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SNAP AEROSPACE NUCLEAR SAFETY PROGRAM
JANUARY - MARCH 1966
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by *GG*

DTIC, date *5/24/73*

Wash. D.C.

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SNAP AEROSPACE NUCLEAR SAFETY PROGRAM
JANUARY - MARCH 1966
(Title Unclassified)

By

R. L. DETTERMAN
Project Manager

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CONTENTS

	Page
I. Program Summary	7
A. Reentry and Abort Studies	7
1. Reactor Disintegration Projects	7
2. Fuel Reentry Burnup Projects	7
3. Fuel Ablation and Particle Formation Projects	8
4. Fuel Properties Project	9
5. Reactor Disposal Projects	9
B. Nuclear Studies	9
1. Reactor Transient Projects	9
2. Critical Configuration Projects	10
3. End-of-Life Shutdown Project	11
II. Reactor Disintegration Projects	13
A. Experiments	13
1. Reactor Ablation-Disintegration Experiment (RADE)	13
2. Aeroheating Experiment	13
B. Analysis	16
1. RADE Analytical Model Development	16
2. Analysis of Experiments	16
3. Development of Basic Methods	17
III. Fuel Reentry Burnup Projects	19
A. Fuel Arc-Jet Experiment	19
B. Analysis	20
1. Fuel Arc-Jet Experiment	20
2. SNAP 8 Fuel Element Reentry Burnup Statistical Study	22
IV. Fuel Ablation and Particle Formation Projects	27
A. Experiments	27
B. Analysis	27
V. Fuel Properties Project	31
A. Thermophysical Properties	31
1. Basic Program	31
2. AI-BMI Data Comparison Program	31
B. Kinetic Studies	31

NAA-SR-11884

~~CONFIDENTIAL~~

CONTENTS

	Page
VI. Reactor Disposal Projects	35
A. Atmospheric Fallout Experiment	35
B. Fallout Studies.	35
C. Ocean Water Contamination Study	36
VII. Reactor Transient Projects	37
A. SNAPTRAN-2 Experiment	37
B. Analysis	43
1. Analysis of SNAPTRAN-2 Destruct Test	43
2. Calculation of Energy Deposition in SNAPTRAN-2 Core	48
VIII. Critical Configuration Projects	55
IX. End-of-Life Shutdown Projects	59

TABLES

1. Deviations in Q_{REQ} Due to Deviations in Parameter Values	23
2. Parameter Survey Results for Q_{AVAIL} for a Random-Tumbling Orientation	24
3. Probability Calculations for SNAP 8-Type Fuel Element Ablation	25
4. Final Conditions for Standard Particle Reentry Cases.	29
5. Peak Powers for SNAPTRAN-2	46
6. Prompt Temperature Coefficients for a Beryllium-Reflected SNAPTRAN Reactor	49
7. Prompt Temperature Coefficient for a Water-Reflected SNAPTRAN Reactor	50
8. Isothermal Temperature Coefficients for a Beryllium-Reflected SNAP 10A/2-Type Reactor.	50
9. Results of 1500°F Anneal of Fuel-Swelling Samples	59

~~CONFIDENTIAL~~

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FIGURES

	Page
1. Aeroheating Experiment Model Configuration	14
2. Aeroheating Experiment Shock Tunnel Configuration	14
3. Particles Ablating During Fuel Arc-Jet Test Run	21
4. Probabilities of Initial Ablation for SNAP 8 Fuel Elements	25
5. Oxygen Mass Flux to a 525-micron-Diameter Particle in 625 torr of Air as a Function of Film Temperature	29
6. Metallographic Cross-Section of Nonhydrided Fuel Alloy.	32
7. SNAPTRAN-2 Reactor and Support Structure in Test Cell	38
8. Close-Up View of SNAPTRAN-2 Reactor	39
9. SNAPTRAN-2 Reactor as Reflected Through Mirror Mounted Directly Above Reactor	40
10. SNAPTRAN-2 Destruct Test	41
11. SNAPTRAN-2 Test Area After Destruct Test	42
12. SNAPTRAN-2 Power Traces Obtained From Nuclear Detectors	44
13. Theoretical Radial Power Profile - SNAPTRAN-2	44
14. Power Profiles for SNAPTRAN-2	47
15. Fission Product Kinetic Energy Loss - SNAPTRAN-2	52
16. Neutron Energy Deposition - SNAPTRAN-2	53
17. Gamma Energy Deposition - SNAPTRAN-2	53
18. Reactivity and Geometry Changes	54
19. System Weights of Intrinsically Subcritical Designs for Medium-Power Systems	56
20. System Weight Changes of Intrinsically Subcritical Designs	56
21. Geometry Experiments in Water Environments	57
22. Gas Release Apparatus	60

The Progress Report for the previous quarter was NAA-SR-11759.

NAA-SR-11884

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I. PROGRAM SUMMARY

A. REENTRY AND ABORT STUDIES

1. Reactor Disintegration Projects

The fabrication and assembly of the disintegration models for the Reactor Ablation-Disintegration Experiment (RADE) were completed. The tests, to be conducted in the NASA-Ames wind tunnel facility, were rescheduled to begin during the next reporting period. The thermal behaviors of the RADE-A and RADE-B experimental models were predicted using the analytical models developed for each. The two cases considered for each type of model were head-on heating and 30-degree angle-of-attack heating.

Plans for the aeroheating tests to be conducted in the Cornell Aeronautical Laboratory were completed. The experiment and subsequent analysis is expected to yield empirical correlations of the aeroheating distributions on a SNAP reactor system as a function of orientation to the airflow. The model configuration selected for the experiment is of the SNAP 8 type at one-fifth scale. The heat transfer sensor (thin-film resistance thermometers) locations were determined to be in proper relation to the model to provide data to satisfy acquisition of heating rate distributions.

The HYHEAT-3 computer program, which was written in the FORTRAN-IV system, was completed. It will be used for pre-test predictions of heating in both the RADE tests and the aeroheating experiment.

2. Fuel Reentry Burnup Projects

The final phase of the fuel arc-ject tests conducted in the NAA-LAD hyper-thermal wind tunnel facility was completed. Meaningful particle photography, utilizing a laser-schlieren system, and thermocouple data were obtained. The results of this final test phase are discussed in greater detail in Section III. The analysis of the results was in progress. Also, a formal report of the experiment was being written for future publication.

A statistical analysis and probability study of the initial ablation of SNAP 8-type fuel elements, released at various altitudes between 200,000 and 300,000 ft, was completed. Deviations in integrated heat required, Q_{REQ} , and in the

NAA-SR-11884

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integrated heat available, Q_{AVAIL} , due to variations in the individual parameters affecting each, were determined and are tabulated in Section III for the selected release altitudes. The probability of initial ablation of SNAP 8-type fuel elements were plotted as a function of release altitude both for random-tumbling and for cross-axial-spinning attitudes. It will be seen from the figure presented in Section III that the probability curves are essentially linear for the release altitudes shown and that at about 240,000 ft, the probability of nonablation is of the order of one in a million or less.

3. Fuel Ablation and Particle Formation Projects

Data analysis of the particle photography obtained during the fuel arc-jet tests was initiated. Useful results were obtained from three of the test runs.

The initial investigation of experimental techniques for the particle suspension experiment was completed. In this investigation, the porous cup particle suspension technique was tested. An 800-micron, stainless-steel particle (ball bearing) was observed to float freely within the porous cup.

The ablation products collected on the particle catchers during the recent fuel arc-jet tests were submitted for chemical analysis of composition and density and for metallographic analysis to obtain data on variations of size and shape.

A study was made of the diffusion of oxygen to the particle as a function of film temperature. The oxygen flux to a 525-micron-diameter particle in 625 torr of air was plotted as a function of film temperature for various particle velocities ranging from 2 to 16 ft/sec. It was seen that in order to obtain oxygen fluxes corresponding to the experiments, film temperatures nearer to ambient conditions will have to be used.

A special-purpose computer code, PATH (Particle Aerodynamic Trajectory and Heating), was written and checked out for particle trajectory analyses. It will enable trajectory computations to be provided with extremely short machine-time expenditure.

A survey of fallout criteria was made which indicates that the ablation particle characteristics significant to fallout studies include size, density, shape, and roughness. Since most characteristics are expected to show wide variations, they may be presented in the form of statistical distributions.

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4. Fuel Properties Project

Experimental measurements of the thermophysical properties of SNAP fuel was completed. The analysis of data and the preparation of a formal topical report were in progress.

Oxidation studies performed by imposing a reentry thermal transient on hydrided and nonhydrided fuel samples was completed. The data were being analyzed by means of computer programming techniques. Preliminary results on the nonhydrided fuel indicate that good agreement was obtained between the transient studies and the previous isothermal work. The data obtained on the isothermal work were reexamined using a least-squares computer program. Equations were established to express the resulting oxidation rate constants.

The study of the oxidation kinetics of liquid-phase fuel alloy was discontinued due to project redirection. Preliminary experiments were performed, however, which establish levitation as a practical method of performing the experimental work.

5. Reactor Disposal Projects

An advanced parametric analysis of fallout was initiated. The analysis considers that: (1) for alpha emitters, it is necessary to predict the concentration in air at the breathing level and integrated concentration over time; (2) for gamma emitters, it is necessary to predict doses and dose rates; and (3) for soluble nuclides, it is necessary to predict concentrations that will occur in major foodstuffs and in typical total diets.

A qualitative review of high-altitude rocket wind observations revealed that distinct low net wind transport conditions prevailed during 6% of the observations. Under conditions of low wind transport, the primary dispersal of debris particulate in the atmosphere will be governed by the particle cloud growth, resulting from the turbulent eddy motion of the atmosphere.

B. NUCLEAR STUDIES

1. Reactor Transient Projects

The SNAPTRAN-2 destruct test was conducted on January 11 at 0952 MST. Power traces obtained from three nuclear detectors indicated that the theoretical predictions are in good agreement with the experimental results. The

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asymptotic period for the destruct test was $206 \mu\text{sec}$. The total reactivity insertion was $\$4.96$; this compares with $\$4.93$ computed with a 6-group kinetics model (using a generation time of $6.5 \mu\text{sec}$) and $\$4.74$ computed with a 7-group, reflected reactor kinetics model.

The total energy release based on integration of the power data ranged from 34 to 60 Mw-sec. The prompt temperature coefficient ranged from -0.19 to $-0.30\text{c}/^\circ\text{F}$. The differences are due to the discrepancy between neutron detector results and the results obtained from energy probe data. These problems in interpreting the test data are discussed in greater detail in Section VII.

A method of obtaining information from the 5 and 2.5 wt % Uranium probes was developed that considers the problem of "background" energy deposition. The 10 wt % U probes absorb gamma, neutron, and fission product recoil energy in the same ratio as does the fuel, since they have essentially the same composition. The 5 and 2.5 wt % U probes, on the other hand, absorb only $1/2$ and $1/4$ as much fission product energy, respectively, as the 10 wt % U probes, although they absorb nearly the same neutron and gamma energy. The energy sources and energy deposition in a SNAPTRAN core are summarized in Section VII.

A heat transfer model was developed to assist in analyzing the heat loss from energy probes during slow SNAPTRAN-1 transients. If this model proves to be a reasonable representative of the physical system, a proper choice of the overall heat transfer coefficients between fuel and trough and between trough and sheath may lead to a fuel temperature response similar to that observed experimentally.

2. Critical Configuration Projects

Intrinsically subcritical designs were studied in a medium power ($\sim 600 \text{ kw}$) shadow-shield application, as characterized by SNAP 8. Geometry variations in core length, radius, and axial reflector dimensions establish a family of reactor geometries with different reactivities in a water environment. One such family of geometries is shown in Section VIII.

An important consideration is the effect of intrinsically subcritical design limitations on power system weight. One conclusion is that intrinsic

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subcriticality will not have a major effect on the power system weight in medium power, shadow-shield systems.

Experiments were conducted that studied the reactivity effect resulting from rearrangement of the outer fuel elements from a hexagonal array to achieve a more compact core, in terms of locating the outer fuel elements closer to the core center. Only small variations in reactivity were observed; the hexagonal array was the most reactive.

3. End-of-Life Shutdown Project

The

decay mechanism has been proposed for use as an intrinsic shutdown mechanism for SNAP U-Zr-H_x-fueled reactors. A feasibility study was being conducted to investigate the effects of adding tritium to the fuel.

Fuel-swelling tests were performed, and a gas release apparatus was constructed to gain an insight into the behavior of ${}^3_2\text{He}$ within the fuel. Since a cracking phenomenon was observed during the preceding reporting period, seven additional specimens were prepared and subjected to an identical annealing cycle. These samples did not crack, but experienced small volume increases of from 0.15 to 0.21% after annealing 24 hr at 1500°F.

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II. REACTOR DISINTEGRATION PROJECTS

A. EXPERIMENTS

1. Reactor Ablation-Disintegration Experiment (RADE)

The head baffle plates and electrical connectors for the gold-plated copper calorimeter models were sealed in place with epoxy and were tested at 40 lb of static water pressure to verify a leakproof seal. The RADE-A and RADE-B head-vessel assemblies were attached to the 0- and 30-degree model support arms to fit and route the water-coolant lines to the hinge point where the flexible water lines will be attached. Two microswitches were attached to the model support bracket near the hinge point to indicate the model position at each end of the actuator stroke (i.e., at the model fully extended and fully retracted positions).

The fabrication and assembly of the RADE disintegration models and supporting hardware were completed. The components were boxed for shipment to the NASA-Ames test facility. The tests were scheduled to be conducted during the next reporting period.

2. Aeroheating Experiment

The primary objective of the aeroheating experiment and subsequent analysis is to provide empirical correlations of the aeroheating distributions on a SNAP reactor system as a function of orientation to the airflow. The aerodynamic heating correlations derived from this experimental program will be applicable to the entire continuum heating regime, especially at the point where vessel ablation occurs.

The model configuration presented in Figure 1 is of a SNAP 8 type at one-fifth scale. This configuration was chosen to represent present and, most likely, future SNAP reactor designs. Locations of heat transfer gages (thin-film resistance thermometers) on the model are also shown in Figure 1. These positions were chosen with respect to estimated streamline positions and points of shock impingement due to interaction. These data and the basic heat transfer correlations on cylindrical and conical shapes are to be obtained from the test.

The selection of a test facility was based on obtaining data from flow conditions most nearly simulating the actual reentry environment. The Cornell Aeronautical

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Figure 1. Aeroheating Experiment Model Configuration

Figure 2. Aeroheating Experiment Shock Tunnel Configuration

NAA-SR-11884

14

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Laboratory (CAL), 48-in., hypersonic shock tunnel was selected for the test, based on the following criteria: (1) hypersonic flow with a Mach number greater than 10 and a unit Reynolds number simulation altitude about 250,000 ft, (2) absolute heat transfer sensor instrumentation and multiple-channel recording capability, (3) usable test gas core of a size compatible with model size, (4) flow field visualization, and (5) accessibility.

A simple schematic of the basic components of the CAL shock tunnel is shown in Figure 2. The shock tube is separated into regions of high (driver) and low (driven air) pressure by a diaphragm. The downstream end of the shock tube is terminated by a convergent-divergent nozzle where the ratio of the nozzle throat area to the shock tube cross-sectional area is small. This has the effect of almost completely reflecting the primary shock wave upstream from the throat, leaving a region of almost stagnant, compressed, and heated air at the end of the low-pressure section of the shock tube. This processed air is then expanded through the nozzle to the desired hypersonic conditions.

The acquisition of data will be conducted in an orderly manner at tunnel conditions simulating the hypersonic reentry environment at 250,000 ft. The model configuration for the first run will consist of the hemispherical head shown in Figure 1 instead of the normal SNAP system head and piping. The data derived from this will provide an anchor point on the reference stagnation heating curve and provide an excellent base to normalize the heating distributions of the SNAP system as a function of flow orientation.

Plans for the aeroheating test were completed. The scope and requirements were discussed with personnel of the Cornell Aeronautical Laboratory. The model configuration and heat transfer sensor locations were determined to be in proper relation to provide data to satisfy acquisition of heating rate distributions. The proposed tunnel operating conditions of about Mach 18 were evaluated with respect to the model. The diameter of the usable core (uniform section of flow profile) in the tunnel is 28 in. for this proposed test condition. The one-fifth scale model will be compatible with this core.

NAA-SR-11884

15

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B. ANALYSIS

1. RADE Analytical Model Development

Work was completed on the analytical model of the external piping portion of the RADE-A experimental model. This portion was merged with the analytical models of the top head, upper grid plate, and reactor core that were developed earlier.

Work was in progress to adapt the RADE-B analytical model to a full-size analytical model of a SNAP 8-type reactor. This model will be used in a parametric study of the reentering of such a reactor.

2. Analysis of Experiments

The HYHEAT-3 computer program was completed; the code is written in the FORTRAN-IV system. It will be used for pre-test predictions of heating in the RADE tests and in the CAL aeroheating experiments.

Trial runs made with the HYHEAT-3 code showed that a modification was required in the method for calculating the effective value of gamma (specific heat ratio) for the real gas. The earlier method gave the correct density along an isentropic expansion, but it gave the incorrect mass velocity at the sonic point. This correction was made.

A study was in progress to resolve the problem of relating aerodynamic heating rates in the arc-jet tunnel to those which would occur in free flight. The HYHEAT-3 code accepts flight velocity and atmospheric pressure and density as inputs, whereas the arc-jet test condition is given in terms of total enthalpy, stagnation pressure, and nozzle exit pressure. The flow chemistry is different in the two cases, thus some difficulties arise in making the conversion.

Prediction were made of the thermal behavior of the RADE-A and RADE-B experimental models in the forthcoming NASA-Ames wind tunnel tests for a reference heat rate of $60 \text{ Btu/ft}^2\text{-sec}$. Two cases were considered for each type of reactor model: (1) head-on heating and (2) 30-degree angle-of-attack heating. The analytical models developed for RADE-A and RADE-B were used in arriving at the predictions.

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3. Development of Basic Methods

The study of methods for calculating air flow, pressure, and heating on bodies of irregular shape, particularly at various angles of attack was continued. The method of characteristics, as well as some simplified perturbation methods developed by NASA, were being studied.

A trial run of the integration package for the Trajectory Integration Program (TIP) checked perfectly with the test case. This integration subroutine will be used in the FORTRAN-IV versions of TIP and RESTORE. Work was in progress to convert RESTORE to FORTRAN-IV.

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17

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III. FUEL REENTRY BURNUP PROJECTS

A. FUEL ARC-JET EXPERIMENT

The fuel arc-jet tests conducted in the NAA-LAD hyperthermal wind tunnel facility were completed. The first phase of the test series was completed during the previous reporting period and was described in the progress report for that period (NAA-SR-11759). The tests conducted during this reporting period are described in the following paragraphs.

All test runs of Group 3, Configuration III, utilized the laser-schlieren system. These runs consisted of five specimens with the same diameters as SNAP 10A fuel and five with the same diameters as SNAP 8 fuel. Eight of these runs were made at a high-density flow region in order to enhance the photographic visibility of hydrogen out-gassing. The initial review of the first two test runs on film negatives indicated no significant detection of hydrogen.

The Group 6, Configuration VI, test runs utilized the laser for particle photography. Successful results were obtained from the last three of these runs.

The remaining test runs, consisting of three Configuration V and three Configuration II (with thermocouple) fuel specimens, completed the series. For these runs, a camera replacement was made to improve the data. The new camera had a factor-of-ten greater shutter speed, which was expected to yield a larger number of particles in focus on the film.

Although the three Configuration V fuel specimens were ablated without difficulty, the laser particle photography was not successful due to an improper focus location of the camera. Because of the manner in which this configuration was placed in the stream (the camera was focused perpendicular to the longitudinal axis) and the erratic ablation of these specimens, it was difficult to determine the proper focus location for the camera.

The final three test runs conducted were Configuration II (instrumented with thermocouple) fuel specimens placed in the jet stream such that the camera was focused parallel with the longitudinal axis of the sample. The particle photography for the first two of these runs also was not successful. Since the original camera setup could photograph every 2 sec, the last run was made utilizing the

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original camera. The results were of significantly greater quality. Meaningful particle photography was obtained for only three test runs of the final phase of the arc-jet tests. The secondary purpose of the Configuration II specimens was to obtain thermocouple data. These data were successfully obtained during the last two of these test runs.

A sample of the photographs that were successfully obtained of the particles ablating from a fuel sample is shown in Figure 3. The light source for these photos was the Q-switched giant pulse laser. Only those particles in focus were illuminated and, therefore, the particle sizes may be measured directly from the photo. The laser pulse width was approximately 60 nanosec which effectively stopped the motion of the particles. The shutter of the camera was open approximately 1/25 sec and a narrow bandpass filter at the ruby laser frequency was used. The light streaks and the glow of the specimen shown in Figure 3 occur during the 1/25 sec the camera shutter was open and could be decreased in intensity by the use of shorter shutter speed and more efficient filter. The rod size shown in the figure is 0.560 in. in diameter and may be used as a reference size for measuring the particles. The particles shown are in the range of 600 microns in diameter.

Reduction of the data from the fuel arc-jet tests was in progress. Data were available for a total of 36 runs in which the sample was rotating in cross-axial flow. Of these, 28 samples had smooth surfaces, while 8 had grooves or cross-hatching. Twelve samples were of SNAP 8 size. Ablation was achieved for 26 runs. The ablation sequences were photographed by means of high-speed (400 frames/sec) film in 14 runs. In addition, laser-schlieren photography was employed in 9 other ablation sequences. The results of this photography were being analyzed.

B. ANALYSIS

1. Fuel Arc-Jet Experiment

The analysis of the fuel arc-jet test data was in progress. A two-dimensional thermochemical model was developed to simulate axial and radial heat and hydrogen flow. This model will be applied to arc-jet test cases in which the specimens were rotated in cross-axial flow with axial heating profiles. The experimental data on the heating rates to be used for these test cases were being studied.

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Figure 3. Particles Ablating During Fuel Arc-Jet Test Run

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21

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A simple FORTRAN computer program was being prepared to facilitate arc-jet test data reduction. This program will convert pyrometer reading temperatures to actual temperatures for a given constant emissivity value. The converted temperatures will be tabulated and will also be plotted graphically using the AICRT-3 subroutine.

An investigation was initiated on the process of SNAP fuel ablation under re-entry conditions. This investigation was being conducted concurrently with the arc-jet test data analysis. Thus, the observed phenomena, up to ablation and during ablation, were being correlated simultaneously with the analytical description.

2. SNAP 8 Fuel Element Reentry Burnup Statistical Study

The statistical analysis and the probability study of the initial ablation of SNAP 8-type fuel elements, released at various altitudes between 200,000 and 300,000 ft, were completed. Deviations in Q_{REQ} , due to deviations in the individual parameters affecting Q_{REQ} , were determined. The results are shown in Table 1. The parameters are listed in the order of greatest to least influence upon Q_{REQ} . Of the 13 parameters, the hydrogen diffusion coefficient was found to be the most influential and the fuel thermal conductivity the least influential parameter. The number of parameters considered, the standard values of these parameters, and the parameter uncertainties are the same in this study as in the corresponding SNAP 10A-type fuel element study. From the results presented in Table 1, the standard deviation in Q_{REQ} was calculated to be equal to 490 Btu/ft². This represents an uncertainty of about 9% in Q_{REQ} for the range of release altitudes considered.

Deviations in Q_{AVAIL} , due to deviations in the individual parameters affecting Q_{AVAIL} , were obtained for the selected release altitudes. Typical results are shown in Table 2 (for a random-tumbling orientation), along with the standard parameter values and the $\pm 2 \sigma$ parameter deviations. The standard parameter values were taken from the reference SNAP 8 vehicle trajectory. The parameter deviations were taken from the estimated maximum and minimum vehicle trajectories computed using the RESTORE code.

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TABLE 1
DEVIATIONS IN Q_{REQ} DUE TO DEVIATIONS IN
PARAMETER VALUES

Order of Influence	Parameter	ΔQ_{REQ} (Btu/ft ²)
1	Hydrogen diffusion coefficient	978
2	Noncatalytic wall effect	889
3	Heat of oxidation	800
4	Method of analytical solution	622
5	Heat of dissociation	609
6	Initial temperature	548
7	Emissivity	418
8	Heat capacity	324
9	Initial hydrogen content	238
10	Melting temperature	234
11	Fuel element radius	84
12	Air stagnation enthalpy	36
13	Thermal conductivity	27

From these results, standard deviations for Q_{AVAIL} were computed, the results of which are presented in Table 3 along with the calculated values of Q_{AVAIL} , Q_{REQ} , and σ_{REQ} (standard deviation for Q_{REQ}). Results of the probability calculations using these values are also given in Table 3.

The statistical analysis and probability study of the initial ablation of SNAP 8-type fuel elements was later extended down to about 190,000 ft in order to cover the range of probabilities at the lower end. Plots of the probabilities obtained as a function of release altitude are shown in Figure 4. For the release altitudes shown, the probability curves are essentially linear.

Some simple calculations were made of the percentage of fuel material which would become oxidized during reentry for SNAP 8-type and SNAP 10A-type fuel elements. These calculations were based on oxidation heating rates currently being used in thermochemical behavior calculations. The results show that only a small percentage of the fuel is oxidized before and during ablation.

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TABLE 2
PARAMETER SURVEY RESULTS FOR Q_{AVAIL} FOR A RANDOM-TUMBLING ORIENTATION

Release Altitude (kilofeet)	Standard Parameter Values			$\pm 2 \sigma$ Parameter Deviations			Deviations in Q_{AVAIL}		
	Velocity v (ft/sec)	Flight Angle γ (degrees)	W/C_{DA} (lb/ft ²)	Velocity v (ft/sec)	Flight Angle γ (degrees)	W/C_{DA} (lb/ft ²)	$(\Delta Q_{AVAIL})_v$ (Btu/ft ²)	$(\Delta Q_{AVAIL})_\gamma$ (Btu/ft ²)	$(\Delta Q_{AVAIL})_{W/C_{DA}}$ (Btu/ft ²)
300	25,709	-0.214	8.486*	± 28	± 0.019	± 1.1	173	18	3,548
275	25,568	-0.444	10.10*	± 41	± 0.010	± 1.3	214	57	3,364
260	25,407	-0.604	12.10*	± 60	± 0.011	± 1.5	240	51	3,171
241	25,065	-0.853	14.74	± 148	± 0.035	± 2.0	422	119	2,732
220	24,453	-1.196	14.74	± 286	± 0.083	± 2.0	541	116	2,153
200	23,578	-1.597	14.74	± 472	± 0.124	± 2.0	628	70	1,576

*Initial value

NAA-SR-11884

24

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TABLE 3
PROBABILITY CALCULATIONS FOR SNAP 8-TYPE
FUEL ELEMENT ABLATION

Release Altitude (kilofeet)	Q _{AVAIL}	σ _{AVAIL}	Q _{REQ}	σ _{REQ}	Probability of Ablation
<u>Random Tumbling</u>					
300	15,913	888	6,051	490	$1 - 1.1 \times 10^{-22}$
275	15,263	843	5,443	490	$1 - 0.7 \times 10^{-23}$
260	13,732	795	5,415	490	$1 - 2.8 \times 10^{-19}$
241	11,085	692	5,290	490	$1 - 4.2 \times 10^{-12}$
220	7,966	556	5,369	490	0.999767
200	5,551	424	5,499	490	0.5323
<u>Spinning Cross-Axially</u>					
300	13,070	719	6,044	490	$1 - 3.5 \times 10^{-16}$
275	13,369	735	5,423	490	$1 - 1.1 \times 10^{-19}$
260	12,180	706	5,418	490	$1 - 1.8 \times 10^{-15}$
241	9,675	600	5,385	490	$1 - 1.5 \times 10^{-8}$
220	6,752	473	5,401	490	0.97615
210	5,703	416	5,439	490	0.6591

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Figure 4. Probabilities of Initial Ablation for SNAP 8 Fuel Elements

NAA-SR-11884

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IV. FUEL ABLATION AND PARTICLE FORMATION PROJECTS

A. EXPERIMENTS

Data reduction of the particle photography obtained during the course of the fuel arc-jet tests was initiated. Useful results were obtained from three test runs (6-5, 6-6, and 2-8). The samples for the first two of these runs were of SNAP 8 size that were each oriented with its longitudinal axis to the jet stream. The sample for the third run was of SNAP 10A size that was oriented cross-axially in the stream. The results of the particle photography are discussed in greater detail in Section III along with the fuel arc-jet experiment.

The stainless-steel spherical particles for testing particle suspension techniques were received. These particles were also used to calibrate the arc-jet particle laser photography setup at NAA-LAD. The particle sizes range from 380 to 1600 microns in diameter.

A particle size calibration utilizing the laser and camera at the NAA-LAD arc-jet facility was completed. Preliminary examination of the photographs indicate that true diameters for each particle size passed through the laser beam. The diameters of the particles used were 1/32 and 1/16 in. (~800 and 1600 microns, respectively).

Testing of the porous cup particle suspension technique was initiated. An 800-micron-diameter, solid spherical particle was observed to float freely within the porous cup. The rate of gas flow through the cup was easily adjusted by means of a much larger than needed regulator. This completed the initial investigation of experimental techniques for the particle experiment. Preparations were being made to secure adequate laboratory facilities at AI for the setup of the experimental apparatus.

B. ANALYSIS

A survey of fallout criteria indicates that ablation particle characteristics significant to fallout studies include size, density, shape, and roughness. Since most characteristics are expected to show wide variations, they may be presented in the form of statistical distributions. Fission product concentrations, as dependent on variations in particle characteristics, are also of basic importance. Particle size and fission product concentrations are presently included in the particle ablation models.

NAA-SR-11884

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The ablation products resulting from the initial stages of fuel rod ablation were collected on aluminum impact plates in the NAA-LAD fuel arc-jet tests. These products were submitted to the analytical chemistry laboratory for composition and density analysis and to the metallography laboratory to obtain data on variations in size and shape.

Extension of the particle ablation model to include initial cloud characteristics would be helpful in the later development of a cloud fallout model. Determination of initial cloud dimensions and properties formed by fuel rod ablation should include a consideration of nonhomogeneous concentration of particle sizes and other particle characteristics in various regions of the initial particle cloud. The slowing down of the rods as they break into fragments, particles, and drops will result in a change in reentry trajectory. Significant differences in elevation between the upper and lower regions of the cloud can result in particle dispersion due to vertical wind velocity and/or direction profile differences. Heat loss from the particle cloud to the atmosphere can set up local convection currents that can aid dispersal of cloud particles. Particle coalescence from small to large particles may, however, modify the fallout pattern. The final three-phase parametric analysis to evaluate ground safety hazards will include: (1) the particle ablation model, (2) the cloud fallout model, and (3) the final radiological hazard resulting from the particle cloud impacting the ground surface.

A set of initial conditions and property values was selected for a standard particle reentry case. The radii and unablated fractions obtained for the standard cases are shown in Table 4.

The NEWTON code for calculating aerodynamic forces was complete, with all subroutines working. These include aero-coefficients for spherical segments, cones or cone frustums, cylinders with or without endplates, and any compatible composite body.

A study was made of the diffusion of oxygen to the particle as a function of film temperature. In previous analyses, it had been assumed that film temperature was the average of the wall and ambient temperatures. These previous analyses yielded oxidation rates lower than experimental measurements. In

NAA-SR-11884

28

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TABLE 4
FINAL CONDITIONS FOR STANDARD
PARTICLE REENTRY CASES

Altitude (ft)	Initial Radius (microns)	Final Radius (microns)	Fraction Unablated
170,000	500	512	0.7251
177,000	630	678	0.8411
189,000	688	720	0.7777
203,000	900	970	0.8464
215,000	1195	1282 *	0.9225 *
228,000	1660	1743 *	0.9796 *

*Conditions are for 20 sec after release.

Figure 5, the oxygen flux is given as a function of film temperature for various particle velocities. In this figure, it is seen that in order to obtain oxygen fluxes corresponding to the experiments, film temperatures nearer to ambient conditions will have to be used. The Langmuir evaporation rates were determined

Figure 5. Oxygen Mass Flux to a
525-micron-Diameter Particle
in 625 torr of Air as a Func-
tion of Film Temperature

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NAA-SR-11884

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for particles of various sizes in laboratory environments. This is the first phase of a study of the diffusion of ZrO_2 away from the particle surface. PAM-6, a code that describes either laboratory experiments or the reentry situation, was checked out both for reentry and for laboratory experiment cases.

The rate of diffusion of vapor molecules through the boundary layer was compared to the Langmuir evaporation rates. For the conditions of interest in laboratory experiments, it was found that the diffusion through the boundary layer is the limiting process.

Using PAM-6, the oxidation rate for 270-micron-diameter particles in 625 torr of dry air was found to vary from 12 to 20 $\text{mg O}_2/\text{cm}^2\text{-sec}$. For these same conditions, Nelson of Sandia experimentally measured an average value of 16.5 $\text{mg O}_2/\text{cm}^2\text{-sec}$.* For 270-micron particles tested in a 20% oxygen-80% argon mixture, analysis with PAM-6 yielded an oxidation rate varying from 9.6 to 14.0 $\text{mg O}_2/\text{cm}^2\text{-sec}$, while Nelson measured an average of 11.5 $\text{mg O}_2/\text{cm}^2\text{-sec}$.

A computer code was written and checked out for particle trajectory analyses. The equations of programmed motion are applicable to particles (small $W/C_D A$) or to steep reentry conditions. The special-purpose code was written to accomplish trajectory computations with extremely short machine-time expenditure. The program has been given the name PATH (Particle Aerodynamic Trajectory and Heating).

*Staff, "Sandia Corporation Aerospace Nuclear Safety Quarterly Report, April 1 to June 30, 1965," SC-PR-65-345 (July 1965). See also: L. S. Nelson, "Combustion of Zirconium Droplets Ignited by Flash Heating," Presented at 1964 Fall Meeting, Western States Section, The Combustion Institute, Salt Lake City, Utah, October 26-27, 1964 (April 30, 1964)

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V. FUEL PROPERTIES PROJECT

A. THERMOPHYSICAL PROPERTIES

1. Basic Program

No additional measurements were conducted on the primary thermophysical property program covering the 0.50, 1.59, and 1.90 H/Zr materials. However, effort was directed to the analysis and data reduction of previous measurements. A final topical report on the thermophysical properties (i. e., thermal diffusivity, specific heat, electrical resistivity, and thermal conductivity) of SNAP fuel will be published.

The completion of the hydrogen drop calorimeter, by the vendor, was delayed by a series of problems which required step-by-step solution. During testing of the receiver, it became necessary to relocate the receiver calibration heater to avoid arcing problems. The receiver was calibrated and all problems associated with it were eliminated. Following receiver calibration, elevated temperature drop tests were attempted which resulted in burnout of the specimen heater. This burnout was traced to an arcing problem between heater windings which was being corrected by changing to a single helix winding so that adjacent turns are not at a large potential difference. Difficulties were also experienced with sticking of the convection shield shutters. Clearances were being increased to relieve this problem. Delivery of the instrument was anticipated during the next reporting period.

2. AI-BMI Data Comparison Program

With the completion of most of the experimental measurements during the previous reporting period, the major effort during this period was concentrated on the preparation of the topical report covering the unhydrided and 1.81 H/Zr materials. The contribution of Battelle Memorial Institute to this comparison program was received. A final report, co-authored by both AI and BMI, will be published.

B. KINETIC STUDIES

As explained in the progress report for the previous period (NAA-SR-11759), work was completed on the study of the oxidation of solid fuel and nonhydrided

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fuel alloy subjected to a temperature transient typical of atmospheric reentry. Analysis of the data had not yet been completed. However, the results obtained for the alloy are in agreement with those found in the isothermal work, except that considerable nitriding was observed, particularly in those cases subjected to the entire transient. Three distinct regions were observed in metallographic examination of the samples: (1) a porous outer layer of oxide, (2) a columnar-grained phase which appears to be depleted in uranium and may be a Zr-ZrO_2 eutectoid, and (3) the alloy. A thin wave-like phase at the interface between the eutectoid and the alloy (see Figure 6) was shown by microprobe analysis to be rich in uranium and essentially devoid of zirconium; this phase is probably uranium (perhaps uranium oxide) which was originally present in the eutectoid region and precipitated at the interface. No cracking of the samples was detected at magnifications as high as 500X.

When the hydrided alloy ($N_H = 6.35$) was subjected to the temperature transient, extremely rapid evolution of hydrogen occurred for the first 40 to 50 sec which reduced the overall hydrogen content by a factor of approximately two and resulted in extensive cracking of the sample and some spallation of the oxide

Figure 6. Metallographic Cross-Section of Nonhydrided Fuel Alloy (Zr-10 wt% U)

NAA-SR-11884

32

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layer. Almost simultaneously with incandescence of the sample, a flame appeared surrounding the sample. Hydrogen evolution ceased, as evidenced by collapse of the flame, immediately upon turning off the induction unit used for heating the samples. The extent of oxidation was less than in the case of the nonhydride alloy, probably due to the shielding effect of the rapidly evolved hydrogen. This conclusion was supported by metallographic examination which, in several instances, revealed a high nitride concentration adjacent to the columnar-grained phase and below the oxide layer. It was also evident that hydrogen was evolved from all surfaces including those of microcracks which extend to the exterior of the sample. The uranium-rich phase segregation was also evident in the case of the hydrided fuel, as it was in the case of the non-hydrided fuel alloy.

The oxidation rate constants for the nonhydrided fuel alloy were redetermined from the original recorder tracings of the isothermal work, using a least-squares computer program with more data points than were used in prior studies. Although the results obtained for oxidation of the nonhydrided fuel alloy in air and in oxygen are the same, within experimental error, the activation energy for air oxidation appears somewhat lower than for oxidation in oxygen. The results are in fair agreement with those reported by other investigators for the oxidation of zirconium in various media. Comparison of the values obtained for air oxidation of the fuel alloy with those obtained for pure zirconium suggests that uranium causes a marked reduction in the activation energy and a small reduction in the range over which a cubic rate expression is valid. The rate constants were found to fit the following expressions:

1) For fuel alloy (air and oxygen rates combined):

$$\text{Log } K(\text{mg}^3/\text{cm}^6\text{sec}) = 3.63 \pm 0.20 - \frac{(29.4 \pm 0.9)10^3}{4.576T} \quad (527-933^\circ\text{C}),$$

$$\text{Log } K(\text{mg}^2/\text{cm}^4\text{sec}) = 9.31 \pm 1.24 - \frac{(60.5 \pm 7.5)10^3}{4.576 T} \quad (950-1190^\circ\text{C}).$$

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2) For fuel alloy (air oxidation rates only):

$$\text{Log } K(\text{mg}^3/\text{cm}^6 \text{ sec}) = 3.30 \pm 0.22 - \frac{(28.0 \pm 1.0)10^3}{4.576 T} \quad (527-900^\circ \text{C}),$$

$$\text{Log } K(\text{mg}^2/\text{cm}^4 \text{ sec}) = 9.33 \pm 1.55 - \frac{(60.3 \pm 9.5)10^3}{4.576 T} \quad (950-1190^\circ \text{C}).$$

3) For air oxidation of pure zirconium:

$$\text{Log } K(\text{mg}^3/\text{cm}^6 \text{ sec}) = 7.73 \pm 0.27 - \frac{(49.6 \pm 1.3)10^3}{4.576 T} \quad (625-1025^\circ \text{C}).$$

Preliminary experiments were conducted on techniques to study oxidation kinetics of the molten SNAP fuel alloy. Levitation experiments with specially designed induction heating coils were performed and extensive technology in the field of levitation melting was acquired. Samples weighing up to 1 lb were levitated in the R. F. field, but melting on these large samples could not be attained. However, a 10-gm sample of fuel was levitated and remained suspended even after the alloy became molten. Although the work was discontinued at this point, the feasibility of the technique for molten metal oxidation studies was demonstrated.

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VI. REACTOR DISPOSAL PROJECTS

A. ATMOSPHERIC FALLOUT EXPERIMENT

Discussions with Aberdeen Proving Grounds and McGill University personnel revealed that the 16-in. gun at Yuma is essentially operational. A coordinated program of upper atmosphere measurements has been established between Barbados, Yuma, Wallops Island, and Eglin AFB. It was also revealed that the current HARP program wind measurements will not provide the information needed for a fallout experiment program.

B. FALLOUT STUDIES

An advanced parametric analysis of fallout was initiated. The analysis began with the consideration that: (1) for alpha emitters, it is necessary to predict the concentration in air at the breathing level and integrated concentration over time; (2) for gamma emitters, such as Cs¹³⁷ or Ce¹⁴⁴, it is necessary to predict doses and dose rates; and (3) for soluble nuclides, which are readily metabolized, it is necessary to predict concentrations that will occur in major food-stuffs and in typical total diets. The debris particulate concentration at the earth's surface is dependent primarily on: (1) the initial distribution of particle sizes and related radioactivity, (2) the initial cloud geometry (shape) and location in space, and (3) atmospheric parameters (density, viscosity, winds, wind shear, and turbulent eddy effects). Examples of secondary but important elements are: (1) the shape, surface characteristics, and density of the individual particulate; and (2) reentry effects on the atmosphere.

As part of the advanced parametric analysis of fallout, a qualitative review of high-altitude rocket wind observations revealed that distinct low net wind transport conditions prevailed during 6% of the observations. Under conditions of low wind transport, the primary dispersal of debris particulate in the atmosphere will be governed by the particle cloud growth, resulting from the turbulent eddy motion of the atmosphere. Considering the result of experimental measurements in a tunnel of the primary ablation products which point to particles of several hundred microns in size, the need for experimental measurements of the growth of clouds of large particles descending through the atmosphere becomes clearer.

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The results of a study of the Chinese nuclear explosion of May 14, 1965, which have been reported in "SCIENCE," December 3, 1965, afford an illuminating interpretation which supplements the current AI fallout studies of the dispersion of debris particulates injected into the high atmosphere by reentry ablation. About 48 hr after the Chinese nuclear explosion, dry fallout from the stratosphere was detected at Tokyo, Japan. Assuming that the original altitude of the nuclear debris was the order of 100,000 ft, the dry fallout at Tokyo corresponds to that expected from the gravitational settling of particles of about 50-micron diameters. A confirmation of the size of the dry fallout at Tokyo can provide important experimental evidence confirming the postulated AI large-particle fallout model. Tokyo was some 2500 mi downwind from the explosion. Information concerning particulate size was requested.

C. OCEAN WATER CONTAMINATION STUDY

The ocean water contamination problem was being evaluated. Approximately 65% of the earth's surface can be considered "deep ocean" for the disposal of dense ($> 1.2 \text{ gm/cm}^3$) solid objects. Materials deposited on the floor of the "deep ocean" have no foreseeable opportunity for endangering humans. The ocean covering the other 10% of the earth's surface is not completely safe for disposal of hazardous solids.

The maximum permissible concentrations of various isotopes in sea water were calculated using the National Academy of Sciences models. The MPC_s values are much lower than the corresponding limits for drinking water (MPC_w). Direct comparison suggests that a release to the ocean might be more hazardous than release to a reservoir. This untenable suggestion indicates that the MPC_s values are of limited value and that a thorough study will be required before hazard index values for ocean release can be substantiated.

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VII. REACTOR TRANSIENT PROJECTS

A. SNAPTRAN-2 EXPERIMENT

Following several successful dry-run tests, the SNAPTRAN-2 destruct test was conducted on January 11, with T-0 occurring at 0952 MST. Figure 7 is a photograph of the reactor and support structure mounted on the test dolly as they appeared before the destruct test. Figure 8 is a close-up view of the reactor, control drums and drum shafts, and part of the instrumentation. Figure 9 is a view looking downward onto the top of the reactor as reflected through the EG&G mirror mounted at the top of the support structure (see Figure 7).

As viewed on TV monitors in the IET area, it appeared that the flash and cloud accompanying the destruct test (see Figure 10) dissipated from the reactor area within less than a minute. There were several localized fires burning within the cube structure of the reactor; these fires burned out within a few minutes. Debris was scattered on the floor of the test cell area.

On the first day following the test, AI, PPCo, and LASL personnel toured the test area. Although limited access was permitted in the test cell near the reactor, the following items of interest were noted (see Figure 11):

- 1) The reactor support structure was intact with the four drive machines hanging in place.

- 2) The reactor, drums, drum shafts, and drum towers were gone from the structure.

- 3) Numerous pieces of beryllium from the external reflector, drums, shims, and internal reflectors were found throughout the area at distances up to approximately 250 to 300 ft from the reactor. Miscellaneous brackets, light fixtures, and other objects were also strewn about within this same radius of the reactor.

- 4) Fuel fragments ranging from minute particles up to about 3/4 in. in size were found throughout the area. The majority of the visible material remained on the test dolly and test cell floors.

- 5) Small pieces of torn fuel cladding were also detected. These were severely mangled.

NAA-SR-11884

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Figure 7. SNAPTRAN-2 Reactor and Support Structure in Test Cell

NAA-SR-11884

38

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Figure 8. Close-Up View of SNAPTRAN-2 Reactor

4-29-66

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NAA-SR-11884

39

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4-29-66

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Figure 9. SNAPTRAN-2 Reactor as Reflected Through Mirror
Mounted Directly Above Reactor

NAA-SR-11884

40

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Figure 10. SNAPTRAN-2 Destruct Test

NAA-SR-11884

41

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7611-01244

Figure 11. SNAPTRAN-2 Test Area After Destruct Test

NAA-SR-11884

42

CONFIDENTIAL

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6) The upper grid plate was located on the beam adjacent to the test cell area at a distance of about 50 ft from the reactor and at about the same elevation as the reactor. The grid plate was mangled but still retained some of the upper fuel indexing pins in the grid holes.

7) Three of the drum shafts were lying on the test cell floor adjacent to the test dolly. These shafts were bent into a horseshoe shape. The fourth drum shaft and the four tower assemblies were not detected on this first tour.

8) The EG&G mirror directly above the reactor and a PPCo mirror approximately 100 ft away had been shattered by flying debris. These mirrors had been used for photographing the destruct test.

9) Penetrations through the heavy mesh screen which stood between the test dolly and the IET test cell furnace were noted.

General cleanup of the IET was undertaken and was still in progress at the close of this reporting period. Preparations were being made by PPCo to mothball this facility.

Fuel debris from the destruct test was awaiting shipment to the AI Canoga Park facility for analysis.

B. ANALYSIS

1. Analysis of SNAPTRAN-2 Destruct Test

The SNAPTRAN-2 destruct test was conducted on January 11, 1966. Figure 12 shows power traces obtained from three nuclear detectors and indicates that the theoretical predictions based on a destruct model for an equivalent spherical reactor are in good agreement with the experimental results. The asymptotic period for the SNAPTRAN-2 test was found to be 206 μ sec.

The total reactivity insertion was \$4.96, based on drum calibrations. This compares with \$4.93 computed with a 6-group kinetics model (using a generation time of 6.5 μ sec) and \$4.74 computed using a 7-group, reflected reactor kinetics model. The results obtained using drum calibration data will tend to overestimate inserted reactivity due to the effect of flux depression in the reflector region

NAA-SR-11884

43

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4-3-66

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Figure 12. SNAPTRAN-2 Power Traces Obtained From Nuclear Detectors

4-26-66

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Figure 13. Theoretical Radial Power Profile - SNAPTRAN-2

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during transients of relatively short periods. This flux depression effect is illustrated in Figure 13 which shows the theoretical radial power profile for a SNAPTRAN-2 core during steady-state operation and during a 200- μ sec period transient (computed from a $1/v$ poisoned transport calculation).

The total energy release based on integration of the power data ranged from 34 to 60 Mw-sec. The large uncertainty is due to the discrepancy between neutron detector results and the results obtained from energy probe data, which will be discussed later in this section. (Typical theoretical predictions are 39 Mw-sec, using a specific heat derived from the SNAPTRAN-3 transient test and a temperature coefficient of $-0.25\text{¢}/^{\circ}\text{F}$, and 34 Mw-sec, using an Einstein Oscillator fit to ZrH_x specific heat data obtained by Finch and a temperature coefficient of $-0.2\text{¢}/^{\circ}\text{F}$.)

The prompt temperature coefficient ranged from -0.19 to $-0.30\text{¢}/^{\circ}\text{F}$, with the differences again due to the discrepancy between energy probe data and nuclear detector data.

The ultimate shutdown mechanism for the transient was mechanical disassembly caused by a buildup of internal hydrogen pressure. Fuel disintegration occurred before melting ensued.

As indicated above, there are several problems remaining in the analysis of the SNAPTRAN-2 test data, and these will be discussed in the remainder of this section. These problems can be divided into three categories — power normalization, energy probe analysis, and temperature coefficient — and they will be discussed in the order listed.

The first problem in the category of power normalization was the apparent time lag in data obtained from various nuclear detectors. A trip to the NRTS was made by AI personnel to resolve this difficulty, and it was decided that the slowing down and diffusion time in ion chamber enclosure walls was of the proper magnitude to explain the observed time lags. Detectors N-16, N-26, and N-30 were found to exhibit no serious time lag, and these detectors were used in the analysis.

Inconsistencies in the magnitude of peak power from various nuclear detector channels, obtained by using the power calibration factors originally provided by

NAA-SR-11884

45

REF ID: A66666

CONFIDENTIAL

PPCo, were noted (see Table 5); the power calibration factors were later revised by PPCo, with the result that the peak power on all channels is $76,000 \pm 4,000$ Mw using the new power calibration factors. The results obtained using the revised calibration factors are not consistent with results obtained from analysis of energy probe data, and the discrepancy is larger than was generally noted during the SNAPTRAN-1 test series. This discrepancy was being investigated.

TABLE 5
PEAK POWERS FOR SNAPTRAN-2

Detector	Original Calibration (Mw x 10 ⁻³)	Revised Calibration (Mw x 10 ⁻³)
N-3	58	76
N-6	78	80
N-12	72	72
N-16	255	80
N-25	50	72
N-26	46	75
N-27	160	77
N-30	60	79

$\hat{P}$ Normalized to 10% Hydrided
Energy Probes

Amplifier Tap	$\hat{P}_{E.P.}$ (Mw x 10 ⁻³)
10	48
100	54

Attempts to determine a power normalization using 10 wt % hydrided energy probe data led to the observation that 10 and 100% amplifier taps for the same energy probe did not produce the same results (see Table 5). The disagreement between 10 and 100% taps led to the discovery of errors in the digitized data, which PPCo was trying to correct. A new normalization will be performed when the corrected data are obtained.

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Another normalization method that was attempted was the normalization of nuclear detectors for the SNAPTRAN-2 test to energy probe data obtained from tests 332 and 340 (preliminary transients run on the SNAPTRAN-2 assembly). This method would provide normalization under conditions where the possibility of energy probe time lags could be discounted. The results indicated that transient 332 gave normalization factors which were similar to those obtained using the SNAPTRAN-1 series data. Transient 340 gave factors which were widely different from those obtained using transient 332. There appear to be calibration errors in the data from transient 340, and these were being investigated. Until the discrepancy is explained, this method cannot be used.

The next series of problems to be discussed are in the category of analysis of energy probe data. For the SNAPTRAN-2 test, three channels of data from 10% hydrided energy probes are available, indicating temperatures to 1800°F.

The first problem in this area is concerned with the spatial power profile based on energy probe data, as shown in Figure 14. The following can be noted:

Figure 14. Power Profiles for SNAPTRAN-2

(1) the 10 and 100% amplifier taps do not agree, as discussed previously; (2) the 100% tap data agree fairly well with the profile from test 332, a preliminary nondestructive SNAPTRAN-2 transient, and with the theoretical prediction; (3) the inconsistent profiles may indicate nonlinearity, calibration errors, or time lags in energy probe response. It is hoped that the improved data being prepared by PPCo will resolve difficulties (1) and (2) and aid in the resolution of (3).

Several two-dimensional heat transfer calculations were performed to determine whether an appreciable time lag exists between the rise in temperature of a fuel element of a typical

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energy probe and the associated temperature rise of the chromel-alumel junction. These calculations indicate that no time lag exists when a perfect weld between wire and fuel element exists. If a region of low thermal conductivity exists around the region of the spot weld, however, it is possible for a time lag to occur.

The final problem area in interpreting the SNAPTRAN-2 test data involves determination of the temperature coefficient. The magnitude is highly dependent on the normalization chosen. A comparison between theoretical and experimental values for the prompt temperature coefficients for a Be-reflected SNAPTRAN reactor, a water-reflected SNAPTRAN reactor, and the isothermal temperature coefficient for a Be-reflected SNAP 10A/2-type reactor is shown in Tables 6, 7, and 8, respectively. These tables indicate good agreement between experimental and theoretical values for the SNAPTRAN-3 test and for the SNAPTRAN-1 test series. The experimental spread in values observed for the SNAPTRAN-1 series is larger than the uncertainty in the theoretical results. The theoretical results obtained for the isothermal temperature coefficient for a Be-reflected SNAP 10A/2 reactor (see Table 8) were obtained in the same manner as the theoretical results for the SNAPTRAN-1 and -3 tests, and indicated good agreement with experimental results.

The experimental and theoretical values for the SNAPTRAN-2 test disagree markedly. This may be due to one or more effects. These include: (1) the power channels may have been normalized based on total energy release rather than on the basis of actual energy absorbed; (2) incorrect specific heat data may have been used for the power normalization, (3) physical effects, such as rod bowing during the test, have been neglected; and (4) errors in the digital data may cause the large discrepancy noted. The theoretical calculations were being refined to obtain more accurate theoretical estimates for comparison with the experimental results.

2. Calculation of Energy Deposition in SNAPTRAN-2 Core

In the SNAPTRAN-2 test, there were only three energy probes that had the same fuel composition (10 wt % hydrided) as the core. The remainder of the probes had less uranium content (2.5 or 5 wt %), and some of these were unhydrided. A method of obtaining information from the 5 and 2.5 wt % U probes

TABLE 6
PROMPT TEMPERATURE COEFFICIENTS FOR A BERYLLIUM-
REFLECTED SNAPTRAN REACTOR

1. Experimental Coefficient Based on Energy Probe Data:

<u>Source</u>	<u>Temperature Coefficient ($\phi / ^\circ\text{F}$)</u>
SNAPTRAN-1:	-0.13 to -0.20
SNAPTRAN-2:	
10% amplifier tap:	-0.25
100% amplifier tap:	-0.30
10% amplifier tap normalized to a peak power of 76,000 Mw:	-0.20

2. Theoretical Coefficient:

<u>Calculations as of December 1962 ($\phi / ^\circ\text{F}$)</u>		<u>Current Calculations ($\phi / ^\circ\text{F}$)</u>	
	Uniform ΔT	Uniform ΔT	$\Delta T \propto \text{Power}$
Axial expansion:	-0.030 to -0.045	-0.030 to -0.045	-0.036 to -0.054
Spectrum change:	-0.030	-0.065	-0.87
Reflector lag:	not considered	-0.020	-0.020
Total	-0.060 to -0.075	-0.115 to -0.130	-0.143 to -0.161

TABLE 7
PROMPT TEMPERATURE COEFFICIENT FOR A WATER-REFLECTED SNAPTRAN REACTOR

1. Experimental Coefficient Based on Energy Probe Data
($\phi/^\circ\text{F}$):

SNAPTRAN-3 -0.22

2. Theoretical Coefficient (Current Calculations) ($\phi/^\circ\text{F}$):

	Uniform ΔT	$\Delta T \propto \text{Power}$
Axial expansion:	-0.030 to -0.045	-0.040 to -0.059
Spectrum change:	-0.135	-0.162
Reflector lag:	-0.020	-0.020
Total	-0.185 to -0.200	-0.222 to -0.241

TABLE 8
ISOTHERMAL TEMPERATURE COEFFICIENTS FOR A BERYLLIUM-REFLECTED SNAP 10A/2-TYPE REACTOR

1. Experimental Coefficient ($\phi/^\circ\text{F}$):

SDR and FS-3 measurements: -0.21 to -0.25

2. Theoretical Coefficient ($\phi/^\circ\text{F}$):

	Calculations as of December 1962	Current Calculations
Axial fuel expansion:	-0.030 to -0.045	-0.030 to -0.045
Spectrum change:	-0.030	-0.065
Grid plate expansion:	-0.120 to -0.140	-0.120 to -0.140
Reflector coefficient:	not determined	-0.020 to -0.040
Total	-0.180 to -0.215	-0.235 to -0.290

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was developed that considers the problem of "background" energy deposition. The 10 wt % U probes absorb gamma, neutron, and fission product recoil energy in the same ratio as does the fuel, since they have essentially the same composition. Some of this energy is absorbed from neutron and gamma ray flux, while the majority is due to fission product kinetic energy loss. The 5 and 2.5 wt % U probes, on the other hand, absorb only 1/2 and 1/4 as much fission product kinetic energy, respectively, as the 10 wt % U probes, although they absorb nearly the same neutron and gamma energy. These differences must be taken into account when analyzing the energy probe data. Another effect that must be considered is that the gamma and neutron energy is absorbed according to a different spatial distribution than the fission product recoil energy distribution, and these distributions must be computed accurately.

The results of the calculation of energy deposition in a SNAPTRAN core indicate that 204 Mev/fission are created in the core, and that 180.4 Mev/fission are absorbed within the core. The neutron calculations were performed using the FORM code (as incorporated into the THEREDDES programming system^{*}), and the gamma ray calculations were performed using the DTF-II S_N one-dimensional transport code.[†] For neutrons, a consistent B1 slowing-down calculation was performed, while a buckling iteration (similar to that employed for neutron calculations) was performed for the gamma ray calculations; all gamma ray flux calculations were performed using the S_4 approximation, and the scattering cross-sections were represented by the first two terms of a series expansion in Legendre polynomials (the so-called P_1 approximation). The multi-group gamma ray cross-section data used with DTF-II were obtained by processing microscopic gamma ray data with the GAMLEG computer program.[§]

*R. A. Blaine, "THEREDDES - Atomics International Thermal Reactor Design System," AI-CE-MEMO-11 (1966)

†W. W. Engle, et al., "DTF-II, A One Dimensional Multigroup Neutron Transport Program," NAA-SR-10951 (March 25, 1966)

§K. D. Lathrop, "GAMLEG-A FORTRAN Code to Produce Multigroup Cross Sections for Photon Transport Calculations," LA-3267 (April 1965)

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A summary of the energy sources and of the energy deposition in a SNAP-TRAN core is shown in Table 5. Fission product decay gammas, as well as beta energy, and neutron energy arising from fission product decay were not included in the energy deposition calculated for the SNAPTRAN-2 test due to the short time duration of the transient. It was felt that these sources would appear after the SNAPTRAN-2 transient had terminated.

Fission product energy deposition, neutron energy deposition, and gamma ray energy deposition as a function of radius are shown in Figures 15, 16, and 17, respectively.

Figure 15. Fission Product Kinetic Energy Loss - SNAPTRAN-2

NAA-SR-11884

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Figure 16. Neutron Energy Deposition - SNAPTRAN-2

Figure 17. Gamma Energy Deposition - SNAPTRAN-2

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Figure 18. Reactivity and Geometry Changes
(2.0-in. Axial BeO Reflector)

NAA-SR-11884

54

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VIII. CRITICAL CONFIGURATION PROJECTS

Intrinsically subcritical designs were studied in a medium power (~ 600 kw) shadow-shield application, with fuel rod diameters equal to that of SNAP 8. From nuclear considerations, the power capability is determined mainly by the core composition and the excess reactivity of the reactor. For the purpose of determining intrinsically subcritical designs, the radial beryllium reflector was assumed to have been ejected before or upon introduction to the water environment. Geometry variations in core length, radius, and axial reflector dimensions establish a family of reactor geometries with different reactivities in a water environment. One family of geometries, with 2.0 in. of axial reflector, is shown in Figure 18. For each core geometry, a particular thickness of radial beryllium reflector will provide a given excess reactivity for operation. These are shown in Figure 18 also. Note from Figure 18 that all designs to the left of the curve, "\$0 Reactivity in Water," are intrinsically subcritical.

One important consideration is the effect of intrinsically subcritical design limitations on the power system weight. The variations of reactor-shield system weights for designs that are \$3.0 subcritical in water are shown in Figure 19. These curves show a range (with a minimum) of system weights over the range of core geometries. These intrinsically subcritical designs are ~ 200 lb (13%) heavier than systems that are \$9.0 supercritical in water. The major conclusion is that intrinsic subcriticality will not be a major effect on the power system weight in medium power, shadow-shield systems. Previously, a similar conclusion was reached with intrinsically subcritical, low-power systems, with fuel rod diameters equal to that of SNAP 10A. The changes in weight, for a 550-lb system that is \$12 supercritical in water, is shown in Figure 20.

One consideration in these studies is the adequacy of the analytical models to predict the effect of geometry changes (see Figure 18) on intrinsically subcritical designs. Critical geometries in a water environment with variations in core length, radius, and BeO axial reflector dimensions were determined

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Figure 19. System Weights of Intrinsically Subcritical Designs for Medium-Power Systems (~600 kw)

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Figure 20. System Weight Changes of Intrinsically Subcritical Designs

experimentally. The SCA-5 fuel pellets were used. These experimental results are compared in Figure 21 with predictions using the same analytical model that was used in the intrinsically subcritical design studies. The similarity in shape and values of the experimental and analytical curves supports the general adequacy of the analytical models to predict constant (critical) reactivity geometries.

Figure 21. Geometry Experiments in Water Environments

The intrinsically subcritical studies in Figure 18 also require the prediction of the reactivity changes associated with geometry changes — i. e., how a design variation can affect intrinsic subcriticality. Incremental reactivity effects of fuel height and BeO axial reflector were studied experimentally. Preliminary comparisons indicate that analysis adequately predicts the fuel height changes but overestimates the reactivity effect of BeO axial reflector by ~50%. These analytical models will be studied later in the program.

Axial and radial flux distributions were obtained in a number of the critical geometries for future evaluation of analytical models.

An additional experiment studied the reactivity effect resulting from rearrangement of the outer fuel elements from a hexagonal array to achieve a more compact core, in terms of locating the outer fuel elements closer to the core center. This is accomplished by moving elements from the corners of the hexagon to the flats and results in a smaller circumscribed core diameter. Only small variations in reactivity were observed. The hexagonal array was the most reactive. These local perturbations cannot be analyzed with simple analytical models, but these experiments are adequate to show that the effects are minor.

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IX. END-OF-LIFE SHUTDOWN PROJECT

The results of and the experimental procedures for annealing tests performed on U-Zr-H - T, 0.15 wt % carbon-modified fuel containing ${}^3_2\text{He}$ were reported in the progress report for the previous reporting period. Four of these samples cracked during the 22-hr annealing cycle subsequent to the formation of $3.5 \times 10^{19} {}^3_2\text{He}$ atoms/cc. In an effort to duplicate this occurrence, additional fuel-swelling samples were prepared and subjected to an identical thermal cycle. These samples were found to be free of surface cracks after annealing. Hydrogen compositions, helium concentrations used, and density data obtained in these tests are presented in Table 9.

TABLE 9
RESULTS OF 1500°F ANNEAL OF FUEL-SWELLING SAMPLES

Sample Number	$\frac{\text{H} + \text{T}}{\text{Zr}}$	${}^3_2\text{He}$ Concentrations at Time of Anneal (atoms/cc $\times 10^{19}$)	Time at Temperature (hr)	Change in Density (gm/cc + 6 mg/cc)
19	1.63	3.5	24	-0.010
20	1.63	3.5	24	-0.013
21	1.62	4.5	24	-0.013
23	1.62	3.5	24	-0.010
24	1.62	3.5	24	-0.012
25	1.62	3.5	24	-0.010
26	1.62	3.5	24	-0.009

No conclusive evidence could be given at this time to explain the cracking of the previously annealed specimens. However, based on the condition of the samples listed in Table 9, it does seem that it may have been the result of some anomaly occurring during the hydriding and tritiding process rather than the direct result of helium bubble formation. At any rate, the recommended tritium loadings* under consideration will form considerably smaller ${}^3_2\text{He}$ concentrations than present in the specimens tested here.

*The SNAP 8 reactor, assuming the tritium is placed uniformly in all fuel rods, will form 0.8×10^{19} atoms/cc of ${}^3_2\text{He}$ (natural decay) after 12 yr.

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As can be seen in Table 9, these specimens had experienced a negative change in density ranging from 0.009 to 0.013 gm/cc. This represents a $\Delta V/V$ of 0.15 to 0.21%. A fair number of U-Zr-H samples containing T and ${}^3\text{He}$ have been tested in out-of-pile annealing experiments. As reported here and in previous progress reports, little or no swelling occurred in these samples.

Figure 22 is a schematic of the gas release apparatus that was fabricated to measure the quantity of ${}^3\text{He}$ released from tritided U-Zr-H fuel specimens at reactor operating temperatures.

Gas samples (mixtures of ${}^3\text{He}$, T, HT, and H) will be extracted from the retort portion of this system and will be analyzed by means of mass spectrometry to measure the quantity of ${}^3\text{He}$ released. Several gas samples will be taken during the course of an annealing cycle to obtain a measure of ${}^3\text{He}$ released as a function of time. By backfilling the manifold of the apparatus with hydrogen, any number of gas samples can be taken without altering the hydrogen composition of the specimen.

This equipment was fully constructed and checked out. However, the actual experiments had not yet been initiated.

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Figure 22. Gas Release Apparatus

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