fuel capsule was predicted.

Suborbital Phase The parameters of earth orbital decay are at least as severe as those of late abort prior to achieving earth orbit. Survival of orbital reentry indicates survival of late abort; therefore the two cases are combined in the following discussion.

Orbital Phase

1. Orbital Decay - Analysis: The heat source was analyzed for both random tumbling and side-on, stable modes of reentry. Analysis indicated that an intact heat source can survive earth orbital decay in the most severe (side-on, stable) mode. In addition, if the graphite reentry protection were removed, the Ta-10 wt % W fuel container would reenter intact in the random tumble mode.
2. Orbital Decay - Test: The heater was subjected to simulated orbital decay conditions in the side-on, stable mode in the Sandia HEAT facility. In this test the bare fragmentation shield was mounted in an arc tunnel. Hot gases were blown across the sample at predetermined heat inputs to simulate reentry into the earth's atmosphere. The ALRH withstood the environment of this decay mode with no indication of damage. The graphite ablation calculated before the test was 190 mils (0.483 cm). The actual ablation during the test was about 160 mils (0.406 cm).

FIGURE 18 - The concrete target after impact by the fragmentation shield shown in Figure 17. (Sandia photograph)

Superorbital Phase Superorbital abort consists of three types of reentry. The first is that of an angle of reentry sufficiently shallow to allow the ALRH to penetrate the atmosphere, but which results in additional orbits. The second case is that of reentry at, or near, the normal reentry angle for space vehicles. The last case is that of increasingly steep angles of reentry.

1. Multiple Orbit Mode - Analysis, Reentry Angle 0 to -5.1° : The ALRH was analyzed to determine the maximum graphite removal as a result of multiple orbits. It was determined that the ALRH reentry protection has adequate thickness to survive multiple orbits and reentry in any mode except for orbital perigee altitudes of 280,000 and 290,000 ft (85,400 and 88,450 m). In these two cases the ALRH retains its protection in the random tumble mode, but if one assumes a side-on, stable orientation and exposure of the same stagnation line at all times, a one-dimensional analysis indicates removal of the graphite in the stagnation region at 144,000 ft (43,920 m). For this condition the fuel inventory would be contained since the equilibrium temperature based on the melt temperature of the Ta-10 wt % W capsule would not be exceeded following graphite burnthrough. This analysis is conservative, since in addition to the side-on, stable orientation, the one-dimensional ablation analysis does not allow heat conduction from the stagnation line.
2. Nominal Mode - Test and Analysis, Reentry Angle -5.1° to -6.75° : Analysis and tests were performed on the heater for the desired reentry angle of -6.25° . Analysis of both random tumble and side-on, stable modes at -6.25° gave maximum stress values below the average strength of the material. Three arc tunnel tests simulating maximum heating and total heat for the -6.25° reentry were successful, both from the standpoint of thermal stress and ablation of material. No melt or other perturbation of the internal components was predicted by analysis, and none occurred in the tests.

3. High Angle Reentry Mode - Analysis, Reentry Angle -6.75° to -90° : Analyses of random tumble and side-on, stable modes were conducted for selected points within the reentry range indicated. Thermal stress failure of the graphite was calculated for all reentries in this range. No test facilities could be located with the capability of confirming or disproving these analytical conclusions; therefore, it is not possible to demonstrate experimentally whether or not a failure limit due to reentry environment exists for the ALRH. This is a low probability failure mode.

Failure of the reentry protection allows release of fuel in the melt zone. Should such a release occur, the maximum lung burden to be expected as a result is less than 1.1×10^{-7} μCi . It should be noted that the present state-of-the-art in detection of lung burdens has, by coincidence, a threshold detection limit of about 0.016 μCi , which is equal to the occupational worker guide number (the body burden accepted by the AEC for industrial radiation workers). Values smaller than this are incapable of being detected. Thus, the maximum lung burden that would be possible from a release of activity amounts to 7/1,000,000 of 0.016 μCi , the occupational worker guide number. The maximum ground concentration is a factor of at least 20 below the AEC and DOD guideline for safety.

Additional Safety Considerations

1. Helium Pressure Buildup - Analysis: The release of helium due to the alpha decay of plutonium-238 causes an increase in pressure within the fuel container since the capsule is not vented. Void volume and strength of material are used to counteract this pressure buildup.
Several analyses were made to ensure adequate pressure containment. The following conclusions were drawn. The Ta-10 wt % W inner liner alone is sufficient to contain the helium pressure even under the extremely conservative parameters of the extended Sandia fireball mode. Pres-

sure can be withstood during all modes of reentry up to at least -6.25°. After earth impact, the capsule, if on the surface, can withstand the internal pressure indefinitely. After impact, if buried and assumed to be at a temperature of 958°F (514°C), the capsule can withstand pressure buildup for at least 50 yr. If the burial temperature is assumed to be 664°F (351°C), the capsule can withstand burial for at least 70 yr.

2. Heat Source Burial - Analysis: In drop tests of the heat source on soil, no penetration of over 1 in. (2.5 cm) was observed. There is, nevertheless, at least a small probability that burial can occur. This situation was examined by analysis. It was concluded that under no circumstances does the ALRH reach a sufficiently high temperature due to burial to allow fuel release due to container degradation.
3. Capsule Dosimetry - Tests: The ALRH must be handled during mounting and testing. It could also be handled by a member of the general populace following an abort. The question of capsule dosimetry therefore is pertinent. Listed below are the averaged figures for capsule dosimetry for total neutron and gamma radiation:

Dose from total assembly:

at surface (max.)	478 mrem/hr (extrapolated)
at 25 cm	12 mrem/hr
at 50 cm	3 mrem/hr
at 100 cm	0.8 mrem/hr

Dose from fueled titanium fragmentation shield assembly:

at surface (max.)	1950 mrem/hr (extrapolated)
at 25 cm	12 mrem/hr
at 50 cm	3 mrem/hr
at 100 cm	0.8 mrem/hr

These radiation levels were well within the safe limits of radiation dosage permitted for workers handling radioactive materials.

Conclusions from Safety Evaluation

The following conclusion was reported by Lt. Col. W. S. Holman, Project Safety Officer, in his summary of the safety analysis:

The Apollo Lunar Radioisotopic Heater has been subjected to a wide variety of pertinent safety tests and analyses. The results of these tests and analyses indicate that the ALRH presents no undue hazard to the general populace under any accident condition provided within the framework of a Saturn V mission.