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PROGRESS REPORT
SNAP AEROSPACE NUCLEAR SAFETY PROGRAM
APRIL - JUNE 1966
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AEC Research and Development Report

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I. PROGRAM SUMMARY FOR FY 1966

This section summarizes the significant accomplishments in the Aerospace Nuclear Safety Program at Atomics International in FY 1966. The reports published in FY 1966 are listed in the bibliography at the end of this report.

A. REENTRY AND ABORT STUDIES

1. Reactor Disintegration Projects

The testing phase of the Reactor Ablation-Disintegration Experiment (RADE) conducted in the NASA-Ames wind tunnel facility was completed. The final two ablation models (RADE-A and RADE-B) were successfully tested at a 30-degree angle of attack. Although neither model ablated much beyond the grid plate, a number of fuel elements did ablate partially. This was also the case in the zero-degree angle-of-attack runs. The data obtained (thermocouple outputs, pyrometer output, and film coverage) were in the process of being analyzed. Also, one of each model was disassembled for physical and metallurgical examinations. Initial comparisons between experimental results and pretest predictions showed generally good agreement.

The test phase of the aeroheating test conducted in the 48-in. hypersonic shock tunnel at Cornell Aeronautical Laboratory was completed. The test series ran very smoothly and based on the preliminary data, excellent aerodynamic heat transfer distributions for the continuum regime were obtained for the one-fifth scale SNAP reentry configuration.

Preliminary analytical models were developed to represent each stage in the sequence of events that a SNAP system undergoes during orbital reentry into the earth's atmosphere. The various phases of the reactor and vehicle reentry disintegration analysis that were investigated may be summarized as follows:

1) A first-phase analytical model was developed to represent the initial reentering package. Using this model, the dynamics of reentry and the altitude of reactor system separation from the parent vehicle were established.

2) An initial study was conducted to determine an optimum SNAP reactor system configuration, basically composed of a SNAP reactor, shadow shield, and aerodynamic skirt. The effect of the presence of an aerodynamic skirt on

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the reactor system's stability was investigated. Initial studies of the ablation characteristics of the reentering SNAP system and their effect on disintegration of the attached reactor were completed.

3) An analytical model was developed to represent a SNAP reactor upon reentry to the earth's atmosphere. Using this model, a preliminary parametric study was conducted to determine the probable mode of reactor disintegration under ideal head-on heating conditions. The results of this analysis were used as the initial conditions of a fuel element bundle ejection study.

4) A preliminary dynamic and thermal analysis was made to represent the ejection of the reactor core bundle from the containment vessel, and a preliminary model was devised to represent this step in the reactor system disintegration sequence.

5) A transient temperature distribution analysis of SNAP reactor cores (or fuel element bundle) during atmospheric reentry was made, taking into account various modes of tumbling (or flight orientation) and the effect of different release altitudes. The times (and altitude drop) required for separation of the fuel elements were determined under certain conditions of flight orientation and grid plate alignment. The calculations were based on postulating that fuel element separation occurs when the grid plates have melted sufficiently to free the individual elements. The results of these studies can be used to determine the initial conditions for fuel burnup analyses.

Continued progress was made in the development of methods for calculating hypersonic flow with equilibrium and nonequilibrium thermochemistry. Modern methods for predicting aerodynamic heating rates to high-velocity bodies were studied, correlated with each other and with experimental data, and developed into usable forms for rapid analysis. A topical report (NAA-SR-11704) was written to summarize the methods used.

Further development was made on the computer code for calculating aerodynamic heating rates to axisymmetric and two-dimensional bodies in hypersonic flow (HYHEAT-3). The code was modified so that a wider range of body shapes could be analyzed, including those having intermediate shocks along their surfaces.

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Improvements were made in methods for calculating the dynamics of bodies moving through the atmosphere. The three-degree-of-freedom trajectory code obtained from NASA-Langley was adapted for use with the NAA computer system and was given the name, TIP-1 (Trajectory Integration Program, No. 1).

Computational methods were developed for predicting the aerodynamic forces and moments on bodies in hypersonic flow. The resulting computer code, called NEWTON, uses the Newtonian theory for pressure distribution which is valid in hypersonic, continuum flow. Preliminary work was done toward extending the methods for use with free-molecule flow.

The Thermal Analyzer Program (TAP-3) was modified for use with the FORTRAN-IV system, as required for compatibility with the NAA computing system. This code is used extensively for analysis of thermal transients and ablation of reentering bodies. A few minor improvements were made to facilitate the preparation of input data to the code.

Studies were made of the aerodynamic flow and heating phenomena in the transitional regime between free-molecule and continuum flow. The published literature on this subject was studied and correlated, and a working method was selected for calculating the drag and heating of bodies in this regime.

2. Fuel Reentry Burnup Projects

The final phase of the fuel arc-jet 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. A brief summary of the results and the conclusions derived from this experiment are presented in Section III of this report.

A statistical analysis and probability study of the initial ablation of SNAP 8-type fuel elements, released from various altitudes between 200,000 and 300,000 ft, was completed. Deviations in integrated heat required, Q_{REQ} , and in the integrated heat available, Q_{AVAIL} , due to variations in the individual parameters affecting each, were determined. The probability of initial ablation was plotted as a function of release altitude both for random-tumbling and for cross-axial-spinning attitudes. It was shown that the probability curves are essentially linear and that at about 240,000 ft, the probability of nonablation is of the order of one in a million or less.

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Previously, the probabilities of initial fuel ablation at various release altitudes were calculated for SNAP 10A-type fuel elements tumbling at random or spinning cross-axially. This statistical probability analysis was conducted concurrently with analytical studies of the transient behavior of zirconium-uranium hydride SNAP fuel elements under atmospheric reentry conditions. These studies were undertaken to describe the conditions which are necessary for burnup and dispersal of the radioactive fuel material. A topical report (NAA-SR-11502) was published which describes these studies in great detail.

3. Fuel Ablation and Particle Formation Project

This project was begun in FY 1966, and work has been done on two tasks. The first task was a study of the aerodynamic flow regimes and aerodynamic heat, mass, and momentum transfer. The second task was the development of a particle ablation model.

A study of the aerodynamic flow regimes showed that the reentering particles experience flow mainly in the free-molecule flow regime. To describe the heat transfer in the near-free-molecule flow regime, a very simple empirical relationship was developed. Using the Lewis relationship, the expression for heat transfer was modified to obtain the expression for mass transfer. These relationships were incorporated in the analytical model described below.

An analytical model to describe the ablation behavior was developed; this model was developed in several stages. In the first stages, the model included only free-molecule transfer mechanisms, simple relationships for the vaporization of the oxide and metal, and a uniform metal density. In the later stages, the model included some of the heat and mass transfer relationships developed in the aerodynamic flow regimes study portion of this project, and it also included the effect of the different oxide density as well as a simple description of fission product release. The study of fission product release showed that under certain conditions, significant reductions in fission product inventory could be obtained.

Concurrent with the development of this model, another model was developed to describe the behavior of the particles in test environments. In this version of the model, different relationships are used in the description of the heat, mass, and momentum transfer. This version of the model was developed for use in the planning of particle disintegration experiments.

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Using the developed models, several parameter surveys and a preliminary influence coefficient study were made. The parameters studied were initial particle size, release velocity, release altitude, vapor pressure of the oxide, vapor pressure of the metal, emissivity of the oxide, emissivity of the metal, heat of oxidation, mechanism of heat and mass transfer, and the amount of initial oxidation.

In these studies of particle behavior, the size of the particle was based on the Weber criteria. The criteria yield only the maximum particle size and no information on size distribution. Data were obtained from arc-jet test films for use in determining a particle size distribution.

4. Fuel Properties Project

Data reduction on both the basic thermophysical properties studies and the AI-BMI comparison programs was completed. Topical reports covering the basic thermophysical property program^{(1)*} and the AI-BMI data comparison program⁽²⁾ were written and scheduled for publication during the first quarter of FY 1967.

The hydrogen drop calorimeter was completed and prepared for shipment to AI in the first few weeks of July. It will be used in the SNAP Reactor Improvement Program during FY 1967 and 1968 to determine the specific heat of unirradiated delta hydride SNAP fuel and of irradiated SNAP fuel as a function of H/Zr, burnup, and temperature.

Experimental work was completed on the oxidation studies performed by imposing a reentry thermal transient on hydrided and nonhydrided SNAP fuel material. The data reduction for these efforts were completed and a topical report (NAA-SR-11951) was published.

5. Reactor Disposal Projects

The study involving feasibility of orbit modification was completed, and a final report⁽³⁾ was published describing this contracted activity. The safety value of reentry burnup was quantified on the basis of reliability for the deboost systems of this orbit modification and destruct charge study.

All available data relevant to the safety and reliability of the SNAP 8 destruct charge system were collected. This summary of current data which includes

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present state-of-the-art analytical methods supported by experimental correlations brings the project to a point where application of these techniques will provide quantified safety results.

The radiological aspects of the reentry burnup of SNAP reactors were studied and a topical report on the subject (NAA-SR-11761) was published. This study led to recommended limitations on this disposal technique which would ensure no undue hazard to the general public.

B. NUCLEAR STUDIES

1. Reactor Transient Projects

A complete data reduction and analysis of the remainder of the SNAPTRAN-1 test series was completed. This included all the transients from No. 180 to No. 256. A revised analysis of the initial step test series was also completed, using the improved parameters and techniques which evolved as the analysis proceeded to its later stages.

The basic kinetics parameters, such as prompt neutron lifetime and prompt fuel temperature coefficient, were determined from nondestructive transients of much shorter periods and higher temperatures and heating rates than has previously been possible. An evaluation of the applicability of the spatially independent kinetics model was made for reactivity insertions up to \$4.10. Also, an evaluation of the time response of the data acquisition and recording equipment was made in rehearsal for the short-period SNAPTRAN-2 destructive test, which was conducted in the third quarter of FY 1966. A topical report (NAA-SR-11906) describing both the SNAPTRAN-1 kinetics experiments and the SNAPTRAN-2 destructive experiment was published at the close of the fiscal year. A topical report on the analyses was being prepared for scheduled publication in the second quarter of FY 1967.

Analysis of the data from the SNAPTRAN-2 test showed that ultimate shutdown was again (as in SNAPTRAN-3) caused by fuel disintegration due to the buildup of internal hydrogen pressure in micro-voids in the fuel. The total energy release was in agreement with that predicted by the theoretical model developed in this program.

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The results from the analysis of these tests were shown to be in general agreement with those expected, except for the temperature coefficient. The temperature coefficients determined from all the short-period SNAPTRAN tests were found to be somewhat higher than might be expected, based on previous experiments and theoretical considerations.

A detailed evaluation of the temperature coefficient results obtained from the SNAPTRAN data analysis was in progress. A correlation between these results and theoretical predictions were being made in an attempt to bring theory and experiment into agreement. This will include modifications of the theoretical model, if dictated by the results.

An investigation of how reflector neutron thermalization delays affect the determination of temperature coefficient in short-period transients was also in progress. This will entail the refinement and application of a spatially dependent kinetics model being completed at the close of the fiscal year.

2. Critical Configurations Projects

The effect of intrinsic subcriticality on the power, temperature, and lifetime of an instrument-rated power system composed of fuel rods of the composition and diameter of those in SNAP 10A was studied. These results were combined with system weight studies of intrinsically subcritical designs (performed in FY 1965) to form an evaluation of the overall effects of intrinsic subcriticality on relatively low-power systems (~100 kwt).

Intrinsically subcritical reactor designs for higher-power (~600 kwt) systems, composed of fuel rods of the composition and diameter of those in SNAP 8, were determined. Variations in core geometry and/or the use of gadolinium poison were considered. The increased nuclear effectiveness of a predominately thermal poison (gadolinium) that results from increasing the neutron thermalization by the presence of water provides a means to enhance intrinsically subcritical reactor designs. The effect of the design changes needed for intrinsic subcriticality on the power, temperature, and lifetime, and on the reactor shield system weight for an instrument-rated shadow shield, were determined.

Experiments were performed to study the effect on criticality in a water environment of variations in core diameter and length and the use of axial BeO reflectors. These experiments verified, in general, the adequacy of calculational models used in the analysis. A topical report⁽⁴⁾ will be published early in FY 1967.

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Analysis has indicated the importance of core composition on intrinsic subcritical designs. Another concern is the variation in the amount of water flooding, and the corresponding reactivity effect, that results from variations in rod lattice spacing that is dictated by power considerations in some reactor designs. Accordingly, experiments were conducted to study these effects in a SNAP assembly.

A critical experiment was designed to study the reactivity capabilities of long-thin-core and thick-reflector designs that are necessary for optimum intrinsically subcritical designs.

3. End-of-Life Shutdown Project

Phase I of this program consists of a series of experiments designed to investigate the various effects associated with tritium additions to fuel. The results of these experiments are summarized as follows:

1) Comparative dissociation pressure tests on $\text{ZrH}_{1.60-1.85}$ and $\text{ZrH}_{1.60-1.85}$ containing tritium concentrations greatly in excess of the tritium loading needed for SNAP reactors were completed. The data obtained indicate that these tritium concentrations will not measurably alter the total dissociation pressure of SNAP hydride fuel. Additional dissociation pressure data showed $\text{ZrT}_{1.70}$ to have a 40% higher dissociation pressure than $\text{ZrH}_{1.70}$ over the range of temperatures and pressures investigated.

2) Fuel swelling experiments revealed that the ${}^3\text{He}$ produced by any of the desired tritium loadings should not add significantly to fission-gas-induced fuel swelling during the mission lifetime.

3) Gas release measurements were being made to indicate the quantity of helium released from the fuel at reactor operating temperatures.

4) Tritium has been shown to redistribute uniformly in 50 hr at 1300°F when initially contained in an isolated portion (on one end) of the fuel rod.

Further development and demonstrations of process feasibility will be continued into FY 1967.

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II. REACTOR DISINTEGRATION PROJECTS

A. EXPERIMENTS

1. Reactor Ablation - Disintegration Experiment (RADE)

An initial RADE test calibration run was made on May 9. The resulting test conditions were very close to those specified. The stagnation enthalpy and pressure were 7500 Btu/lb and 0.05 atm, respectively.

The testing of a wooden model on May 13 was successful and gave no indication of flow blockage. The thermocouple mounted in the tip of the center NaK cap read out for approximately 5 sec, providing a very adequate checkout of the data acquisition system.

The calorimeter model runs were then conducted and all were highly successful. The first run was made with the dome head. The data received were excellent and well within predicted values. Two runs were made with the SNAP 10A head and both yielded equally excellent and repeatable data. The final runs were made with the SNAP 8 head; once again, the data were well within predicted results.

The final two ablation models (RADE-A and RADE-B) were successfully tested in the NASA-Ames wind tunnel facility at a 30-degree angle of attack on May 20, thus completing the testing phase of the experiment. Figures 1 and 2 show the models installed in the tunnel before the start of their respective runs. Figure 3 is a photograph of the RADE-B model taken during the run. Figure 4 shows opposite views of the RADE-B model taken after the run.

For both models, the total run time was 15 min and neither ablated much beyond the grid plate, which was also the case at 0 degrees angle of attack. A number of fuel elements, however, did ablate partially (see Figures 5 and 6). The data received consisted of all thermocouple outputs, pyrometer output, and film coverage (24 and 400 ft/sec).

Two of the RADE models were disassembled for physical and metallurgical examinations. The first was a RADE-B model, which was tested at 0 degrees, and the second was a RADE-A model, tested at 30 degrees. Several wafers were cut from selected fuel (ZrH) elements to determine hydrogen content. Some of

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Figure 1. RADE-A Model in Tunnel Before Test Run
(angle of attack = 30 degrees)

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Figure 2. RADE-B Model in Tunnel Before Test Run
(angle of attack = 30 degrees)

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Figure 3. RADE-B Model During
30-degree Angle-of-Attack Test Run

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Figure 4. Two Views of RADE-B Model After 30-Degree Angle-of-Attack Test Run

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Figure 5. RADE-A Model After Ablation Run

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Figure 6. RADE-B Model After Ablation Run

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Figure 7. Hypersonic Shock Tunnel Used in Aeroheating Test

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the metal flowback (molten and resolidified) was also broken away to determine its composition.

Results of the experiment were being correlated to the analytical results of the RADE-B 30-degree angle-of-attack case. Good correlation was obtained for all of the external thermocouples on the top head and NaK pipe, with the exception of the portion of the experimental model around heat sensor G. At this heat sensor location (interface of head and vessel), an exceptionally high heat flux was measured, which is difficult to duplicate with the analytical model. Work was initiated on the heat flux distribution to be used for correlating the RADE-B head-on heating case.

The millivolt-vs-time traces from the various thermocouples on the RADE-A, 30-degree angle-of-attack test condition were being reduced to temperature-vs-time traces.

2. Aeroheating Experiment

The test phase of the aeroheating test conducted in the 48-in. hypersonic shock tunnel (see Figure 7) at Cornell Aeronautical Laboratory was completed. The final number of runs was reduced by three. The three deleted were at the high angles of attack (one at 80 degrees and two at 90 degrees), since the preliminary heat transfer data indicate that flow variation is low at the high angles of attack for this blunt configuration.

Figure 8 is a photograph of the model installed in the tunnel (30-degree angle of attack). Figure 9 is a close-up view of the vessel, head, and NaK pipe portion of the model showing the location and positioning of some of the 44 heat transfer gages.

The first run was performed on June 23. The model configuration was the hemispherical head at zero-degrees angle of attack and proved to be the shake-down run for the test program. Tunnel conditions were not met exactly and heat transfer records were noisy due to a loose cable connection. Therefore, this run was repeated, and all conditions were satisfied. The Reynolds number per foot and Mach number at the test section were 35,000 and 18.4, respectively. The hemisphere stagnation point heat transfer rate derived from the data exhibited excellent agreement with that predicted by the Fay and Riddell correlation.⁽⁵⁾ These heat transfer rates are 28.70 and 28.75 Btu/ft²-sec, respectively. The

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Figure 8. Aeroheating Test Model Installed in Tunnel
(angle of attack = 30 degrees)

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Figure 9. Reactor Portion of Aeroheating Test Model
(showing locations of heat transfer gages)

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heat transfer rates obtained at selected points (body angles of 0, 30, 45, 60, and 90 degrees) on the hemisphere were normalized by the stagnation point rate and compared to the theoretical distribution around a hemisphere predicted by means of the HYHEAT code and the correlation developed by Lees.⁽⁶⁾ These data and the correlations are shown on Figure 10 where very good agreement with theory is seen over the entire range of body angles.

A typical shock wave structure from a schlieren photograph is presented in Figure 11. The model orientation in this run was at a 50-degree angle of attack and zero roll (piping in the shadow of the reactor). The leading edges of the shock waves wrapped around the body are seen in this view normal to the flow. The flow field around the upper portion of the reactor at point A in Figure 11 is three-dimensional around the heat and approaches two-dimensional flow in region B along the cylindrical body. However, the influence of the aerodynamically blunt shield results in the standing normal shock (point C) and the detached curved shock wave (region D) passing over the lower section of the reactor vessel and shield.

The test series ran very smoothly and based on the preliminary data, excellent aerodynamic heat transfer distributions for the continuum regime were obtained for this SNAP reentry configuration.

B. ANALYSIS

1. RADE

All of the RADE calorimeter test results were reduced and converted into heat flux units for each heat sensor location on the various models. Two measurements were taken at each heat sensor location for the head-on and 30-degree angle-of-attack heating cases for both the RADE-A and RADE-B model configurations. These runs showed very good repeatability in the test condition for each case. The calorimeter measurements on the dome-head model gave a value of approximately $73 \text{ Btu/ft}^2\text{-sec}$ as the stagnation heating on a 1-ft sphere, as compared to q_{stag} of $60.0 \text{ Btu/ft}^2\text{-sec}$ which was used in the pretest predictions. A careful evaluation of the experimental results will yield a more accurate value for the experimental q_{stag} .

In general, the RADE-B calorimeter results agree fairly well with the heat flux distributions used in the head-on and 30-degree pretest predictions. The

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Figure 10. Heat Transfer Distribution Around a Hemisphere

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Figure 11. Schlieren Photograph of Aeroheating Test Model (showing typical shock wave structure)

experimental results appear to be somewhat lower than the analytical values used for the NaK pipe portion of the analytical models.

The RADE-A calorimeter test results for both the head-on and 30-degree angle-of-attack cases vary widely from those used in the pretest predictions. The Rhodes and Bloxsom data⁽⁷⁾ formed the basis of the RADE-A pretest heat flux distributions.

The initial experimental temperature results for three ablation cases were converted to temperature-vs-time traces. The three cases considered were the RADE-B head-on and 30-degree angle-of-attack and the RADE-A head-on heating conditions. Only partial data were available on the RADE-B head-on heating case.

From initial comparison of the experimental temperature traces to those of the pretest predictions, it was found that good agreement exists for both RADE-B cases. Wide discrepancies exist between the experimental and analytical results for the RADE-A head-on case.

Effort toward the close of the reporting period was concentrated toward correlating the RADE experimental results to previously developed analytical

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models and toward the development of methods for predicting heating rates over bodies at selected angles of attack.

2. SNAP 8 Analytical Model Development

In order to analytically investigate the aerodynamic heating and meltdown of a reentering SNAP 8 reactor vessel and core, several thermal models were devised for use with the TAP-3F Thermal Analyzer Program; these are described as follows:

1) Model 1 — This model represents the entire reactor core and the reactor vessel, except for the top head. It is made such that it can be used in connection with the thermal model developed for the top head. Variable thermal properties of the stainless steel are taken into account.

2) Model 2 — This is a model in which the entire front grid plate is taken as one node. Heat loss to space and to the reactor core is taken into account. Essentially, this model gives the average grid-plate temperature. The simplicity of this model makes its use desirable for a study in which the various parameters can be varied over wide ranges.

3) Model 3 — This model represents the vessel wall alone, with radiation heat rejection to space and to the reactor core elements. Disconnection of nodes when melting temperature is reached is provided for. Preliminary indications are that meltdown of the vessel wall during head-on reentry (where the total heat input to the vessel wall is from the side) may be difficult.

4) Model 4 — This is a detailed thermal model of the grid plate alone.

A thermal model was also prepared which represents the front head of the SNAP 8 system and the reactor core, grid plate, and vessel. This model, a combination of the models described above, will show the time (altitude) at which the front head will separate from the reactor core and what the temperature distribution will be in the reactor at the time of this separation. A model representing just the reactor core will then be used to determine the thermal conditions in the reactor during the remainder of the trajectory.

Using the analytical model of the complete SNAP 8 reactor, several computer calculations were being made to determine the effect of initial temperature and

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aerodynamic heating on the time and altitude at which the top-head portion of the reactor ablates. The output from these calculations will serve as the input parameters to the analytical model representing the SNAP 8 core and upper grid plate to obtain the effect of initial temperature on the time and altitude of fuel element ejection or grid plate ablation.

3. Thermal Analysis of a Reentering SNAP System

The thermal analysis of a reentering SNAP 8-type reactor system was undertaken. Some preliminary results from trials of the thermal model which treats the grid plate as a single node (thus determining the "average" grid plate temperature) are summarized in Table 1. Note that in the four cases reported in which a reasonable heat loss (both by radiation to space and conduction into the reactor core) is accounted for (Runs B, C, E, and F), the melting temperature is reached at very nearly the same time and altitude.

TABLE 1
PRELIMINARY RESULTS FROM THERMAL ANALYSIS
OF A REENTERING SNAP SYSTEM

Run	Starting Conditions					Melting Temperature (°F)					
						2600		2800		3100	
	t_o (sec)	Alt _o (kft)	T _o (°F)	H _{eff} (Btu/ft ² -sec-°F)	ε	t (sec)	Altitude (kft)	t (sec)	Altitude (kft)	t (sec)	Altitude (kft)
A	1300	307.5	80	0	0	1637	280.5	1659	278.0	1689	274.2
B	1300	307.5	80	0.013	0.7	1839	246.1	1866	238.3	1902	225.7
C	1300	307.5	80	0.013	1.0	1860	240.2	1888	231.0	1925	215.9
D	1640	280.2	1000	0	0	1765	262.4	1779	259.8	1798	255.9
E	1640	280.2	1000	0.013	0.7	1851	242.8	1875	235.4	1906	224.1
F	1640	280.2	1000	0.013	1.0	1867	238.0	1892	229.5	1927	215.0

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III. FUEL REENTRY BURNUP PROJECTS

The fuel arc-jet tests conducted in the NAA-LAD hyperthermal wind tunnel facility were completed during the previous reporting period and were described in the progress report for that period (NAA-SR-11884). A brief summary of the results and the conclusions derived from this experiment are presented in the following paragraphs.

SNAP fuel specimens of various configurations were tested in the NAA-LAD arc-jet under various flow conditions. Both rotating and nonrotating configurations were employed.

Surface flux measurements were made with a special cylindrical calorimeter assembly for each of the twelve flow conditions used. The flow conditions themselves were distinguished in each case by supplementary stagnation pressure and enthalpy measurements. Both axial stagnation-line heating distributions, which were not always uniform, and peripheral heating distributions were obtained from the calorimeter measurements. From the peripheral heating data, an average-to-stagnation-point heating ratio of 0.31 was obtained for a rotating cylinder in cross-axial flow.

The transient behavior of the fuel test specimens in the arc-jet environment was observed and recorded by means of 24- and 400-frame-per-second motion picture film. Generally, it was found that the fuel behavior may be characterized by the following events:

- 1) Heavy zirconium oxide buildup occurred at the surface of the specimens, usually resulting in flaking and spalling of the oxide at high temperatures.

- 2) Hydrogen outgassing was visually observed (in the 24-frame-per-second film) to be generally uniform and continuous along the surface for those specimens which were not severely cracked.

- 3) Completely solid fuel specimens developed a fine network of micro-cracks, but rarely incurred large radial or longitudinal cracks. Such large cracks seemed to be confined to configurations with tungsten rod holders. (Post-test macrographic studies indicated that such cracks emanate from the holes for the holder rod.)

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4) The surface oxide layer was often tenacious enough to inhibit fuel ablation until a substantial portion of fuel material became molten underneath the oxide layer.

5) End or corner heating effects for the 2-in. cylinder specimens were conspicuously absent. This was true for specimens with or without the ceramic end pieces. Much greater heating usually occurred at the axial center, resulting in large temperature variation along the axial length.

Fuel ablation sequences were recorded with 400-frame-per-second motion picture film and with instantaneous photographs from a laser system. A large number of still photographs were made from these films, some of which are shown in Figure 12.

Particle size distributions were obtained from the laser photographs for a fuel specimen ablating in an end-on orientation and in a stationary, cross-axial orientation. Most frequent particle diameters for these cases were found to be about 600 and 450 microns, respectively. However, it was observed in the film data that substantially larger fuel fragments appear to be extruded from rotating specimens in cross-axial flow.

It was found that fuel ablation was not enhanced by surface irregularities, such as grooves or cross-hatches.

Determinations of the fuel surface emissivity were unsuccessful due to poor thermocouple contact caused, at least in part, by fuel shrinking and void formation under rapid heating and dehydrating conditions. Also unsuccessful were attempts to photograph the hydrogen outgassing from the fuel specimens using the laser-schlieren system.

An aluminum particle catcher was designed and successfully employed to collect particulate matter dispersed from the fuel during ablation. Material composition was identified and categorized. Limited particle size determinations were also obtained.

Post-test sectioning and macrographs were made on unablated specimens which had been heated to near melting temperatures. Considerable void and microcrack formation was evident in the macrographs. Fuel material which had melted underneath the oxide layer and resolidified during cooling was

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Figure 12. Sample of Still Photographs Showing the Ablation Sequence of a Fuel Arc-Jet Specimen in Cross-Axial Flow

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identifiable. Surface oxide layer thicknesses measured from 13 to 32 mils for specimens which had been rotated in cross-axial flow. A corresponding front-face oxide thickness for a specimen held stationary in cross-axial flow was found to be about 52 mils. The difference in oxide thickness for the two cases may underlie the gross difference observed in ablation characteristics.

Fuel surface temperature history calculations, using the current analytical model, were found to correlate well with the pyrometer data for those flow conditions in which surface catalycity effects were found to be small. This was true for specimens of both SNAP 8- and SNAP 10A-sized diameters. The gross effect of surface catalycity on the heat flux was scanned, over various flow conditions, using calorimeter heat flux measurements. For this, the calorimeter was coated with materials of known catalytic efficiency magnitude. A significant variation in heat flux with flow condition was observed for these materials.

By comparing the fuel pyrometer data with the analytical calculations, the heating reductions due to the noncatalytic fuel surface were evaluated for each flow condition. These heating reductions were found to be consistent with the corresponding reductions for the coated calorimeters and ranged up to about 30% of the total heating for certain flow conditions. The heating reductions were found to correlate well with the controlling parameters of nonequilibrium boundary layer theory.

It may be concluded that the surface of the fuel does not exhibit perfect catalycity to atom recombination and, as a result, the effects of nonequilibrium chemistry on fuel burnup predictions cannot be ignored.

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IV. FUEL ABLATION AND PARTICLE FORMATION PROJECTS

A. EXPERIMENTS

The analysis of data from the particle photography obtained during the course of the fuel arc-jet experiment at NAA-LAD was completed. A brief summary of the experiment and pertinent conclusions drawn therefrom are discussed, along with the fuel arc-jet experiment, in Section III.

Metallurgical cross-sectioning and examination of a few of the post-test ablation specimens was completed. Macrographs of these samples were taken, along with several measurements of the oxide thickness remaining on the specimens.

Several engineering drawings of the fuel particle experiment apparatus were completed. The remaining drawings were scheduled to be completed during the next reporting period. This will complete the design phase of the particle experiment.

B. ANALYSIS

1. Particle Reentry Behavior

An analysis was made to determine the influence of various parameters on the final radius of the particle. In this study, the influence coefficient was defined as follows:

$$\text{Influence Coefficient} = \frac{\Delta r/r_s}{\Delta P/P_s},$$

where r is the final radius and P is any parameter. The subscript, s , refers to an arbitrary standard case (525-micron-diameter particle released at 177,000-ft altitude with an initial velocity of 14,200 ft/sec). Using this definition, the influence coefficients presented in Table 2 were obtained.

The order of influence of parameters affecting the behavior of reentering SNAP fuel particles was determined by observing the effects of deviations in the parameters on deviations in the final radius. Table 3 shows the order of influence for the altitude-independent terms. Not included in Table 3 are the

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TABLE 2
PARTICLE REENTRY INFLUENCE COEFFICIENTS

Parameter	Standard Value	Influence Coefficient
Initial radius (microns)	262	0.96
Release altitude (ft)	177,000	0.70
"B" coefficient in oxide vapor-pressure relationship ($^{\circ}\text{K}$)	78334	0.44
Oxide density (lb/ft^3)	342	-0.37
"A" coefficient in oxide vapor-pressure relationship	24.66	0.36
Metal density (lb/ft^3)	425	0.31
Gamma	1.4	0.24
Release velocity (ft/sec)	14,200	-0.17
Oxide emissivity	0.5	0.12
Heat of oxidation (Btu/lb of Zr)	5150.0	-0.032
Specific heat of air (based on value of R) ($\text{ft}^2/\text{sec}^2 - ^{\circ}\text{R}$)	1716.0	0.030
Initial temperature ($^{\circ}\text{F}$)	3200	-0.026
Heat of oxide vaporization (Btu/lb of Zr)	2200	0.026
Initial oxide fraction	0.0	0.022
Particle specific heat ($\text{Btu}/\text{lb} - ^{\circ}\text{F}$)	0.07	0.011
Model time interval (sec)	0.01	-0.0033
Air temperature ($^{\circ}\text{R}$)	481	-0.0026
Maximum allowable temperature change per time interval ($^{\circ}\text{F}$)	0.02 T	0.00043

effects of deviations in the initial radius and in the altitude of release. These two effects are functions of the altitude. Deviations in release altitude arise from uncertainties in the fuel element ablation studies and from the fact that a finite time is required to ablate a fuel element, and during this time the particle release altitude is changing.

Deviations in the initial particle radius are due to the size distribution of the released particles. Table 4 gives the range in final particle sizes for ablating SNAP 10A fuel elements released at various altitudes. In this table, it assumed that the radius of the particles ranges from 250 microns up to the critical radius.

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TABLE 3
DEVIATIONS IN FINAL RADIUS DUE TO
DEVIATIONS IN PARAMETER VALUES

Order of Influence	Parameter	Influence Coefficient	Standard Deviation (%)	Radius Deviation (%)
1.	Oxide Emissivity	0.12	50	6
2.	Initial Oxide Fraction	0.022	100	2.2
3.	Initial Velocity	-0.17	10	-1.7
4.	Metal Density	0.31	5	1.55
5.	Vapor Pressure Density	0.36	3.7	1.33
6.	Vapor Pressure Activation Energy	0.44	2.7	1.18
7.	Heat of Oxidation	-0.082	10	0.82
8.	Oxide Density	-0.37	2	0.74
9.	Particle Specific Heat	0.07	50	0.35
10.	Model (PAM-6)	0.003	100	0.33
11.	Heat of Oxide Vaporization	0.026	10	0.26
12.	Gamma	0.24	0.8	0.19
13.	Specific Heat of Air	0.03	5	0.15
14.	Initial Temperature	0.026	6	0.135
15.	Air Temperature	0.0008	100	0.08
	All of the above			7.01

Final size-ranges for particles coming from ablating SNAP 8 fuel rods were obtained. These final size-ranges were obtained by means of the PAM-6 code. The initial size-range was assumed to be from 250 microns to the critical radius. The critical radius was determined from the conditions existing at the time of fuel element ablation.

A study was completed in which the effect of fuel particle surface tension on particle instability was analyzed. Figure 13 shows the critical fuel particle radius as a function of particle reentry velocity and altitude for the minimum and maximum values of surface tension, σ .

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Figure 13. Critical Fuel Particle Radius as a Function of Particle Reentry Velocity and Altitude for Minimum and Maximum Values of Surface Tension

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TABLE 4
FINAL PARTICLE SIZES FOR ABLATING SNAP 10A FUEL ELEMENTS

Fuel Element Release Altitude (kft)	Mode of Reentry	Average Initial Radius (microns)	Range of Final Particle Radii (microns)	
275	cross-axial	1165	321	2343
260	cross-axial	839	307	1297
250	cross-axial	620	304	1118
245	cross-axial	576	280	1046
275	random-tumbling	950	309	1829
260	random-tumbling	670	296	1214
250	random-tumbling	490	293	799
242	random-tumbling	428	278	662

Recent experiments by Cornell Aeronautical Laboratory have indicated that the emissivity of zirconium particles in their test facility is 0.90 ± 0.03 . In AI studies, it has been assumed that the emissivity of the particle oxide is 0.5. To observe the effect of the difference, two problems were compared. In these problems, a 525-micron-diameter particle is assumed to be released at 177,000-ft altitude with a velocity of 14,200 ft/sec. Using the different emissivities, the behaviors obtained are summarized as follows:

Emissivity	Radius 10 sec After Release (microns)	Maximum Temperature (°F)
0.5	303.85	5488
0.90	311.57	5114

2. Aeroheating

A simple model was developed during the previous reporting period to determine the heat reduction to a reentering fuel particle due to vapor blocking. A comparison was made between this simple model and an earlier method developed by AI for calculating the heat reduction due to vapor blocking. The comparison was made by calculating the aerodynamic heating to a 10^{-4} -ft-radius sphere at an altitude of 229.14 kilofeet, traveling at a velocity of 20,000 ft/sec

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and at a temperature of 4720°R. Using the simple model, the heat reduction due to the vaporization of ZrO_2 is 6.6 parts per 100,000. Using the previously developed method of calculation, the heat reduction was found to be 3.3 parts per 100,000. This shows that relative to particle disintegration, this model gives conservative results. This model was programmed in FORTRAN-II for inclusion into PAM-6.

Based on previous studies, it is known that a greater amount of ablation takes place for particles released at lower altitudes. For a 525-micron-diameter particle released at 177,000-ft altitude and 14,200-ft/sec initial velocity, the maximum vaporization rate is $0.0663 \text{ lb/ft}^2/\text{sec}$. At this time, the particle temperature is 5500°F and the particle velocity is 12,224 ft/sec. Under these conditions, the model for vapor blocking calculates a heat reduction of 3.5%. For this particular case, this is the maximum reduction; and at other times, the value is considerably less.

3. Fission Product Removal

The PAM-6 subroutine that calculates the amount of fission product removal from disintegrating particles was checked out for two mechanisms (i.e., the removal directly proportional to oxide vaporization and the direct vaporization of the fission products when the oxide coating is removed). For the case approximating the reentry of SNAP fuel particles, the oxide is never completely removed; and a fission product removal is allowed only by removal with oxide vaporization. Analysis has shown that 6.9% of the fission products are removed by this mechanism. Table 5 gives the final activity per particle in microcuries for reentry at various times after reactor shutdown.

TABLE 5
ACTIVITY PER PARTICLE AT VARIOUS TIMES AFTER
REACTOR SHUTDOWN

Decay Time in Orbit (yr)	Beta Activity (microcuries)	Gamma Activity (microcuries)
0	96.0	39.0
1	0.289	0.165
50	0.024	0.014
200	7×10^{-4}	4×10^{-4}

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This analysis was based on a reactor operation of 0.36 watt/cm^3 for 1 yr. The particle considered had a 525-micron diameter and was released from the fuel rod at 177,000-ft altitude at 14,200 ft/sec. The final oxidized size of the particle is approximately 600 microns.

A new model for fission product release was developed and checked. In this model, it is assumed that once the oxide coating on the particle has melted, fission products are allowed to evaporate, provided that the fraction of the particle that is oxide is less than a given value known as f_{ox}^* . With this model, the evaporation of a fission product is given by:

$$\psi_{\text{fp}} = \psi_{\text{fp}}^{\circ} \left(1 - \frac{f_{\text{ox}}}{f_{\text{ox}}^*}\right),$$

where

ψ_{fp}° = the evaporation rate of a fission product ($\text{moles/ft}^2\text{-sec}$),

ψ_{fp} = the Langmuir evaporation rate for the unoxidized fission product ($\text{moles/ft}^2\text{-sec}$),

f_{ox} = the fraction of the fission product that is oxide, and

f_{ox}^* = the maximum fraction of oxide for which evaporation is allowed.

This model is a preliminary attempt to simulate the diffusion of fission products through the oxide layer on the particle. It was checked for arbitrary values of f_{ox}^* . Whenever f_{ox}^* is zero, direct fission product evaporation is allowed only when all of the oxide has been removed. (This is the same as the previous model for fission product removal.) The fraction of initial fission products remaining in the particle after reentry is given as follows:

<u>Value of f_{ox}^*</u>	<u>Fraction of FP Remaining</u>
0.0	0.931
0.1	0.00039
0.25	0.00031
0.5	0.00029
0.75	0.000283
1.0	0.000279

In obtaining these fractions, it was assumed that the evaporating fission product species was unoxidized. A better estimate would be obtained if the evaporation had been based on the evaporation of the oxidized fission product species.

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In the foregoing tabulation, it is seen that if fission products are allowed to diffuse through an oxide layer whose mass fraction is 10% of the particle mass, a considerable reduction in the final fission product is realized. This again points to the necessity of knowing the diffusion of fission products through the oxide layer.

4. Comparison Studies

Using PAM-6, results were obtained for comparison with Nelson's experimental data.⁽⁸⁾ These comparisons were made with different air viscosity relationships and different emissivities. In these comparisons, the viscosity of air was expressed in the following form:

$$\mu = A T^b,$$

where

μ = the viscosity of air (lb/ft-sec),

A = an arbitrary constant,

T = the temperature ($^{\circ}$ R), and

b = a second arbitrary constant.

When the data of McCabe and Smith⁽⁹⁾ are analyzed, one finds that A is 8×10^{-4} and b is 0.527. For the comparisons with experimental data on particle disintegration, arbitrary changes were made in A and b. These changes were completely arbitrary and should not be construed as being representative of errors in either A or b. The values of A and b that were used are as follows:

<u>Case</u>	<u>A</u>	<u>b</u>
1	8×10^{-4}	0.527
2	8×10^{-4}	0.580
3	8×10^{-4}	0.474
4	4×10^{-4}	0.527
5	12×10^{-4}	0.527

The comparison of these various viscosity relationships with Nelson's experimental data is given in Figure 14, where the relative weight is given as a function of time for 270-micron-diameter particles tested in 625 torr of dry air. It is seen in the figure that Case 1 comes the closest to agreement.

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Figure 14. Effect of Air Viscosity on Relative Particle Weight

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Using the viscosity relationship of Case 1, a study was made of the effect of particle emissivity. In this study, the following emissivities were used: 1.0, 0.67, 0.5, 0.4, and 0.3. These values are completely arbitrary and should not be construed to be indicative of errors in the emissivity. In this analysis, it was found that emissivity had little effect on the relative weight as a function of time.

To make these comparisons, it was necessary that vaporization be neglected. A preliminary check of vapor diffusion shows that the vaporization process in these laboratory experiments is limited by the diffusion of the vapor from the particle. In the future, the description should include the diffusion of vapor from the particle.

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V. REACTOR DISPOSAL PROJECTS

A. FALLOUT STUDIES

The arc-jet particle size experimental data were reduced and fit with analytical expressions (see Figure 15) for use in fallout dose calculations. The external radiation field dose from fallout of ablation particles with this particle size distribution was calculated for conditions of zero net wind transport. The result obtained, 2.4 rem equivalent residual dose for a 40-kw reactor, is essentially the same as the result obtained using the BMI particle size distribution.⁽¹⁰⁾ While the AI particles are smaller than the important BMI particles, some 2/3 of the mass was contained in very small (<20-micron) particles in the BMI measurements.

A preliminary evaluation of the hazards as a function of particle size for the reentry of a space vehicle containing radioactivity was made which indicates that: (1) the number of people exposed reduces with increasing particle size, (2) the magnitude of the exposure increases with increasing particle size, and (3) the type of biological effect under consideration and the variations in preceding relations will be combined to produce the desired functional relation between hazard and particle size.

Radiation doses to the world's population, which would result from the atmospheric disposal of fission products from a nuclear rocket, were calculated. Assuming 5×10^3 -Mw operation for 10 min., the genetic dose from the rocket would be about twice the dose from ablation of a SNAP 10A-type reactor after a year in operation. The rocket fission products could produce about one genetic injury in all future generations of the world's population, based on the Federal Radiation Council model.

B. DISPOSAL MODES STUDY

The basic flight mechanic relations were evaluated for the various disposal modes (earth escape, orbit enhancement, or reentry). This evaluation was based on a reactor system in the power range of the SNAP 8 (35kwe) and 1966 state-of-the-art engineering analysis and disposal systems. This leads to the possibility of developing a correlation of disposal weight requirements for reentry conditions. The conditions of interest are for cases where the entire

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Figure 15. SNAP Fuel Ablation
Particle Size Distribution
Based on Data From
Arc-Jet Experiments

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Figure 16. Velocity Required for Deboost From Orbit

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reentry event occurs over a segment of the earth less than 180 degrees. The objective of this is to increase reliability of the impact point definition and make the study as general as possible.

A study of the quantitative material required to determine system design tradeoffs and cross-coupling effects was nearing completion. These analyses include propulsion weight as a function of system and velocity increments required for orbit deboost over an earth arc segment ranging from 30 to 180 degrees (see Figure 16). This velocity correlation was derived to allow intelligent qualitative estimates on reliability, effect on operating system, effect on configuration, and cost of recovery dependent on propulsion requirements and circular error probable (CEP) at impact.

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VI. REACTOR TRANSIENT PROJECTS

A. EXPERIMENTS

1. SNAPTRAN-1 Post-Test Evaluation

The post-test evaluation of SNAPTRAN-1 includes both destructive and non-destructive examination of five fuel elements positioned in the core as shown in Figure 17. Elements designated E-255 and E-256 were subjected to permeation tests. Elements designated E-260, E-211, and E-192 were subjected to destructive examinations.

The elements as received from the Phillips Petroleum Company are shown in Figure 18. Pertinent pre-irradiation data for the five elements are summarized in Table 6.

Visual examination of the five intact elements revealed no gross anomalies. Diametral measurements across the cladding OD were taken at equal intervals along the length of each element. The maximum clad hoop strain based on mean pre- and post-diameter measurements was as follows:

<u>Element</u>	<u>Percent Hoop Strain</u>
E-256	0
E-211	0.5
E-192	0.24
E-260	0.24
E-255	0.96

Two SNAPTRAN-1 fuel elements (E-255 and E-256) were permeation tested. Plans called for tests at 1200°F, but both elements were leaking at rates greater than the 8.8-cc(STP)/hr instrumentation limit. The temperature of the fuel elements was reduced to 1100°F, and the measured hydrogen loss rate of each element at this temperature was 8.0 cc(STP)/hr. Based on these data, the hydrogen loss rates at 1200°F were extrapolated to be of the order of 28 cc(STP)/hr-element. At acceptance, these elements had hydrogen permeation rates of 0.74 and 0.48 cc(STP)/hr at 1200°F. The occurrence of damage to the ceramic hydrogen barrier and to the cladding is obvious from the above data. The final

(a) DESTRUCTIVE TEST, i.e., FUEL AND CLAD
METALOGRAPHY AND BURNUP ANALYSIS
(b) INSTRUMENTED ELEMENTS
(c) PERMEATION TEST

LEGEND
X X = CORE POSITION
Y Y Y = ELEMENT NUMBER

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Figure 17. SNAPTRAN-1 Fuel Element Core Schematic

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Figure 18. SNAPTRAN-1 Fuel Elements as Received at AI

TABLE 6
PRE-IRRADIATION FUEL ELEMENT DATA - SNAPTRAN-1

Parameter	E-192	E-211	E-255	E-256	E-260
Fuel rod number	620-3	577-4	651-6	652-4	662-4
Hydrogen (wt %)	1.810	1.820	1.789	1.792	1.810
Carbon (wt %)	0.20	0.44	0.18	0.14	0.185
Cladding diameter (in.)					
Minimum	1.250	1.251	1.248	1.250	1.250
Maximum	1.256	1.255	1.251	1.253	1.252
Fuel column diameter (in.)					
Minimum	1.210	1.210	1.2102	1.2102	1.2103
Maximum	1.210	1.210	1.2102	1.2102	1.2103
Element TIR (in.)	0.002	0.002	0.002	0.002	0.001
Element length (in.)	12.447	12.443	12.454	12.449	12.448
Fuel column length, overall (in.)	12.102	12.098	12.252	12.252	12.250
Average fuel column-to-cladding radial gap (in.)	0.002	0.002	0.0024	0.002	0.003
Permeation rate (cc/hr at 1200°F)	6.58	3.42	0.74	0.48	0.69
Fuel N _H	6.53	6.60	6.48	6.49	6.52
Fuel density (gm/cc)	6.040	6.074	6.064	6.060	6.060

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Figure 19. SNAPTRAN-1 Element E-192 After Disassembly

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Figure 20. SNAPTRAN-1 Element E-211 After Disassembly

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Figure 21. SNAPTRAN-1 Element E-260 After Disassembly

loss rate corresponds to the rate expected through about 80 cm^2 of bare cladding tube under the same conditions. The area of cladding tube of each element is about 300 cm^2 .

Elements E-192, E-211, and E-260 were disassembled to obtain data on the condition of fuel, barrier, and cladding. Visual examination of the disassembled elements (see Figures 19, 20, and 21) showed the fuel to be somewhat cracked in a tangled, hair-like pattern predominantly near the central section of the rods. The barrier material could, in all cases, be easily removed from the clad ID by bending the cladding, thus indicating a poor ceramic-Hastelloy-N bond. In addition, fuel from elements E-192 and E-211 showed evidence of a yellow discoloration located near the central sections. This is typical of a nitriding effect.

Diameter measurements were also made at 0-degree (with an arbitrary reference) and 90-degree orientations along the length of each fuel rod. The fuel rods in elements E-211 and E-260 showed no change from pre-irradiation measurements. The fuel column in element E-192 increased in diameter a maximum of 0.17%, based on mean pre- and post-test measurements.

2. SNAPTRAN-2 Post-Test Evaluation

The post-test evaluation of SNAPTRAN-2 consists primarily of a detailed destructive examination of identifiable debris obtained from elements as shown in Figure 22. Pertinent pre-irradiation data for nine elements from the core, portions of which were under examination, are presented in Table 7.

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(a) SUFFICIENT MATERIAL TO EXAMINE BOTH FUEL AND CLAD
 (b) SUFFICIENT MATERIAL TO EXAMINE CLAD ONLY

XX = CORE POSITION
 YYY = ELEMENT NUMBER

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Figure 22. SNAPTRAN-2 Fuel Element Core Schematic

TABLE 7
PRE-IRRADIATION FUEL ELEMENT DATA - SNAPTRAN-2

Parameter	E-034	E-042	E-045	E-061	E-094	E-097	E-103	E-104	E-283
Fuel rod number	585-6	576-2	577-6	592-3	609-5	607-2	606-2	608-3	652-1
H ₂ (wt %)	1.83	1.80	1.78	1.82	1.82	1.80	1.82	1.76	1.787
Carbon (wt %)	0.385	0.44	0.415	0.435	0.15	0.16	0.19	0.14	0.14
Element OD (in.)									
Minimum	1.252	1.253	1.253	1.254	1.254	1.253	1.252	1.253	1.254
Maximum	1.260	1.255	1.261	1.258	1.257	1.257	1.256	1.259	1.249
Element TIR (in.)	0.010	0.005	0.011	0.008	0.008	0.007	0.006	0.009	0.003
Element ovality (in.)	0.004	0.003	0.006	0.006	0.010	0.006	0.001	0.002	-
Fuel column diameter (in.)									
Minimum	1.2101	1.2103	1.2095	1.2102	1.2100	1.2045	1.2102	1.2099	1.210
Maximum	1.2104	1.2105	1.2100	1.2104	1.2100	1.2095	1.2107	1.2102	1.210
Element length (in.)	12.443	12.447	12.447	12.450	12.437	12.446	12.447	12.448	12.449
Fuel column length (in.)	12.246	12.249	12.247	12.242	12.250	12.251	12.252	12.251	-
Cladding/fuel column radial gap (in.)	0.003	0.004	0.003	0.003	0.004	0.003	0.002	0.002	0.0025
Permeation rate *	2.28	0.67	0.09	1.79	0.04	0.03	0.03	0.02	0.32
Fuel N _H	6.63	6.52	6.45	6.60	6.59	6.52	6.59	6.38	6.47
Fuel density (gm/cc)	6.066	6.083	6.078	6.074	6.057	6.067	6.059	6.067	6.061
Cladding, wall thickness (in.)									
Minimum	0.0149	0.0149	0.0149	0.0149	0.0150	0.0149	0.0150	0.0149	0.0148
Maximum	0.0150	0.0155	0.0150	0.0150	0.0150	0.0150	0.0151	0.0150	0.0150

*Element 283, cc/hr at 1200°F; all others cc/hr at 1100°F.

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Figure 23. Typical SNAPTRAN-2
Unidentifiable Debris

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Figure 24. SNAPTRAN-2 Fuel Debris
(arrow shows typical adhering green spheroid)

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In addition to the indentifiable debris, fragments of fuel elements (primarily fuel) which had been dispersed from the reactor various distances ranging from 70 to 250 ft were obtained. Figure 23 illustrates the type of debris obtained.

Visual examinations of the unidentifiable material revealed highly porous-appearing fuel with adhered ceramic barrier, and spheroidal fragments, green in color, which resembled ceramic coating (see Figures 24 and 25). A photomicrograph of one of these spheroidal particles is shown in Figure 26.

During the next reporting period, specimens of fuel and cladding from selected elements from both the SNAPTRAN-1 and -2 experiments will be examined metallographically to determine fuel structural changes. In addition, selected spheroidal particles observed in the unidentifiable debris from SNAPTRAN-2 will be subjected to electron microprobe analysis. The post-test examination of both experiments is scheduled to be completed during the next reporting period.

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Figure 25. SNAPTRAN-2 "Green Spheroids"
Believed to be Ceramic Coating

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Figure 26. Photomicrograph of Spheroid Specimen
From SNAPTRAN-2 Fuel Debris

B. ANALYSIS

1. SNAPTRAN-1

A comparison of theoretical temperature coefficients with SNAPTRAN and other results was compiled. Some of the results are presented below. In some cases, a range of results is given. This indicates either a band of uncertainty on that item or a variation of the item with temperature.

1) Prompt temperature coefficient for the Be-reflected SNAPTRAN reactor ($\beta/^\circ\text{F}$):

- a) Experimental — SNAPTRAN-1: -0.13 to -0.20
- b) Experimental — SNAPTRAN-2: -0.21 to -0.32*
- c) Theoretical calculation: -0.14 to 0.16

*These results may be in error due to a systematic error in the COMPOST analysis, discussed elsewhere in this report.

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2) Prompt temperature coefficient for the H₂O-reflected SNAPTRAN reactor ($\beta/^\circ\text{F}$):

- a) Experimental - SNAPTRAN-3: -0.22
- b) Theoretical calculation: -0.22 to -0.24

3) Isothermal temperature coefficient for a Be-reflected SNAP 2/10A-type reactor ($\beta/^\circ\text{F}$):

- a) Experimental - SDR and FS-3: -0.21 to -0.25
- b) Theoretical calculation: -0.235 to -0.29.

The agreement between the theoretical and experimental temperature coefficients is somewhat better than has been obtained in past comparisons with SNAPTRAN data. This is primarily due to:

- 1) Use of new spectral coefficient data presented by General Atomics at the recent American Nuclear Society meeting
- 2) Inclusion of the effect of spatial temperature distribution, an effect which has been ignored or under-emphasized in some past tabulations
- 3) Inclusion of an estimate of the effect of departure from spatially dependent kinetics behavior.

A study was being conducted to verify the temperature coefficient results obtained from the sub-prompt-critical SNAPTRAN-1 step tests. In these tests, no suitable temperature data were available for direct use because the internal fuel thermocouples experienced large time lags, while the energy probes experienced significant heat loss. Thus far, the approach has been to correct the energy probe data by applying a simple heat loss model. This approach, however, has only met with limited success. It now appears that a relatively complicated model would be required for an accurate description of the heat transfer occurring during these tests. The new approach is designed to supplement and, hopefully, improve upon the results obtained using the heat loss model.

The approach is to determine calibration factors for several nuclear detectors by correlating the power and energy probe data for those step transients which were sufficiently fast to eliminate energy probe heat losses. These power calibration factors are then applied to the sub-prompt-critical transients under

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consideration. The temperature, as calculated from the normalized power, is then used in the temperature coefficient calculation.

These calculations were performed for the initial SNAPTRAN-1 test series. Normalization factors were determined for four nuclear detectors and are as follows:

<u>Nuclear Detector</u>	<u>Normalization Factors</u>
N-3	1.45 ± 0.10
N-9	1.31 ± 0.06
N-10	1.39 ± 0.04
N-16	1.32 ± 0.03

These factors were determined by averaging the results from several transients and are presented as 95% confidence intervals. They represent factors which must be divided into the nuclear detector results to bring them into agreement with the energy probe data. These factors were applied to the sub-prompt-initial step tests and temperature coefficients were determined as outlined above.

Discussions with personnel at Phillips Petroleum Company resolved many of the problems encountered in interpreting the nuclear detector data for the early transients of the SNAPTRAN-1 test series. The method used to calibrate the detectors during the first few transients was reviewed, and it is now possible to decide which detectors were recording correct data during the early transient tests. This information can now be used in the statistical evaluation of the peak powers obtained on transients 111 through 159.

Also, additional peak power data were obtained from PPCo for these tests. These data were from channels with log amplifiers and had not previously been interpreted by AI. The new data were combined with the rest of the peak power data.

A statistical analysis of the peak powers obtained during this test series will be attempted to estimate the uncertainty in the recorded peak power values. With this uncertainty estimate, the discrepancy between energy probe data and nuclear detector data will be evaluated.

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Investigation of the possibility of a time lag between the temperature rise of a fuel lump and the temperature rise of a thermocouple wire connected to it during a SNAPTRAN transient was continuing. A simulated oxide region was incorporated into the two-dimensional heat transfer model being used to analyze this problem; the simulated oxide region is based on examination of photomicrographs taken of the weld region on probes used during many SNAPTRAN-1 transients. Preliminary results indicate that a time lag will exist where serious oxidizing has occurred.

An improved in-hour curve for the SNAPTRAN-1 reactor was obtained, using data taken from all transients initiated by reactivity step insertions of \$1.10 or more. For all but one transient (transient 201), the reactivity computed on the basis of drum insertion data matched the reactivity computed from reactor power quite well. A lifetime of 6.6 μ sec was computed using the in-hour curve.

2. SNAPTRAN-2

The calculation of energy deposition in a SNAPTRAN core was completed; the results of this study are summarized as follows:

<u>Available energy (Mev/fission):</u>	
Fission fragment K. E.	168.00
Prompt gamma ray sources	10.07
Neutron sources	4.86
Fission product decay gammas	7.00
Beta energy	6.00
Neutrino energy	<u>8.00</u>
Total	203.93
<u>Energy absorbed (Mev/fission):</u>	
Fission fragment K. E.	168.00
Gamma ray energy	8.5
Neutron energy	<u>3.89</u>
Total	180.39

These data are necessary to relate the neutron detector response to fuel temperature.

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The study aimed at determining nuclear detector calibrations from transients 332 and 340 was completed. The calibration factors were determined by correlating the energy from integrated power to the energy determined from the 10% hydrided energy probe data. The resulting factors (PCAL's) are numbers which must be divided into the power data in order to bring the resulting energies into agreement with the energy probe results. The same heat capacity data used to analyze the SNAPTRAN-1 tests was employed. This procedure was intended to minimize the effect of any time lags in the energy probe response by basing the calibration on the longer period transients 332 and 340.

Calibration factors for two scintillation detectors and two gamma detectors were determined. These factors were subsequently applied to the SNAPTRAN-2 destructive test data; the results are summarized in Table 8.

TABLE 8
SNAPTRAN-2 POWER NORMALIZATION
(Based on nuclear detector calibration factors)

Detector	Detector Type	Calibration Transient	PCAL	SNAPTRAN-2 Normalized Peak Power (Mw x 10 ⁻³)	
				Absorbed	Released
N4 3	SCINT*	340	1.16	62	69
N30	SCINT	332	1.26	58	65
N10	GAMMA	332	1.32	61	68
N10	GAMMA	340	1.21	68	76
N9	GAMMA	340	1.37	46	52

*Fast neutron scintillation detector

The normalized peak powers for the destruct test have been given on the basis of both "absorbed" and total "released" energy. As can be seen, the results from the two scintillation detectors are in quite good agreement, while the gamma detector results have a much larger variation. Averaging these results, we obtain a peak power (based on total release energy) of 66,000 Mw, which corresponds to a total energy release of about 47 Mw-sec.

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The peak power predicted by the adjusted PPCo calibration factors is 72,000 Mw. A review of the procedure followed in adjusting these factors indicates that the results are based strongly on the calibrations of the two scintillation detectors, N-23 and N-43. A further investigation of this procedure was being conducted.

Power normalizations were determined for the SNAPTRAN-2 destruct test by applying the SNAPTRAN-3 heat capacity to the 2-1/2 and 10% energy probe data. The corresponding temperature coefficients were also determined. The results were evaluated and computed with those obtained by normalizing to the energy probe data on transients 332 and 340. A summary power normalization study is presented in Table 9.

TABLE 9
SNAPTRAN-2 SUMMARY POWER NORMALIZATION

Source of Normalization	Normalized Peak Power (Mw x 10 ⁻³)		Absorbed Energy (Mw-sec)	Temperature Coefficient (°/°F)
	Absorbed	Released		
10% EP's (SNAPTRAN-2)	61	69	44	-0.25
All EP's (SNAPTRAN-2)	53	60	38	-0.29
2-1/2% EP's (SNAPTRAN-2)	47	53	34	-0.32
EP - 154 (SNAPTRAN-2)	72	81	52	-0.21
10% EP's (332 and 340)	69 60*	78 68*	48 43*	-0.22
N-23 and N-43 (PPCo calibration)	64	72	46	-0.24

*These results use the semi-empirical heat capacity data used to analyze the SNAPTRAN-1 test series rather than the SNAPTRAN-3 data.

The treatment of 2-1/2% U probes in the SNAPTRAN-2 analysis was reviewed. It was found to involve an inaccuracy in correcting from 2-1/2 to 10% U. This change will make the 2-1/2% U energy results about 10% higher, in better

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agreement with the 10% U data. These changes were incorporated into the SCRAP code and were being applied to the data.

Axial power profiles for SNAPTRAN were calculated for steady-state and for an inverse period of 5000 sec^{-1} . It was found that the axial power profile does not depend on the inverse period to any discernible extent. This is to be expected, since there is essentially no reflector on the ends.

A preliminary analysis was made on the radial and axial movement of the SNAPTRAN-2 reactor during the destruct test. The results of this analysis indicate that the respective values for radial and axial growth during disassembly were 370 and 590 ft/sec.

The effect of reflector thermalization delay on the temperature coefficient observed in SNAPTRAN-2 was evaluated. A set of synthetic data, approximating the SNAPTRAN-2 data, was calculated using known values of temperature coefficient and reflector parameters. These data were then analyzed using the normal COMPOST analysis. The COMPOST analysis gave a temperature coefficient that was 0.02% larger in magnitude than the known value. This error is the result of spatial flux shape changes during the transient, and is large enough to be of significant interest. The calculation performed is admittedly a crude substitute for a true spatially dependent kinetics calculation, but its results are thought to indicate the approximate magnitude of the effect of reflector thermalization delays on temperature coefficient.

A meeting was held with PPCo personnel to discuss differences in the temperature coefficient and power normalization determined from the SNAPTRAN-2 data. It had been noted in recent project briefings in Washington that PPCo had determined a temperature coefficient of -0.35% , compared to -0.25% determined by AI.

Several areas of difference were isolated as a result of the discussions. An adjustment of undisclosed nature in the PPCo calculations, which changed their coefficient from -0.35 to -0.315% , was also noted. The main areas of differences were the heat capacity models being used, the method of determining average temperature, and the conversion of average temperature to energy. The effect of these discrepancies on the AI analysis was evaluated, and corrections were being made where they appeared to be appropriate.

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An examination of the error inherent to the COMPOST method of temperature averaging has disclosed that surprisingly large errors can result if the probes are located preferentially near the center of the core. The problem arises from the step in which COMPOST correlates the various temperature data channels using a predetermined radial and axial profile. The power profile is used for this correlation. This is very accurate for small temperature changes, and is acceptable for larger changes if the transducers are scattered throughout the core in a relatively random fashion.

A better method is the one used in the SCRAP program. Temperature changes are converted to energy deposition by using the heat capacity. The energy depositions indicated by the several channels are then correlated using the power profiles. The resulting mean energy deposition can then be converted to temperature. This relationship between mean energy and temperature is unique for a given power profile. It is calculated by means of a two-dimensional spatial integral in the TBAR code, and is fit with a polynomial for later use. The resulting relationship is an "effective heat content." It differs slightly in magnitude from the simple integral of the heat capacity, depending on the variation of heat capacity with temperature.

Unfortunately, the instrumentation in the SNAPTRAN tests was located preferentially near the center of the core. This can cause errors as large as 14% in the mean temperature obtained by COMPOST, depending on the magnitude of the temperature change and the location of the transducers. The results of SNAPTRAN-2 were being re-analyzed, using the SCRAP method, to eliminate the COMPOST problem. An improved analysis of the SNAPTRAN-1 data was also initiated to eliminate the COMPOST temperature-averaging error. It is anticipated that the improved analysis will result in slightly lower temperature coefficients (~10%) for those transients with large temperature changes. This could alter the relationship among temperature coefficient results obtained from the cascaded steps, since the correction is dependent on the temperature change and not on the absolute temperature. This should clarify the trend of increasing temperature coefficient with the magnitude of the temperature.

3. Spatially Dependent Kinetics Code

The time-dependent Sn code (TDSN) has progressed to the state of calculating time-dependent fast and thermal fluxes correctly and, in addition, of treating

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temperature feedback due to spectral and density changes. To expedite the TDSN work, a two-group, spatially independent kinetics code (TDFN) was also written. This is a small code, requiring about a day to write, which uses the same method for solution of the time-dependent problem as TDSN uses. TDFN was being used to test the numerical method used in TDSN and to check the validity of the "O-derivative" assumption for fast flux. The numerical methods were found to be satisfactory, but a revised method of source calculation was required to permit acceptably large time-steps to be used. As a result, this revision was also made to TDSN. The fast-flux treatment was valid. Logic for obtaining CRT plots from the code was developed and was being implemented. This is required due to the large mass of data produced by a space-time calculation. This, plus some cleanup work, is expected to complete the initial version of the code.

The cross-section library required for the re-evaluation of the SNAPTRAN temperature coefficient was produced from the 100 GT data tape. The library, in a 26-velocity-group format, was used successfully in a spectral coefficient calculation, with the following results:

Temperature Range (°F)	Spectral Coefficient (ϵ /°F)
73.4 to 590.0	-0.063
590.0 to 1292.9	-0.100

These preliminary results were being evaluated and intermediate temperatures were being included in the calculation.

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VII. CRITICAL CONFIGURATIONS PROJECTS

A. EXPERIMENTS

Measurements on the worth of beryllium oxide as an axial reflector on the SCA-4B assembly were completed. Reflector thicknesses of 1, 2, and 4 in. with no water in the interstitial spaces of the reflector region were studied. Approximately 70 fuel elements were x-rayed to study the pellet distribution. This completed the experimental program, and cleanup of the facility was begun.

Design layouts for modification of the SCA-4A reflector were completed and approved. These modifications permit variable reflector lengths up to 24.0 in., reflector thicknesses up to 7.0 in., and various-size core arrays. These modifications will permit the study of SNAP-type cores, especially intrinsically subcritical designs.

Experiments that will examine the effects of core composition on intrinsic subcriticality were begun. SCA-5 fuel in a water environment (SCA-4B assembly) will be used, and the composition will be varied by placing aluminum or polyethylene wafers between the fuel pellets. The polyethylene wafers will simulate the effect of reducing the fuel fraction in the zirconium-hydride matrix. The aluminum wafers will simulate an overall reduction in material densities within the core. The calculated reactivity effects are given as follows:

Wafer Thickness (in.)	ΔK From Base (\$)	
	Polyethylene	Aluminum
0 (base)	0	0
0.01	+0.44	-2.06
0.02	+0.59	-4.06
0.03	+0.71	-6.00

B. ANALYSIS

Preliminary investigations were made to obtain intrinsic subcriticality without requiring removal of the external beryllium reflector. The major problem is that water flooding must act as a nuclear poison; whereas, in SNAP 10A and

SNAP 8 designs, water flooding results in ~\$7 to \$10 increase. Mapping studies were made of placing poison-surrounded channel regions in the core, which act as flux traps upon water flooding. Important variables are the size and compositions of both the channel and fuel regions. Channel variations were considered with constant fuel region parameters with SCA-5 fuel. The channel composition must not thermalize neutrons during operation, and the dimensions must be sufficient to thermalize and trap a significant number of neutrons upon water flooding.

NaK, NaK-Ni, and NaK-BeO channels, with the NaK replaced by water upon flooding, were found to be less desirable, in that order. The reactivity effect of water flooding with gadolinium-surrounded NaK channels alternated with 8.48 cm of fuel were:

Channel Width (cm)	ΔK
0	0.2132
2.0	0.1275
6.0	0.0645
10.0	0.0571

Although water flooding does not act as a poison in any of these models, a 6.0-cm channel provides most of the possible reduction in the worth of water flooding.

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VIII. END-OF-LIFE SHUTDOWN PROJECT

An interim report (NAA-SR-11956) was published describing the results of dissociation pressure studies on the Zr-H-T system and annealing experiments performed on SNAP fuel specimens containing tritium. It was found that the dissociation pressure of $\text{ZrT}_{1.70}$ is approximately 1.6 times that of $\text{ZrH}_{1.70}$. No measurable effect on dissociation pressure was observed upon addition of tritium to zirconium hydride in amounts corresponding to 1% of the H/Zr ratio. Similar concentrations of tritium in SNAP fuel yielded negligible swelling in annealing experiments conducted at 1300°F (up to 930 hr) and at 1500°F (up to 262 hr). The He^3 concentrations obtained in the annealing experiments, up to 4.5×10^{19} atoms/cc, were approximately 100 times that which occurs after 1 yr at the proposed tritium loading levels (5×10^{18} atoms/cc).

Measurements of the amount of He^3 released at 1470°F from partially tritided SNAP fuel was attempted. The surface areas of the samples used were unknown due to pre-existing cracks. On the basis of the inconclusive results, it seems that the rate of release is probably dependent upon surface area; the concentrations of He^3 and tritium appear to have a negligible effect. These measurements will be repeated, therefore, using crack-free cylindrical specimens of at least two concentrations, two different areas, and two surface-to-volume ratios.

Preliminary experiments were performed to determine the rate of redistribution of tritium in fuel. In these two experiments, a small tritided "button" and a length (~8 in.) of fuel rod (tritium-free) were annealed together at 1300°F for 48 and 114 hr. After cooling, the "button" and sections of the fuel were partially dehydrided and a portion of the gas was collected and analyzed by means of mass spectrography. The results obtained were inconclusive, since in no case was all of the gas removed from the specimens. These experiments will be repeated under conditions such that all of the gas will be removed from the specimens before it is sampled for analysis. In addition, the feasibility of determining redistribution by means of autoradiography will be studied. With such a technique, it may be possible to measure the variation of tritium concentration as functions of fuel rod length, depth of penetration, and time of redistribution.

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