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SANDIA LABORATORIES QUARTERLY REPORT
AEROSPACE NUCLEAR SAFETY PROGRAM
APRIL 1 TO JUNE 30, 1968

388

**AEROSPACE
NUCLEAR
SAFETY**

MASTER

AEROSPACE NUCLEAR SAFETY DEPARTMENT 9510

SANDIA LABORATORIES

ERATED FOR THE UNITED STATES ATOMIC ENERGY COMMISSION BY SANDIA CORPORATION | ALBUQUERQUE NEW MEXICO LIVERMORE CALIFORNIA

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SANDIA LABORATORIES QUARTERLY REPORT
AEROSPACE NUCLEAR SAFETY PROGRAM
APRIL 1 TO JUNE 30, 1968

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ABSTRACT

This report describes research, development, support, and test activities in the Sandia Laboratory Aerospace Nuclear Safety Program from April 1 to June 30, 1968.

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SUMMARY

SNAP-27

Autoignition tests to determine the effect of the GLFC hot surface and the oxygen concentration on ignition temperatures of propellants were completed; some additional tests are being conducted to resolve some anomalies. Computer calculations were performed to estimate the amount of helium released from the fuel during a typical SNAP-27 capsule history followed by reentry; the results of the calculations will be utilized for guidance in capsule heating experiments. Thermal analyses were conducted on the GLFC secondary heat shield and on stainless-steel and titanium end-caps. The environmental parameters resulting from SNAP-27 lunar return trajectories were compared with parameters resulting from typical flight/sled testing techniques.

SNAP-29

A detailed review of the Martin Preliminary Safety Analysis Report was completed. Comments were provided to Martin and other concerned organizations. Three atmospheric diffusion models were used to predict tropospheric levels of ^{210}Po from a large high altitude release; levels were compared and converted to dose for the general population. $^{242}\text{Curium}$ was investigated as a possible alternate to ^{210}Po for the SNAP-29 heat source; it is recommended that ^{242}Cm be considered as a fuel for SNAP-29.

NAVSAT

Aerodynamic, trajectory, and thermal analyses were completed for various proposed NAVSAT configurations.

TRACKING, SEARCH, DETECTION, AND RECOVERY

A report documenting the AEC meeting on tracking, search, detection, and recovery of nuclear heat sources was distributed.

ADVANCED FUELS

Analysis of debris generated by stirring microspheres in water shows that the particle size distribution is log normal; leaving the debris immersed in water resulted in a continuing decrease in particle size. The heat fluxes to which microspheres were exposed in arc tunnel experiments were defined; predicted melt times were compared with actual measured melt times, and substantial agreement is evident.

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RADIOISOTOPE SYSTEMS SAFETY SUPPORT

SNAP-19

The SNAP-19 is a 30-watt thermoelectric generator which contains an intact reentry heat source (IRHS). Two SNAP-19 generators were mounted in tandem on the Nimbus B experimental weather satellite to supplement the power generated by the satellite solar panels. SNAP-19B was launched as part of Nimbus B on May 18, 1968. Range safety destruct of the launch vehicle occurred two minutes after launch.

Emergency Plan (L. A. Hanchey)

Support was provided to AEC/ALO in their preparation of an emergency plan for SNAP-19 impact prediction, search, and recovery operations in the event an abort occurred on a mission on which the SNAP-19 was employed.

Review of Intact Reentry Heat Source (IRHS) Supplement (L. A. Hanchey)

A cursory review of the Martin SNAP-19 IRHS Supplement was performed. The document updates the safety evaluation presented in the August 1967 draft of the SNAP-19 IRHS Addendum to the Safety Analysis Report (SAR) and covers the testing performed since preparation of the latter report. The approaches used in this document are essentially the same as those used in the previous SNAP-19 SAR's.

Recovery Operation (D. W. Larson)

An analysis was performed to determine the steady-state temperature of a SNAP-19 generator when the generator is enclosed in an 80-gallon drum following recovery of the generator from the ocean. Neglecting convection, the drum's outer surface temperature varied from 569° to 204°F for emissivities of 0.1 to 0.9, respectively. For a drum emissivity of 0.9 and with the generator inside the drum in air, the generator's surface temperature was approximately 510°F with fins intact and approximately 700°F without the fins.

A thermal model was constructed to determine the temperature of the surface of the SNAP-19 after the generator was pulled from the water and placed on deck. With the generator fins intact, and considering radiative losses only, the surface reached 398°F in 60 minutes; without the generator fins the surface temperature reached 625°F in 30 minutes. A second thermal model was constructed to determine the temperature response of the 80-gallon drum when the drum is filled with water prior to placing the SNAP-19 generator in the drum. The water temperature (and drum surface) required 60 hours to reach 206°F, which is approaching the equilibrium temperature of 212°F at sea level.

SNAP-27

The SNAP-27 is a 63-watt thermoelectric power supply designed for lunar operating conditions. It will be used as the electrical power generator for the Apollo lunar surface experiment package (ALSEP). During the trip to the moon, the fuel capsule will be contained in a graphite LM fuel cask (GLFC); this is intended to protect the capsule during atmospheric reentry resulting from possible mission aborts. Final assembly of the SNAP-27 will be performed by astronauts on the lunar surface by inserting the fuel capsule into the generator assembly.

Safety Evaluation Schedule (J. E. Taylor)

The latest SNAP-27 safety evaluation schedule established by the AEC is as follows:

Safety analysis Report distributed	- July 28, 1968
Reentry Analysis Addendum distributed	- September 15, 1968
Interagency Panel meeting	- September (3rd week) 1968
AEC Safety Evaluation Report (SER) completed	- October 15, 1968
Panel sign-off of SER	- November 1, 1968
AEC Commission review	- November 7, 1968
AEC Commission approval	- December 1, 1968
Space Council review	- December 7, 1968
Flight approval	- December 31, 1968

Review of GE Safety Analysis Report (SAR) (J. E. Taylor)

Review of the SNAP-27 safety analysis documentation is continuing. To date, we have reviewed and provided appropriate comments on approximately 14 sections of the Accident Model and the Safety Analysis Reports. Eight sections are currently undergoing review.

NASA Information for SAR (J. E. Taylor)

Additional information was received from NASA on Apollo abort probabilities. Sandia and GE representatives attended a meeting at NASA/MSFC on May 23 concerning additional data needed from NASA for the Safety Analysis Report, particularly information on explosive aborts, LM reentry angles, and LM breakup analyses.

Autoignition Test Program (R. P. Wemple/D. J. Sasmor)

At the request of AEC/NASA-MSFC, we developed a test plan and conducted a series of experiments to determine the effect of the hot surface of the SNAP-27 GLFC and the oxygen concentration in the environment on the autoignition temperatures of monomethylhydrazine (MMH) and Aerozine 50 (Hydrazine/unsymmetrical dimethylhydrazine). All of the originally planned tests were completed; however, we are in the process of retesting Aerozine 50 in a nitrogen atmosphere. The results of the initial tests of this material in the nitrogen atmosphere appear to be anomalous with respect to its behavior in other test environments.

Gas Release from SNAP-27 (C. J. Northrup, Jr.)

The SNAP-27 is to be tested in several simulated reentry environments. In order to include the effects of the internal gas pressure, the quantity of gas generated before and during reentry must be known. Results of experiments on production grade fuel provided the basis for choosing the initial parameters for the analysis. A typical temperature history of several fuel annuli was obtained, and HECON2 was programmed to print the quantity of gas released at selected instants during the lifetime of the fuel. The selected parameters indicated between 44 and 87 percent of the gas available from the fuel since spheroidization would be released by the end of an earth-orbit-decay reentry. These parameters also indicated that less than 3 percent of the final quantity of free gas in the capsule would be released during an actual reentry. Other reentry environments are being examined, and

as more reliable parameters that describe the fuel become available, improvements will be made on the predictions for the fuel-gas behavior in the SNAP-27.

Radiant Heat Test (L. L. Keller)

A verification capsule (V2) was received from GE; a test plan was prepared; and a radiant heat test (simulated fireball/afterfire thermal profile) was performed on May 28, 1968. Complete post-test results are not yet available, but two visual observations were made: (1) there was no obvious change to the physical dimensions, and (2) after cool-down the emissivity coating was no longer on the cylindrical surface of the capsule. The time or nature of the coating removal is not presently known, but fragments of the material were present in the test fixture under the capsule after cool-down following the test. Following a cursory examination, the capsule was returned to GE for post-test evaluation.

A test plan for the SNAP-27 fuel capsule radiant heat test was received from GE. The test plan describes the test of a capsule in a GLFC experiencing earth orbit decay with (1) side-on spinning reentry and (2) side-on nonspinning reentry. The test plan is a product of Sandia's preliminary test plan and GE's thermal calculations (time vs temperature) for the capsule clad.

Two radiant heat capsules were received from GE. The G-Meters were tripped, but there was no obvious damage to the capsules or containers. There was no protective material between the capsules and the fiberglass sleeves to prevent abrasion during shipment. The epoxy (from the fiberglass sleeves) was removed from the emissive coating per GE instructions. There was no obvious damage to the emissive coating. The pressurizing plumbing was attached to the capsules in a helium atmosphere, and the capsules were transferred to the radiant heat test group for instrumentation.

Burial at Impact (L. L. Keller)

The probabilities of burying and uncovering a GLFC were reviewed and updated for aborts from on-pad through reentry. Probabilities were calculated for two additional configurations: (1) bare FCA and (2) FCA/beryllium heat shield assembly.

GLFC End-Cap Thermal Analysis (D. W. Larson)

A thermal model was constructed to determine the temperature response of a 0.063-inch stainless steel end-cap on the fuel capsule forward support in a launch pad abort. With the graphite cask blown off by the explosion and the end-cap exposed to the fireball, the end-cap melted within 3 seconds. The maximum capsule clad temperature reached was 2640°R. The end-cap material was then changed to 0.125-inch titanium. The titanium end-cap melted 7 seconds after exposure; the maximum capsule clad temperature reached was 2305°R.

Thermal Analysis of GLFC Secondary Heat Shield (D. W. Larson/D. E. Berg)

A thermal model was constructed of the GLFC with the 0.565-inch beryllium secondary heat shield. The model was used to predict the temperature response of the secondary heat shield and the fuel capsule with the graphite removed. In an on-pad launch abort, the beryllium shield reached a maximum temperature of 2440°R; the fuel capsule cladding reached 2340°R. During atmospheric reentry with the graphite removed, the beryllium secondary heat shield melted for orbital decay and -6.4° superorbital velocity reentry. This exposed the fuel capsule to aerodynamic heating, and it melted in both cases above 200,000 feet altitude, releasing fuel to the atmosphere. For a -38° superorbital velocity reentry, the beryllium secondary heat shield did not melt; the fuel capsule remained below the melt temperature. In all the above cases, end effects are not included and the system is assumed to be reentering in a crossflow spin mode.

GLFC Environmental Comparison Study (S. McAlees)

The environmental parameters resulting from SNAP-27 lunar return trajectories were compared with the parameters resulting from typical flight/sled testing techniques. The parameters of interest are shown in Table I. When compared on a time basis (Figures 1, 2, and 3), it is apparent that the SNAP-27 supercircular reentry environment is not closely matched by any of these testing techniques. Complete results of the study, including descriptions of the Athena and Hypersonic Test Vehicle systems, will be published in the near future.

TABLE I

Comparison of Environmental Parameters for SNAP-27
Lunar Return Trajectories and Typical Flight Test Capabilities

System	Maximum Convective Heating Rate, $q \sqrt{R}$ (Btu/ft ^{3/2} -sec)	Total Integrated Heat, $\int q \sqrt{R}$ (Btu/ft ^{3/2})	Total Pressure P_{T2} (atm)	Acceleration/ Deceleration (g)	Cost Estimate* (\$)
SNAP-27 -38° Lunar Return	1672	9,108	5.4	206.0	-
SNAP-27 -20° Lunar Return	1350	13,500	3.0	115.0	-
SNAP-27 -6.25° Lunar Return	454	25,091	0.37	14.2	-
Sled Test	323	371	60.0	150.0	50K
HTV (Taws, Terrier, Recruit)	940	4,000	108.0	47.0	100K
Athena Mod II	510	3,500	1.5	98.0	750K

*Cost estimate does not include payload development or fabrication.
Tests of this type would require an estimated 6 months preparation for launch.

Figure 1. Comparison of reference heating rates for SNAP-27 GLFC LUNAR return trajectory and typical flight test capabilities

Figure 2. Comparison of reference heating rates for SNAP-27 GLFC LUNAR return trajectory and typical flight test capabilities

Figure 3. Comparison of reference heating rates for SNAP-27 GLFC LUNAR return trajectory and typical flight test capabilities

Proof Tests of GLFC (H. R. Spahr)

The facility survey and Action Item 8, which was established at AEC Headquarters on February 13-14, were completed, and the survey was documented.* No facilities were found where proof tests could be conducted of a full scale SNAP-27 GLFC and struts reentering at the severe supercircular velocity.

Live Fuel Impact Tests (B. S. Hill)

Three live fuel impact tests were completed during this quarter; two capsules contain aged, thermally cycled fuel, and one contained production grade fuel from Mound fuel batch 126 which was produced on August 10, 1967.

The two capsules containing the aged fuel were impacted into a granite target at 1000°F at impact velocities of 104.3 and 102.4 fps, respectively. The purpose of these tests was to determine the effect of fuel aging on the production of fines; the fines data will be compared with similar impacts of newer, production grade fuel. A less than 20 μ m representative sample of the particulate was sent to Tracerlab West, Richmond, California, for a 0 to 20 μ m analysis.

The third capsule, containing the newer production grade fuel, was impacted into a granite target at 1000°F at an impact velocity of 317.3 fps. The purpose of this test was to determine the fines production resulting from a higher velocity impact. This capsule has not been opened, but x-ray examination showed that the fuel is compressed 1.085 inch from its original column height into a compacted mass.

*Memo, H. R. Spahr, 9314, to S. McAlees, 9314, "Final Information on Facilities for Proof Testing of SNAP-27 GLFC and Struts for Reentry Environment Survivability," dated April 8, 1968.

Fragment Model for S-IVB Stage of Saturn (R. E. Berry)

Information continues to be obtained for use in developing a fragment model for the S-IVB stage of Saturn. Visits to McDonnell Douglas Corporation, Grumman Aircraft Corporation, Lear Siegler Service Corporation, and the Air Force Rocket Propulsion Laboratory provided additional information on the dome(S-IVB) breakup characteristics when it is subjected to a 1 percent TNT equivalent explosion; on the structural characteristics of the lunar module and the location of pressure bottles and tanks; on the approach being used to define the blast and fragment environment resulting from a missile explosion; and on the approach, instrumentation, data reduction techniques, and test results of the project PYRO tests.

The fragment model uses individual inputs from the following general areas:

1. Fragment size distribution,
2. Fragment velocity distribution,
3. Explosive yield probability, and
4. Fragment impact probability.

These inputs were combined to form two matrices, one for low yield and one for high yield. Refinements of the fragment model will continue during the next quarter.

SNAP-29

The SNAP-29 radioisotope thermoelectric generator (RTG) is a 400-watt (electrical) power supply designed for an earth orbital mission of 144 days maximum duration. The heat source is ^{210}Po packaged in 16 cylindrical rods. The rods are evenly spaced in a rectangular, flat graphite plate. The temperature to the thermoelectric conversion system is regulated by a thermally controlled shutter panel. The heat rejection system consists of heat pipes.

Review of Preliminary Safety Analysis Report (R. T. Finnell)

A large number of comments were generated within Sandia as a result of a detailed review of draft copies of the Martin Preliminary Safety Analysis Report (PSAR). Teams were established to review the comments in the following categories: Hazard Identification and Probabilities; Reentry Evaluation; Atmospheric Release; Water Release; Dose Evaluation; and Miscellaneous. A more detailed statement on the aerothermodynamic review appears on page 22.

A compilation of our ANS comments were transmitted to the Sandia Space Isotope Power Department, and copies were sent to the AEC, Martin, and Mound on May 9. Martin representatives visited Sandia during the week of May 13; numerous telephone discussions took place between individuals at Sandia and Martin. A final tabulation of our comments, together with a brief statement concerning the resolution of each comment, was distributed on May 17. Although agreement was reached concerning the action on each item, we feel there are several important areas that require more attention, including the rate of fuel release, the duration of fuel release before recovery, manufacturing reliabilities, pad abort analysis, atmospheric distribution hazards, and dose studies.

^{242}Cm (D. J. Sasmor)

The feasibility and advantages of using ^{242}Cm as an alternate to ^{210}Po for the SNAP-29 heat source were investigated. Based on a preliminary study, it is concluded that ^{242}Cm is competitive for use in the SNAP-29 generator. Because of the large increase in safety that would result, we recommended to the AEC that the use of ^{242}Cm be studied in more detail and that it be considered as a fuel for SNAP-29.

Pertinent data concerning the availability, specific power, and cost of ^{242}Cm and ^{210}Po , as well as a comparison of the amount of ^{242}Cm and ^{210}Po necessary for a SNAP-29 generator were forwarded by letter (dated May 9, 1968) to the Safety Branch, SEPO.

Some questions have since been raised concerning the oxidation of the Cm_2O_3 to CmO_2 in the temperature range 200° to 500°C . Discussions were held with Oak Ridge National Laboratory and Savannah River Laboratory personnel regarding this oxidation reaction. From these discussions, we concluded that the reaction will not necessarily be detrimental to the use of Cm_2O_3 - Am_2O_3 mixed oxide (35 percent ^{242}Cm as metal) as a heat source, but appropriate data will be needed.

Capsule Burial (F. L. Baker)

Burial tests of two simulated SNAP-29 capsules were conducted in Ottawa sand. Both units were buried horizontally, the first unit at a depth of one-half its diameter and the second at a depth of six inches. Each unit was instrumented to monitor the capsule's surface temperature and was operated for a period of 48 hours. The maximum temperature recorded on the lower surface of the partially buried unit was 1695°F . The maximum temperature of the fully buried unit was 2665°F .

Aerothermodynamic Analysis

Fuel Block Hypersonic Aerodynamic Coefficients (A. C. Bustamante/H. R. Spahr) -- The GE Arbitrary Body Computer Code was used successfully to compute the theoretical free molecule and continuum aerodynamic coefficients for the SNAP-29 fuel block. This code will also be used to obtain theoretical coefficients for the autorotating block.

Pitch Damping Test (A. C. Bustamante) -- The pitch damping test on the SNAP-29 fuel block, conducted at AEDC for Sandia, was completed. After experiencing considerable difficulty with the model support system, the original test plan was modified and the high rpm runs deleted. Results showed that the block will not autorotate when spun initially to a low angular rate (approximately 300 rpm) but will trim at $\alpha = 90^\circ$ and oscillate $\pm 15^\circ$ about this trim position.

AEDC Free Flight Data (A. C. Bustamante) -- Preliminary analysis of the free flight data on the fuel block showed angular rates as high as 15,500 rpm and as low as 500 rpm. These data are presently being reduced in a position time history format. The data will be used to obtain average aerodynamic static and dynamic coefficients.

AEDC Magnus Force Test (A. C. Bustamante) -- Analysis of the data from the magnus force test showed a negligible magnus force on the fuel block (Figure 4). This conclusion appears reasonable since the angular rate of the plate was low (approximately 5000 rpm). The measured drag coefficient for the rotating block agrees with the theoretical drag predicted by mathematically averaging static drag data.

Figure 4. SNAP-29 fuel block magnus force test

PSAR Aerothermodynamic Review (A. C. Bustamante) -- The aerothermodynamic review of the Martin PSAR for the SNAP-29 was completed. The volumes of prime concern to the Sandia Reentry and Space Sciences Division are Volume II and Appendix A (Error Analysis) of Volume III. There were no serious comments or disagreements with Martin's aerothermodynamic analysis as presented in the PSAR. In fact, there is good agreement between our aerothermodynamic studies and Martin's; this reflects the closely coordinated effort that has existed between Martin and Sandia since the start of the program.

^{210}Po in Soils (M. A. Parsont)

The equilibrium distribution coefficients, K_d , of $^{210}\text{Po Cl}_4$ solutions in two Colorado soils were determined (Table II).^{*} The soils were basic Brown (Nunn Silty Clay Loam) and Fraser Experimental Station Grey-Brown Podzol (Darling). Based on the similarities in distribution coefficients, it is estimated that the A horizons of the two soils would exhibit approximately the same ion exchange properties for $^{210}\text{Po Cl}_4$. A preliminary study indicated that the distribution coefficient for alkaline soil is inversely proportional to soil particle size (Table III).

An elution study with the top layer (A_{11} horizon) of the Nunn Silty Clay Loam indicated that 99 percent of the soluble polonium was retained in the first three centimeters of depth after one mean annual rainfall (Table IV).

Table V presents data on the uptake of ^{210}Po from $^{210}\text{Po Cl}_4$ -contaminated soil. The largest uptake was observed in the greens of radishes and potatoes. More data on vegetables and plants which were slower to mature will be forthcoming.

^{*}Research was performed at Colorado State University under AEC Contract. See: Watters, R. L., J. E. Johnson, and W. R. Hansen, A Study of Unsupported Polonium - ^{210}Po for Ion Exchange in Soil and Uptake in Vegetation. First Technical Progress Report, AEC Contract No. AT(11-1)-1733, May 8, 1968.

TABLE II
Equilibrium Distribution Coefficients (K_d)

Soil Type and Location	Horizon	$K_d \pm \text{S.E.}$	pH Range	No. of Samples
Fort Collins Brown, Nunn	A ₁₁	131 $\pm$ 3	7.6	8
	A ₁₂	137 $\pm$ 6	7.6	8
	B ₁	1134 $\pm$ 56		8
	B _{2t}	913 $\pm$ 25		8
	B _{3ca}	1372 $\pm$ 88		8
	C _{ca}	1174 $\pm$ 65		8
Fraser Exper. Forest Podzol, Darling	A ₂	104 $\pm$ 17	4.7-5.5	5 Locations 32 Samples
	B	75 $\pm$ 23	5.0-6.0	3 Locations 40 Samples
	C ₁	91 $\pm$ 30	6.00	2 Locations 16 Samples
	C ₂	25 - 300	5.5-6.3	3 Locations 24 Samples

TABLE III
Equilibrium Distribution Coefficient as a Function of
Soil Particle Size

Soil Type	Horizon	Particle Size Range (μm)	$K_d \pm 1 \sigma$
Nunn Silty Clay Loam	B ₁	>50	24 $\pm$ 2
		50 - 20	167 $\pm$ 39
		20 - 5	254 $\pm$ 86

TABLE IV

Elution of ^{210}Po from the A_{11} Horizon, Nunn Silty Clay Loam*

Depth (cm)	Radioactivity (μCi)	Percent of Total ^{210}Po
1	1.4×10^{-1}	95
2	4.2×10^{-3}	2.8
3	1.6×10^{-3}	1.1
4	9.0×10^{-4}	0.6
5	5.1×10^{-4}	0.3
6	4.0×10^{-4}	0.3
7	3.6×10^{-4}	0.2

*Eluted with one annual mean rainfall at the rate of 1-2 ml/hour

TABLE V

Plant Translocation of $^{210}\text{Po Cl}_4$ from Contaminated Soil

Plant Sample	Soil Concentration nCi/g on Harvest Date	Percent Uptake Dry wt. $\pm 1\sigma$	Percent Uptake Wet or Natural wt. $\pm 1\sigma$	No. of Samples
Potatoes	0.6 - 1.0	0.18 ± 0.09	0.036 ± 0.018	6
Potato Greens	0.6 - 1.0	0.72 ± 0.59	0.056 ± 0.046	7
Radish Bulbs	0.60	0.44 ± 0.22	0.026 ± 0.013	11
Radish Greens	0.60	0.82 ± 0.38	0.054 ± 0.025	5
Spinach	0.55	0.13 ± 0.026	0.019 ± 0.005	5

NAVSAT

Preproposal Conference (L. A. Hanchey)

On June 3, 1968, our representative presented a brief discussion on the NAVSAT safety criteria at the Preproposal Conference. A question and answer period was provided during the afternoon, but very few questions, were asked relative to the safety criteria.

Orbital Lifetime of Fuel Microspheres (H. R. Spahr)

The orbital lifetimes of 50- and 250- μ m fuel microspheres were calculated. The results of these calculations for a 600 nautical mile polar orbit are summarized below:

	<u>Lifetime of 50 μm Microspheres</u>	<u>Lifetime of 250 μm Microspheres</u>
Billik, using the 1959 ARDC Model Atmosphere	2.8 years	14.1 years
Westinghouse Astronuclear Lab Orbital Lifetime Code	7.7+ years	38.2+ years

Additional calculations are being made which include the extremes in orbital lifetime due to variations in atmospheric density.

"Terminal Velocity" of a Proposed Fuel Capsule (H. R. Spahr)

Preliminary "terminal velocity" calculations were made for drop test models of a proposed fuel capsule at the request of the Isotope Projects Division. These calculations were performed to determine if the 400 to 500 fps impact velocity indicated by a drop test of the capsule was reasonably accurate. These preliminary calculations on "terminal velocity" showed that the impact velocity would be in the range of 400 to 500 fps. Final calculations are being made using the measured metro data for the drops with more precise drag data. These calculations will be documented.

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SAFETY TECHNOLOGY

ADVANCED FUELS SAFETY

Analytical Study of the Hypersonic Reentry of Small Spherical Particles (B. W. Marshall)

General Electric Valley Forge Space Technology Center is performing a theoretical study of the atmospheric reentry of small spheres. Initial efforts concentrated on the following release condition matrix:

Release Altitude:	120,000 - 280,000 ft
Release Velocity:	12,000 - 26,000 ft/sec
Particle Diameter:	50 - 250 μm

A number of pertinent aerodynamic parameters were computed for this range of conditions. These include the Reynolds, Knudsen, Weber and Bond numbers, the drag coefficient, the ballistic parameter, the initial rate of deceleration, and the characteristic slowing-down time. The Reynolds and Knudsen number data indicate that the release conditions overlap the free molecule and the transition regimes. As was already known, the Weber and Bond numbers fall within the range of their previously estimated critical values. One of the objectives of the investigation is, of course, to obtain better estimates of these critical values.

The drag coefficient and the ballistic parameter are shown in Figure 5 as a function of release altitude. The drag coefficient curves were computed from the correlation given in Reference 1. In order to estimate the effect of the drag coefficient on the stability criterion, neutral stability curves were computed based on the stability criterion given in Reference 2.

In Reference 2 it was assumed that $C_D = 2$, which led to

$$We_\infty = \frac{4}{3} \pi \approx 4.18$$

Figure 5. Drag coefficient and ballistic parameter ($W/C_D A$) for spherical particles as functions of release altitude

as the neutral stability condition. This should actually be,

$$We_{\infty} = \frac{8\pi}{3 C_D} .$$

The neutral stability curves based on these two conditions, using data from Figure 5 in the latter case, are shown in Figure 6. While it is hoped that an improved stability criterion can be obtained, this does illustrate the fact that it should be considered a function of the release conditions.

As a part of this study, a dynamic similarity analysis of the heating and melting phenomena associated with the hypersonic particle reentry problem was performed. The results of this study should be considered as preliminary since further refinements will be made. Nevertheless, several important conclusions can be drawn. First, the

Figure 6.
Neutral stability curves
based on stability criteria
of Reference 2

ratio of the characteristic slowing-down time to the characteristic heating time is significantly greater than unity for most of the possible release conditions. This indicates that the assumption of quasi-steady free stream conditions is reasonably valid. Secondly, the ratio of the melt velocity into the particle to the tangential velocity at the liquid at the gas-liquid interface was determined to be:

$$\frac{V_m R}{V_e \ell} \sim \frac{1}{P_{r_\ell}}$$

where

V_m = melt velocity into the particle

R = particle radius

ℓ = liquid layer thickness

V_e = tangential velocity of liquid layer surface

P_{r_ℓ} = liquid Prandtl number

For the material of interest we have

$$\frac{V_m R}{V_e l} \approx \frac{1}{20} \approx 0.05 .$$

Suffice it to say that unless the ratio on the left-hand side is of order unity, the liquid layer flow field could hardly be in a steady state. This means that the ultimate liquid layer analysis will probably have to include transient effects. It also illustrates the importance of the liquid Prandtl number, from both the theoretical and experimental points of view.

A similar analysis is being carried out with regard to liquid layer stability, but this is not yet complete.

In the immediate future, efforts will be made to refine the analysis given in Reference 2. Work will continue on the stability analysis. When this is completed, recommendations will be formulated with regard to further, more complete computations. Recommendations will also be made with respect to the problem of scaling experiments in the most useful manner.

References:

1. G.E. Contract Report, "The Effects of Atmospheric Reentry on Graphite Particles", Contract SNPC-10, (Sec. II-C), January 1964.
2. Scala, et. al., "Theoretical Studies of the Reentry Plutonium Fuel", SC-CR-67-2573, GE/Space Sciences Laboratory for Sandia Laboratory, Albuquerque, New Mexico, June 1967.

Reentry Ablation Testing in a Hyperthermal Arc Tunnel (I. B. White/B. W. Marshall/K. L. Romine)

A new type of sampling device was fabricated for use in the Sandia 40 kw hyperthermal arc tunnel. This sampler should increase substantially the percent of debris collected from ablated specimens; this will provide a more accurate particle size distribution.

Design of a heating element was initiated. This device will be used to preheat cermet and solid solution type fuel materials just prior to exposure to the reentry environment in the hyperthermal arc tunnel. This preheating will reduce the temperature gradient effects of the step function arc tunnel heat input and provide a better approximation to the response incurred in the transient heating pulse of reentry.

Thermal Response of $^{238}\text{PuO}_2$ Microspheres in a Hyperthermal Arc Tunnel (B. W. Marshall)

Numerous experiments on the thermal and ablation response of $^{238}\text{PuO}_2$ microspheres in a hyperthermal arc tunnel environment were conducted during the past several months; the data were reported in several previous ANS monthly and quarterly reports. Recent detailed analysis has provided better definition of the heat flux on a particle in the arc tunnel. Table VI gives the heat flux conditions used in the tests taking into account nonequilibrium gas effects, low Reynolds number effects, and noncatalytic surface effects.

TABLE VI
Test Conditions

<u>Condition</u>	<u>Enthalpy (Btu/lb)</u>	<u>Model Pressure (atm)</u>	<u>Stagnation Heat Flux (Btu/ft²-sec)</u>	<u>Weber Number</u>
A	11,000	0.0485	650	1.0
B	10,000	0.0737	950	1.6
C	9,500	0.0593	800	1.2
K	13,000	0.0987	1800	2.2
L	3,600	0.0237	100	-
M	12,000	0.276	2800	4.6

Using these data, the expected melt times in the arc tunnel for the various melt conditions were calculated by the Sandia computer code with which the reentry melt envelope was generated. The melt times observed in the arc tunnel tests on $^{238}\text{PuO}_2$ microspheres are compared with the calculated melt times in Table VII. There is substantial agreement between the experimental and calculated results, and it appears that predictions made by the computer code can be used with confidence.

TABLE VII
Comparison of Arc Tunnel Results and Computer
Calculations of Microsphere Melting

Run	Test Condition	Material	Diameter (μm)	Observed Time to Melt (sec)	Calculated Time to Melt (sec)	Particle Number
253	B	$^{239}\text{PuO}_2$	280	0.14	0.14-0.15	
254	B	$^{239}\text{PuO}_2$	261	0.12	0.14	
259	B	$^{239}\text{PuO}_2$	276	0.16	0.14	
255	C	$^{239}\text{PuO}_2$	280	0.1 (broke)	~0.2	
256	C	$^{239}\text{PuO}_2$	277	0.17	0.2	
269	B	$^{238}\text{PuO}_2$	227	0.138	0.12	1-24-6
270	B	$^{238}\text{PuO}_2$	253	0.144	0.14	1-24-15
276	B	$^{238}\text{PuO}_2$	236	0.146	0.13	1-24-17
324	B	$^{238}\text{PuO}_2$	253	0.140	0.14	1-25-20
332	B	$^{238}\text{PuO}_2$	254	0.136	0.14	1-25-16
274	C	$^{238}\text{PuO}_2$	234	0.185	0.18	1-24-8
277	C	$^{238}\text{PuO}_2$	235	0.190	0.18	1-24-14
287	C	$^{238}\text{PuO}_2$	221	0.2	0.17	1-24-1
271	A	$^{238}\text{PuO}_2$	225	0.193	>0.2	1-24-7
285	A	$^{238}\text{PuO}_2$	221	0.188	>0.2	1-24-19
333	A	$^{238}\text{PuO}_2$	224	0.198	>0.2	M-6
335	A	$^{238}\text{PuO}_2$	218	-	>0.2	M-3
292	K	$^{238}\text{PuO}_2$	216	0.046	0.04	1-25-1
293	K	$^{238}\text{PuO}_2$	230	0.040	0.04	1-25-5
309	K	$^{238}\text{PuO}_2$	248	0.042	0.05	1-25-2
318	K	$^{238}\text{PuO}_2$	225	0.044	0.04	1-25-1
321	K	$^{238}\text{PuO}_2$	234	0.041	0.04	1-25-3
336	K	$^{238}\text{PuO}_2$	231	0.066	0.04	M-2
337	K	$^{238}\text{PuO}_2$	235	0.072	0.04	M-15
347	K	$^{238}\text{PuO}_2$	223	0.055	0.04	M-35
358	K	$^{238}\text{PuO}_2$	218	0.056	0.04	M-31
354	M	$^{238}\text{PuO}_2$	235	0.020	0.03	M-29
355	M	$^{238}\text{PuO}_2$	227	0.019	0.03	M-37
356	M	$^{238}\text{PuO}_2$	220	0.021	0.03	M-33
369	L	$^{238}\text{PuO}_2$	225	No Melt		M-10
371	L	$^{238}\text{PuO}_2$	219	No Melt		M-22
373	L	$^{238}\text{PuO}_2$	221	No Melt		M-16
376	L	$^{238}\text{PuO}_2$	227	No Melt		M-32
378	L	$^{238}\text{PuO}_2$	222	No Melt		M-30

Advanced Fuel Form Thermal Analysis (R. D. Klett/D. W. Larson/
D. E. Berg)

The temperature responses of advanced fuel forms in a launch pad abort fire were computed.* The fuel forms investigated were mixtures of PuO_2 with Pt-Rh, MgO, ZrO_2 , and HfO_2 . The configurations were 1/8 to 1 inch-long solid cylinders, 2.374 inches in diameter. The surface emissivity was found to have a larger effect on the temperature than the thermal conductivity, heat capacity, or cylinder length.

Melt Envelope Parametric Study (C. B. Watkins)

A parametric analysis was initiated to determine the effect on the location of the microsphere melt envelope of variations in certain of the microsphere characteristics. The parameters to be investigated are thermal conductivity, thermal diffusivity, emittance, thermal accommodation coefficient, and initial temperature. The effect of changing the initial temperature from 1100°F to 2400°F was investigated, and the results are shown in Figure 7. It is apparent that in this case the melt envelope is shifted only slightly, the difference being more significant at the lower altitudes than at the higher.

Figure 7.
Effect on microsphere melt
envelope of changing initial
temperature

*SC-RR-68-222, Advanced Fuel Form Thermal Analysis, R. D. Klett, D. W. Larson, and D. E. Berg, Sandia Livermore, Albuquerque, New Mexico, March 1968.

Analysis of Microsphere Debris (J. Hudson)

In an experiment performed by Los Alamos Scientific Laboratory, plasma torch production microspheres were stirred in water with a magnetic stirrer. The observation that the microspheres were largely reduced to fine particulates prompted us to request a sample for further particulate analysis.

The following description of Los Alamos experiment LJM-3 is extracted from an office memorandum furnished May 31, 1968, by J. A. Leary.

The subject experiment was started to determine the apparent solubility of $^{238}\text{PuO}_2$ microspheres (plasma torch product 72-B-1) in distilled water. An initial amount of 11.6 mg of microspheres was placed in an erlenmeyer flask, and 100 ml. distilled water was added. After adding a magnetic stirring bar, the flask was placed on a Mag-Mix magnetic stirrer and stirring was started. After 4 hours the concentration of the unfiltered solution was 1.3 mg Pu/l and the temperature of the water had risen to 43°C as a result of heat generated by the Mag-Mix motor. The heat transfer problem was eliminated and for the remainder of the experiment, the temperature of the water was 25 (± 1)°C. After 11 days the concentration of the unfiltered solution was 10 ± 2 mg Pu/l and the concentration of the filtered solution was 5.0 (± 0.5) mg Pu/l. Visual examination of the microspheres showed that they had disintegrated. The mixture was filtered through a fine porosity pyrex filter (4 - 5.5 micron pore size). The fraction of solids which could be easily transferred to the filter were redesignated as fraction A. Another fraction of the solids clung tenaciously to the erlenmeyer flask. These were eventually isolated and designated as fraction B. Both fractions of solids were examined under the microscope and a sample of fraction A was submitted for x-ray powder diffraction analysis.

Material Balance

Solids

Fraction A: 7.5 mg (fines)

Fraction B: 2.6 mg

Solution from water
solubility test 0.5 mg

Losses (by diff.) 1.0

Total 11.6

The fine particles, which amounted to about 75 per cent of the material, were shown to be principally PuO_2 by x-ray powder diffraction analysis.

The fine particulate debris from the Los Alamos experiment was furnished to Sandia for analysis as a dry powder. This debris was sampled and then allowed to stand in distilled water without stirring.

A sample was taken after the debris was allowed to stand in water for twenty-seven days, and another sample was taken after fifty-four days. The size distribution of the debris, as determined by alpha counting, nuclear emulsion, and optical techniques, is shown in Table VIII. Figure 8 shows the results of the analysis. The debris as received and the debris after twenty-seven days in water are log normally distributed in size.

The small particulate which remained after the debris was allowed to stand in water for fifty-four days formed many agglomerates, and therefore no accurate size distribution was obtained for this material. For this sample; the amount of debris larger than $1.0 \mu\text{m}$ in diameter was compared with the total debris in the sample.

The arithmetic mean diameter of the debris as received is $1.9 \mu\text{m}$, and the arithmetic mean diameter of the debris after twenty-seven days in water is $1.2 \mu\text{m}$. The extrapolated arithmetic mean diameter of the particulate after fifty-four days in water is $0.62 \mu\text{m}$.

TABLE VIII

Size Distribution of Particulate Debris

Diameter of the particulate (μm)	Percentage of mass		
	As received	Twenty-seven Days in water	Fifty-four Days in water
< 0.250	1.7	6.9	70.4
0.250 - 0.500	5.3	11.5	70.4
0.500 - 0.750	9.9	12.6	70.4
0.750 - 1.0	10.8	10.7	70.4
1.0 - 2.0	17.6	31.8	15.7
2.0 - 3.0	17.2	26.5	12.9
3.0 - 4.0	18.7	-	
4.0 - 6.0	6.5	-	
6.0 - 8.0	7.1	-	
8.0 - 10.0	5.2	-

Figure 8. Size distribution of debris

Ultra-High Temperature Studies by the Falling Droplet Technique
(L. S. Nelson and H. S. Levine)

Combustion of Zirconium Droplets in Oxygen/Rare Gas Mixtures and Mechanism -- Efforts directed toward understanding the combustion of zirconium droplets falling freely in O_2 /rare gas mixtures continued, in collaboration with AeroChem Research Laboratories. These efforts resulted in the submission and acceptance of a paper for publication in the Proceedings of the 12th Symposium (International) on Combustion, Poitiers, France, July 15, 1968.

Studies of the oxidation processes continued this quarter. These involved: (1) new high speed, high magnification photography of the droplets made possible by ignition with a laser* and (2) gravimetric studies of droplets in which the combustion was interrupted at various stages by quenching in liquid argon.

The high speed photography showed the formation of a luminous front that envelops the droplet shortly after ignition (Figure 9). The diameter of the front is about 40 percent larger than the droplet diameter, and it contains many luminous heterogeneities which are thought to be condensing droplets of liquid zirconia. In pure oxygen, the heterogeneities tend to move circumferentially upward in the surface of the front, coalescing into a larger droplet which follows just above and in the wake of the parent droplet. Several times during the reaction, the follower touches the parent and is drawn into it by surface tension forces. When the combustion is performed in 50 percent He/O_2 , however, the follower droplet is not observed, even though a front with tiny heterogeneities still is formed around the parent droplet.

Figure 9.

Luminous condensation front enveloping 0.5 mm droplet of zirconium as it burns in oxygen at 625 torr. Note follower droplet just above parent

*Nelson, Richardson, and Prentice, Rev. Sci. Instr. 39, 744 (1968).

The gravimetric studies were performed with 525 μm initial diameter droplets of zirconium burning in pure oxygen and in a 50 percent He/O_2 mixture (Figure 10). As reported earlier* the droplets that burned in pure oxygen increased in weight for about 180 msec, after which the curve leveled off at a 35 percent weight gain. This corresponds to complete oxidation of the droplet to stoichiometric zirconia, ZrO_2 . When droplets of the same diameter burned in the 50 percent He/O_2 mixture, however, they gained weight for about 210 msec, with the curve leveling off surprisingly at a weight gain of approximately 21 percent. Preliminary x-ray diffraction studies and metallographic examination have shown only completely oxidized zirconium to be present when the curve levels off. This suggests that some metal is lost by vaporization during the combustion in He/O_2 mixtures, even though the burning in the presence of a diluent lowers both the oxidation rate and the droplet temperature. It is believed that the presence of the follower droplet is associated with the conservation of metal during combustion in pure oxygen.

Figure 10. Relative weight gain of 0.5 mm droplets of zirconium burning in O_2 and in 50% He/O_2 at a total pressure of 625 torr as a function of oxidation time.

*Nelson, Proc. 11th Symposium (International) on Combustion, Berkeley, California, p. 409 (1966).

"Spearpoint" Analysis -- Preliminary experiments were made on the structure of "spearpoints" formed by freezing of $\text{ZrO}_2(l)$ droplets. Initial supercoolings of about 570°K have been observed by use of ratio pyrometry, whereas peak surface temperatures at the end of freezing are systematically lower than the equilibrium melting temperature of ZrO_2 by approximately 200°K . A time-resolved luminosity trace at the spearpoint also showed a finite rise time not exceeding $150\ \mu\text{sec}$ for a $479\ \mu\text{m}$ droplet in a 50 percent O_2/He mixture at 625 torr.

To rationalize the observed surface temperature-time history at the spearpoint of $\text{ZrO}_2(l)$, a simple model for the solidification process was formulated based on energy conservation requirements at the solidification wave front and on the kinetics of crystallization over a wide range of temperatures. The temperature of the spherical droplet with the moving internal heat source (crystallization wave front) can be found only if the solidification kinetics is known.

Initial results for the surface temperature of a supercooled droplet, assumed to solidify at a constant velocity, shows trends that are qualitatively correct, i.e., the surface temperature lags significantly behind the crystallization-front temperature if the crystallization velocity for the oxide is on the order of the thermal velocity. Future refinements will be directed toward incorporating an exponential or power law dependence on supercooling for the crystallization velocity.

Property Measurements at Ultra-High Temperatures -- Studies of high temperature chemical reactions of freely falling droplets suggest a way to measure the properties of nonreacting materials at temperatures far above those possible by conventional techniques. Although these comments mostly concern proposed measurements, it is felt that the techniques are well enough established to warrant discussion at this time.

Two basic experiments will be performed. One will involve determination of the droplet's temperature at various times by high speed brightness (one-color) or ratio (multicolor) pyrometry, while the other will involve intercepting the droplet during fall with a microcalorimeter to determine the heat content. The pyrometer will employ monochromatically-filtered photomultipliers with both oscilloscope and

rapid analog-digital recording. The calorimeter will use either the metal block-thermopile technique or the vaporization of liquid argon to measure enthalpy.

It is anticipated that emittances and heat transfer coefficients can be obtained from the high speed pyrometry, while heat capacities, heats of fusion, energy associated with other phase changes, and possibly phase diagrams will be obtained by coupling the pyrometric and calorimetric techniques. The temperature range to be explored is 3000-6000°K.

Particle Dynamics Related to Small Particle Experiments in a Ballistic Gun Range (R. M. Elrick)

In conjunction with ACDRL, Sandia is performing a series of hypervelocity ablation experiments which simulate conditions causing reentry particle ablation. Toward the longer range goal of developing an ablation model, the Sandia Aerospace Sciences Division, 5271 was asked to sample these ablation products in an attempt to obtain not only a size spectrum of the particles but to do this as a function of angle around the flight path and the time from the onset of particle breakup. About 20 samplers were designed, installed, and analyzed by 5271 for the first of two planned test series.

The primary projectile (~400 μ m diameter gold sphere) was fired down a 120-foot range at speeds of approximately 22,000 fps in air at room temperature and a pressure of several torr. Some of the ablation particles formed debris craters in impact plates placed along the range and around the flight path; an impact plate was also placed at the end of the range.

Several assumptions were made to correlate the size of a debris crater and its distance from the flight path to the size of the particle producing the crater and the particle's point of generation on the path. First, the results of previous hypervelocity impact studies by ACDRL relating particle size and energy to crater size for a particular impact material was used, inferring that extrapolation to smaller particles is valid. Also, the average flow conditions behind the projectile shock, which control the debris motion, were estimated from the position of certain of the largest craters and simplifications made on the equations

of motion of these crater-forming particles. These simplifications were later justified. Velocities and trajectories of sized particles under the influence of this average flow field were computed from integrals of their equations of motion.

The consequence of this analysis suggests that a unique relation exists between crater size and the size of the crater-forming particle for a definite distance from the flight path. Thus, not only can a debris size spectrum be measured but the point of generation of a debris particle can be marked on the flight path, as well as the angular distribution of particles around the path.

Ablation debris larger than $1\text{ }\mu\text{m}$ was completely inventoried for the $380\text{ }\mu\text{m}$ particle traveling at $22,150\text{ fps}$ from the preheat section into the 4-torr flight range ($We = 44$). No mass or size distribution could be established for particles $< 1\text{ }\mu\text{m}$ because, although electron diffraction patterns showed the presence of gold on surfaces positioned to have collected only particles in this size range, the precise morphological source of the patterns could not be separated from the contaminant background. From the measured debris size distributions along the flight path (for particles $> 1\text{ }\mu\text{m}$) and the assumption of a log normal fit to the distributions, approximate values for the geometrical mean diameter, d_g , and the standard deviation of the logarithms of the diameters, $\log \beta_g$, were assumed. For instance, during the early stage of ablation $d_g \sim 15$ to $20\text{ }\mu\text{m}$ and $\log \beta_g$ lay between $1/2$ and 1 , while at the end of the trajectory when the $380\text{ }\mu\text{m}$ gold sphere had ablated to $\sim 125\text{ }\mu\text{m}$ diameter, $d_g \sim 2\text{ }\mu\text{m}$ and $\log \beta_g$ was again between $1/2$ and 1 .

A mass balance between the particle prior to ablation and the particle plus calculated debris after ablation indicated that 40 percent of the initial mass was unaccounted for. It is presumed the difference can be attributed to one or a combination of the following: debris particles $< 1\text{ }\mu\text{m}$, particles ablated farther upstream but out of reach of the samplers, and/or an improper correlation between particle size and velocity and the resulting crater size. As an example, if all particle sizes were estimated 13 percent low, this would account for the 40 percent difference in the mass balance.

Samplers, redesigned for increased sensitivity to particles $< 1\text{ }\mu\text{m}$ and repositioned in the flight range to sample farther upstream, were

installed for the second series of ablation tests ($We = 5, 7.5, 11$, and 44) which were conducted during the first part of May; the results of these tests are being analyzed.

Neutron Activation Analysis of Debris Resulting from Small Particle Experiments in a Ballistic Gun Range (Gas Gun Tests)
(B. T. Kenna/P. E. Harrison)

Eight shots of gold microspheres were fired in the AC Defense Research Laboratory Light-Gas Gun Facility; the results of the shots were reported previously.* A detailed analysis of the gold particle distribution for one of these shots has been completed. This analysis is of the paper from within the sampler for which the impact data are reported in the previous section of this report.

A 380- μm gold sphere (0.55 mg Au) was fired at a velocity of 22,150 fps using the facility shown schematically in Figure 11. Each sampler consisted of a tube 4 inches in diameter and was lined with a 12- x 12-inch collection paper. The flight path of the particle was from left to right in Figure 11, and the particle impacted on a plate at the end of sampler No. 4.

D68-11655

Figure 11. Light-gas gun facility

*SC-PR-68-212, Sandia Laboratories Quarterly Report, Aerospace Nuclear Safety Program, January 1 to March 31, 1968, Sandia Laboratories, Albuquerque, New Mexico, April 1968.

Sampler No. 1 was lost due to extensive blast at the time of firing. The gold collected on the sampler papers in the other samplers was analyzed by thermal neutron activation analyses. Each sampler paper was cut into 12 pieces in order that particle distribution as a function of "left" or "right" of the trajectory and distance down the trajectory could be defined. Each strip of paper was ashed in a quartz tube, sealed, and irradiated at a thermal neutron flux of 2×10^{14} n/cm²/sec for 8 hours with appropriate standards and controls. The quantitative results are presented in Figure 12.

Figure 12. Distribution of gold in samplers

The conclusions drawn from these data are: (1) the particle traveled along the intended trajectory, since "right" and "left" data are in good agreement; (2) the amount of gold ablated increased with distance, and rebound from the impact plate undoubtedly made the data for sampler No. 4 high; and (3) the total gold found in this study was $16 \pm 2\%$ of the initial mass of the gold particle. The data obtained in this work are expected to contribute to a definition of the flight patterns of these small particles and to a quantitative description of spall rates.

TRACKING, SEARCH, DETECTION, AND RECOVERY

Report Publication (R. G. Illing)

A report documenting the AEC meeting on tracking, search, detection, and recovery of nuclear heat sources, which was held at Sandia Laboratory on January 16-18, was distributed.*

TRW Briefing (R. C. Cranfill)

Under Sandia contract, TRW Systems completed a 14-month investigation to determine the feasibility of using radar tracking to predict earth impact locations of RTG systems returning from orbit. A SNAP-27 fuel cask and a SNAP-29 fuel block were the primary reentry bodies considered in the study. A final briefing on the study was given by TRW at AEC Headquarters on April 19, and handouts summarizing the results were provided at that time. The final report on the study will be distributed by Sandia in the near future.

FLIGHT TEST STUDY

Athena Capability Review (R. T. Finnell)

The Athena rocket system was briefly evaluated as a possible carrier for some SNAP reentry tests. It was determined that the Athena was designed originally to reenter a 50 pound payload at 22,000 fps from 250,000 feet altitude. It can carry payloads of up to 200 pounds at reentry velocities of 17,000 fps at angles of about -24° .

* SC-M-68-148, AEC Meeting on Search Detection, and Recovery of Nuclear Heat Sources (U), Sandia Laboratory, Albuquerque, New Mexico, April 1968, RS 3410/1149 (SFRD).

INTACT HEAT SOURCE

Terminal Velocity Analysis (G. W. Stone)

A theoretical analysis of the translational motion of a vehicle dropped from altitude with zero initial velocity was conducted in support of capsule drop tests. The results of this study confirm an empirical chart (Figure 13) that yields the velocity of an object dropped from rest if the distance fallen and the time of flight are known. Figure 13 is independent of the atmospheric density, vehicle weight, and vehicle drag characteristics.

Figure 13. A comparison between the theoretical and empirical results for the free-fall ballistics chart

Aerodynamic and Trajectory Analyses of a Cobalt 60 Fuel Capsule
(H. R. Spahr)

The configuration analyzed was a right-circular cylinder fuel capsule 3.5 inches in diameter and 5.7 inches long, weighing 34 pounds. The capsule was assumed to be in a crosswise orientation. Free molecule flow theory was used to compute a hypersonic free molecule flow ballistic coefficient for an S number of 14 and a steady-state space surface temperature of 1998°R. Modified Newtonian flow theory was used to compute a hypersonic continuum flow ballistic coefficient, including a correction for the finite aspect ratio of the cylinder.

Computer code HRS015 was used with the Sandia Quicktran remote terminal and the IBM 7040/44 in Los Angeles to compute the variation in ballistic coefficient in the transition flow regime. Figure 14 presents the hypersonic ballistic coefficient as a function of altitude for the fuel capsule.

Figure 14.
Variation of hypersonic
ballistic coefficient
with altitude for a
cobalt 60 fuel capsule,
reentering crosswise

The results of computer code HRS004 were used to define a set of initial conditions for an orbital decay trajectory, assuming the fuel capsule was initially in a polar orbit and started reentry by itself. The initial reentry angle was -0.013° and the initial inertial velocity was 25,698.51 fps, with the reentry assumed to start at a latitude of 0° .

The Sandia TTA trajectory code was then used to compute the orbital decay trajectory for the fuel capsule. The resultant trajectory had a maximum convective aerodynamic heating rate parameter, $\dot{q}_c \sqrt{R}$, of 327 Btu per foot^{3/2}-sec. This trajectory provided the re-entry environment for the thermal analysis of the fuel capsule.

Thermal Analysis of a Cobalt 60 Fuel Capsule (D. W. Larson)

A one-dimensional thermal model of a cobalt 60 fueled SNAP system was constructed to determine the capability of the system to contain the fuel during atmospheric reentry. The cobalt fuel was enclosed in a cylindrical tungsten heat accumulator with a 3.5-inch diameter and 5.7-inch length (Figure 15). The temperature response of the 4550 thermal watt system was determined for an orbital decay reentry with the system spinning in crossflow. The tungsten heat accumulator reached a maximum temperature of 4000°F, well below tungsten melt (6110°F). However, tungsten oxidation rates in the atmosphere become significant at 750°F, and, therefore, material removal by oxidation should be examined in detail.

Figure 15. Cobalt 60 system

Fuel Capsule Design (R. D. Klett)

A report describing the environments which have an adverse affect on intact reentry of space nuclear power supplies and the effects each environment has on the design will be published in the near future. Some basic intact design concepts are suggested. Parametric thermal studies for early phases of a design are discussed.

Samaria-Tungsten Cermet Impact Tests (B. S. Hill)

Impact testing of two 20 percent tungsten-samarium cermets clad in tungsten-25 rhenium capsules was completed. The cermets were designed and loaned to us by Donald W. Douglas Laboratories (DWDL), Richland, Washington, and the results obtained are for the mutual benefit of DWDL, Sandia, and the AEC.

The two cermets were impacted into a granite target using the Sandia 18-inch Horizontal Actuator. The impact velocities were 200 and 242 fps, respectively, and the cermet temperature at impact was 1000°F. The tests were conducted to determine the impact resistance of the tungsten-25 rhenium clad and to determine whether a cermet would maintain its as manufactured form without exhibiting gross failure. Gross failure is defined as complete break up of the cermet, with secondary fracture (fines production) of the samaria microspheres.

Metallographic analyses of the cermets after impact show that a samaria-tungsten cermet encapsulated in a tungsten-25 rhenium clad with dimensions of about 0.75-inch diameter by 0.75 long will withstand granite impact up to 242 fps without gross failure of the cladding or the cermet. The tungsten-25 rhenium capsules cracked, but the capsules remained intact and contained the cermets. Both cermets had one or more cracks extending through the cermet area, but crack propagation was minimal and the cermet remained intact with very slight damage. Figure 16 shows the cermet after the 242 fps impact; little or no damage is evident.

A report giving complete details of this project will be published.

Figure 16.

General view of cermet
after 242 fps granite
impact (50X)

Earth Burial (F. L. Baker/G. H. Elkins)

A burial test, designated the Long Rod Heater Test, was performed as an approach to determining soil thermal conductance. The heater used was a 24-inch firerod, 0.5-inch in diameter. It was buried vertically in a 5 foot cube of bentonite at a depth of approximately 45 inches to the centerline. Power was applied in 50 watt increments up to 400 watts and was allowed to stabilize at each level. Stabilization was considered attained when the temperature at 6 inches from the heater changed no more than 0.5 percent in a 24-hour period. We instrumented the capsule surface and the near soil at 0.25, 0.5, 1.5, 2, 2.5, 3, 6, and 12 inches from the capsule surface.

The steady state temperatures generated by the above experiment are shown in Table IX as a function of the input power q and radial distance r .

TABLE IX
Steady State Temperatures Attained

Input Power, q (watts)	Temperature ($^{\circ}$ F) at									
	Heater Surface H_s	0.25 in. from H_s	0.5 in. from H_s	1 in. from H_s	1.5 in. from H_s	2 in. from H_s	2.5 in. from H_s	3 in. from H_s	6 in. from H_s	12 in. from H_s
0	60	60	60	60	60	60	60	60	60	60
50	412	340	312	278	252	232	215	201	148	104
100	694	572	522	463	416	385	355	330	233	143
150	980	811	741	660	595	548	504	467	330	190
200	1180	1000	910	807	728	672	621	577	406	235
250	1370	1180	1070	960	858	793	732	682	481	280
300	1550	1330	1230	1100	990	920	841	782	556	323
350	1710	1490	1370	1230	1115	1030	953	888	631	370
400	1845	1660	1530	1360	1230	1140	1060	990	702	410

For distances sufficiently close to the capsule surface an effective conductance k is defined such that

$$q = -kA \frac{dT}{dr}$$

where q = power input to heater
 k = effective conductance of the soil
 $A = 2\pi rL$ = area through which heat flows
 $\frac{dT}{dr}$ = rate of change of temperature with respect to distance for a given q .
 L = effective length of heater

Solving the above equation for k

$$k = - \frac{q}{2\pi Lr \frac{dT}{dr}} .$$

It is desired to calculate k at a given distance r_1 . $\frac{dT}{dr}$ evaluated at $r = r_1$ is a function of q . Let this dependence on q be represented by

$$\left. \frac{dT}{dr} \right|_{r = r_1} = \frac{dT}{dr} (r_1; q)$$

with this definition

$$k = - \frac{q}{2\pi Lr_1 \frac{dT}{dr} (r_1; q)} .$$

Since $q = q(T)$, $k = k(q) = k(T)$.

Figure 17 shows temperature (T) vs. input power (q) for $r_1 = 0.4$, 0.5 , and 0.6 inch from the centerline, or 0.15 , 0.25 , and 0.35 inch from the capsule surface. Figure 18 shows $\frac{dT}{dr} (r_1; q)$ vs. T . Since $2\pi Lr_1$ is a constant, k is determined by graphically dividing q from Figure 17 by $\frac{dT}{dr} (r_1; q)$ from Figure 18 for each r_1 , $i = 1, 2, 3$. These results are shown in Figure 19 by the dotted curves. The average of these three curves is taken as the curve for k , which is shown by the solid line.

Figure 17 Temperature vs input power for $r_1 = 0.4, 0.5,$ and 0.6 -inch from centerline

Figure 18. $\frac{dT}{dr}(r;q)$ vs input power

Figure 19. K vs temperature for $r_1 = 0.4, 0.5$, and 0.6 -inch from centerline; average value is also shown

Thermal Conductance of Soils (J. B. Boyd)

The National Bureau of Standards (NBS) completed the first soil test series on all nine soils at temperatures as high as 1740°C . The second and final test series was stopped at about the mid-point because additional platinum heater wire is needed. Early heater problems used up more of this special resistance wire than was anticipated.

DOSE MODEL

Experimental Alpha Dosimetry of $^{238}\text{PuO}_2$ Microspheres (W. L. Holley)

Under Sandia contract, Oak Ridge National Laboratory is performing experimental alpha dosimetry work. Recent results are reported below.

The alpha spectrum was obtained from a PuO_2 microsphere with an NE-102 plastic scintillator and analyzed in a Nuclear Data Model ND-110, 128 channel analyzer. Five microspheres were prepared, and each was placed on a plastic adhesive tape and fixed in an inverted position over

the plastic scintillator which was coupled through a lucite light pipe to a phototube. The spectra were converted into absorbed dose by the computer program DOSEW. Corrections were made for nonlinearity of scintillator response, stopping power ratios, and channel bandwidth variations.

All measurements were made at pressures less than 150×10^{-3} torr; source to detector distances varied from 5.45 to 12 centimeters. The absorbers were films of Mylar (polyethylene terephthalate) whose thicknesses were measured with a Zeiss light-section microscope.

Table X lists the measured dose rates from the five $^{238}\text{PuO}_2$ microspheres as a function of absorber thickness and source-detector distance. Assuming that little, if any, scattering of the alpha particles takes place in the vacuum counting chamber, one can extrapolate, using the inverse square law relationship, and arrive at a value for the dose rate at the surface of the particle. Table XI gives the results of these calculations along with an estimate of the relative activity of the particle in terms of $\text{rad-sec}^{-1}\text{-microcurie}^{-1}$. Both sets of values are shown in Figure 20. The calculated dose rate, in rads per second, appears to be independent of particle size and contained activity. ORNL believes this is because the range of the alpha in PuO_2 is short enough for the spheres to appear as infinitely thick sources.

The average surface alpha dose rate was found to be $25,910 \pm 2,580$ rads per second or 9.33×10^7 rads per hour for the five sources used. This compares closely with the calculated value of 9.6×10^7 rads per hour reported by LASL for a $188.93 \pm 20.52 \mu\text{m}$ diameter $^{238}\text{PuO}_2$ microsphere.

Calculations of the dose rate per unit contained activity, as a function of particle size, gives an indication of the relative amount of radiation escaping from the microspheres. For example, in Figure 20 it can be seen that on the surface of a particle $125 \mu\text{m}$ in diameter the dose rate is ten times greater per microcurie of source activity than is the dose rate from a particle $225 \mu\text{m}$ in diameter.

TABLE X
Measured Dose Rates from $^{238}\text{PuO}_2$ Microspheres as a Function of
Absorber Thickness and Source-Detector Separation

Source No.	Diameter (μm)	Activity (μCi)	Distance (cm)	Dose Rate (rad/hour)				
				0	Absorber Thickness (μm)	6.38	14.4	20.78 26.60
M - 13	225	693	12	78.73	53.91	27.79	11.44	2.534
M - 8	148	204	7	90.12	62.39	32.57	13.78	4.547
M - 12	175	357	5.45	256.6	173.8	87.57	39.27	8.219
M - 14	219	704	9.05	144.77	102.2	51.63	22.76	4.175
Gp 4 #1	123	70.2	7.25	71.74	49.20	25.03	10.50	2.291

TABLE XI
Extrapolated Values at Surface of
 $^{238}\text{PuO}_2$ Microspheres

Source No.	Diameter (μm)	Activity (μCi)	Dose Rate Rad-Sec^{-1}	Effective Activity $\text{Rad-Sec}^{-1}-\mu\text{Ci}^{-1}$
Gp 4 #1	123	70.2	27,720	395
M - 8	148	204	21,810	107
M - 12	175	357	27,810	77.4
M - 14	219	704	27,470	39.0
M - 13	225	693	24,880	35.9
Average			25,910	
S.D			$\pm 2,580$

Figure 20.
Alpha dose rate at surface
of ^{238}Pu microspheres

As thicker absorbers were interposed, the maximum alpha energy observed decreased. Using a $41\text{ }\mu\text{m}$ thick absorber, there is little, if any evidence of alpha radiation, and the calculated dose rate is $\sim 1.95 \times 10^{-3}$ rads/minute, or < 0.003 percent of the value for zero absorber thickness. Consequently, for practical purposes ORNL assumes that the range of the alphas emitted by these microspheres will be less than $41\text{ }\mu\text{m}$ in tissue. NUS Corporation has theoretically determined the $^{238}\text{PuO}_2$ alpha range to be $40.5\text{ }\mu\text{m}$. A graph of dose rate versus absorber thickness for microsphere M-13 is shown in Figure 21.

Figure 21.
Measured alpha dose rate from
 $^{238}\text{PuO}_2$ microsphere M-13 at
7.0 centimeters

Release of ^{210}Po at High Altitude (R. J. Everett)

Three atmospheric models were compared relative to their troposphere predictions for a large ^{210}Po release at high altitude. The resultant time-integrated concentrations were converted to dose and applied to the general population. Individual dose and total man-rem were compared to radiation standards and criteria currently in use in the aerospace community. The Stardust model gave levels several orders of magnitude lower than the three-compartment models. The means of evaluating a release of this type using threshold and linear theories of risk was also described. Table XII gives the results of computations for a 10^6 Ci release of ^{210}Po using the three models.

GEOGRAPHIC AND DEMOGRAPHIC MODELS

New Tape from the Defense Communication Agency (E. S. Phinney)

A new 1968 population data tape was received from the Defense Communication Agency (DCA). The DCA tape is now being processed in order to develop a new Sandia master population tape.

TABLE XII
Results of 10^6 Ci Release of ^{210}Po

Model	Half Residence Time (yr)			Average $\bar{x}^1$ $\frac{\text{Ci-sec}}{\text{M}^3}$	Lung Dose per Person ² (rem)	Man-rem
	Mesosphere	Stratosphere	Troposphere			
GE ³	10	5	0.16	4.73×10^{-7}	2.83×10^{-3}	9.59×10^6
Smith ⁴	2	0.67	0.16	1.27×10^{-7}	7.61×10^{-4}	2.58×10^6
Stardust ⁵	-	-	-	2.50×10^{-9}	1.50×10^{-5}	5.08×10^4

1 - Time integrated air concentrations ($\bar{x}$) were computed over a 7-year period.

2 - The world population was taken to be 3.39×10^9 .

3 - SNAP-27 Safety Analysis Report, Vol. I DIN:6300-299 - General Electric Co.

4 - Sandia Corporation - personal communication.

5 - Release at 37.5 km and $17^\circ 27'$ south latitude.

ABORT MODEL

Autorotation Studies

Flat Plates (G. W. Stone) -- Analysis of the photographic data obtained during the Phase III autorotation wind tunnel test in September 1967 at Edgewood Arsenal was completed. Approximately 7000 feet of 16-mm film records were converted to digital records of the model's angular position variation with time. The digital data represented 138 test runs on 10 flat plate models with rectangular, circular, and triangular planforms. During the test, damped and undamped oscillatory motions, oscillatory limit cycles, and autorotational motions were observed. The test was conducted at sea level atmospheric density at airspeeds up to 150 mph. All of the configurations tested autorotated, and a steady-state angular velocity of 15,600 rpm was obtained by an aspect ratio 6 plate at 75 mph.

The digital data were analyzed on the CDC 3600 computer using the OSCIL and AUTOSPIN programs to compute static and dynamic aerodynamic moment coefficients from the model motions. The OSCIL computer program uses least squares numerical techniques to find the "best" damped or undamped cosine wave that fits the oscillatory model motion; it computes the effective linear static and dynamic moment coefficients from the parameters of the "best" cosine wave. By using the program to analyze three-cycle segments of the data, it was possible to determine the effective nonlinear static and dynamic coefficients. The AUTOSPIN computer program uses least squares numerical techniques to compute the total angular energy from the autorotation motion of the tumbling models. Using the nonlinear autorotation theory for a one degree-of-freedom system presented by Bustamante and Stone,* it is possible to calculate the instantaneous dynamic moment coefficient from the total angular energy of the system.

A typical variation of steady-state autorotation angular velocity with airspeed is shown in Figure 22 for the fuel puck model. Over the range of airspeed that could be achieved in the tunnel, the steady-state

*SC-RR-67-778, Autorotational Characteristics of Flat Plates and Right Circular Cylinders at Subsonic Speeds, A. C. Bustamante and G. W. Stone, Sandia Laboratory, Albuquerque, New Mexico, November 1967.

autorotation rate increases almost linearly with free stream velocity. However, the data for all of the models seem to indicate that for airspeeds above approximately 125 to 150 mph the angular rate begins to level off. Because of the very high angular rates encountered at the higher airspeeds, testing at these conditions is limited by safety considerations.

Figure 22. Steady-state autorotation rate for the fuel puck model

A typical effective static moment coefficient variation with angle of attack is shown in Figure 23 for the oscillatory motion of the fuel puck model. The dynamic moment coefficient was found to correlate with the square of the reduced frequency, and the variation of this coefficient with the correlation parameter is shown in Figure 24 for both oscillatory and autorotation motions of the fuel puck model. Figure 24 shows the typical stability boundary between oscillatory and autorotation motions of flat plate models.

All of the dynamic data are currently being analyzed in an effort to find correlation parameters for the steady-state autorotation rate and moment coefficients with model size, planform, aspect ratio, thickness, and moment of inertia.

Figure 23. Typical variation of the effective static moment coefficient with angle of attack

Cylinders (G. W. Stone) -- A one degree-of-freedom autorotation wind tunnel test of cylindrical capsule configurations was conducted at Mach numbers of 5, 7, and 11 in the Sandia 18-inch hypersonic blown-down tunnel. The configurations tested were a basic $\frac{L}{D} = 2$ right circular cylinder, the cylinder with hemispherical end-caps, and the cylinder with clipped corners of 0.15D, 0.30D, and 0.45D.

Figure 24. Typical variation of the dynamic moment coefficient with the square of the reduced frequency

The results of this test showed that the basic cylinder will autorotate at hypersonic speeds but that the autorotation rate is very dependent upon Reynold's number (Figure 25). Further, the test showed that the basic cylinder, with hemispherical end-caps and with 0.150 clipped corners, would not autorotate with only one degree-of-freedom. The basic cylinder with 0.30D and 0.45D clipped corners autorotates at high angular rates independent of Reynold's number (Figure 26). The dynamic data on the cylinder with hemispherical end-caps was analyzed using the AUTOSPIN computer program; the resulting aerodynamic damping coefficients are shown in Figure 27.

Drag Data (A. C. Bustamante) -- Drag coefficient data for a flat plate experiencing broadside, edge-on, and autorotating motions were derived from published data and from the results of experimental tests conducted at the Edgewood wind tunnel facility. The results of these studies are presented in Figures 28 through 30.

Figure 25. Steady state tumble rate for the basic cylinder configuration for wind tunnel conditions in the Sandia 18-inch hypersonic test facility

Figure 26. Steady state tumble rate for the cylinder configuration with 30- and 45-percent clipped corners in the Sandia 18-inch hypersonic wind tunnel

Figure 27. Damping moment coefficient variation with angular rate for the basic cylinder with hemispherical end caps

Figure 28. Flat plate drag coefficient for broadside and autorotating attitudes

Figure 29. Flat plate drag coefficient for edge on attitude

Figure 30. Autorotation drag coefficient vs velocity (flat plate - $AR = 1.0$)

Computer Codes

Computer Code HRS015 (H. R. Spahr) -- Computer code HRS015 is operational on the Sandia Quicktran facility, which is linked to an IBM 7040/44 in Los Angeles. This code calculates the hypersonic transition flow regime ballistic coefficient variation, with altitude, for specified values of the continuum and free molecule ballistic coefficients and a characteristic dimension.

Confac II Computer Code (H. R. Spahr/D. W. Larson) -- A sample problem was run on Confac II on the Sandia IBM 7090 computer. This computer code calculates geometric configuration and form factors for radiant thermal analyses for complex configurations.

Martin Computer Code (D. E. Randall/H. R. Spahr) -- A Martin computer code was received which computes averaged aerodynamic heating inputs for a specified motion and set of experimental data. While modifying this code to make it operational on the UNIVAC 1108, it was discovered that input/output features available only on the IBM 360 computer had been used. The computer code will be rewritten.

GE Arbitrary Body Computer Code - UNIVAC 1108 Version (H. R. Spahr) -- The GE Arbitrary Body computes the hypersonic aerodynamic coefficient of complex configurations using free molecule and modified Neutronian flow theory. The modified Newtonian flow option of the Sandia version of this code was successfully checked on the UNIVAC 1108. The free molecule flow option of this code will be checked as soon as the Sandia error function routine, GOFU, is completed for the UNIVAC 1108.

GE Arbitrary Body Computer Code - SC-4020 Plot Package Version (C. N. Waggoner) -- The GE Arbitrary Body computer code was modified to allow plotting of each body subsurface on an SC-4020 plotter. This modification will be a valuable aid in determining whether the subsurface data were input correctly. The program was checked on the IBM 7090 and the UNIVAC 1108.

CINDA Computer Code (D. W. Larson) -- A thermal model of a SNAP-27 GLFC was constructed for use in the CINDA (Chrysler Improved Numerical Differencing Analyzer) computer code. The CINDA results obtained with various inputs to the system were compared to results obtained from a similar thermal model run previously on the HERMAN heat transfer computer program. Comparison indicates that the two programs predict similar temperature responses; however, the results from the CINDA code appear to be more precise because of the smaller time step this program uses for numerical integration. The CINDA code is considerably more flexible than the HERMAN program. At present, the ablation subroutine in the code does not produce results comparable to the CMA computer code.

ENVIRONMENTAL TRANSPORT MODEL

Stardust Atmospheric Fallout Studies (R. E. Smith)

The data published by the AEC Health and Safety Laboratory (HASL) on SNAP-9A plutonium surface air concentrations as measured in the World Wide Sampling Network were plotted against the simulated SNAP-9A injection as determined by the Stardust fallout model. In general, reasonable agreement is present, especially in the shape of the curves. However, the Stardust model indicated too much material entering the northern hemisphere and not enough material in the southern hemisphere when compared to the observed data. A trip is planned to discuss the problem with Isotopes, Inc., and HASL in an attempt to resolve the problems for future simulated injections.

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