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**SNAP FUEL REENTRY BURNUP
EXPERIMENT IN A HYPERTHERMAL
WIND TUNNEL**

AEC Research and Development Report

ATOMICS INTERNATIONAL

A DIVISION OF NORTH AMERICAN AVIATION, INC.

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SNAP FUEL REENTRY BURNUP
EXPERIMENT IN A HYPERTHERMAL
WIND TUNNEL

By
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ATOMICS INTERNATIONAL

A DIVISION OF NORTH AMERICAN AVIATION, INC.
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ABSTRACT

Specimens of SNAP fuel material were tested in a simulated reentry environment. This behavior in this environment was observed and is described in this report. This behavior was compared to and agreed with computations using a simple thermal approximation to the fuel material. The behavior was also extrapolated directly to that of an orbital reentry (with release of the reactor fuel rods from the reactor vessel at an altitude of approximately 240,000 ft).

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I. INTRODUCTION

A. PROGRAM OBJECTIVE

The operation of a nuclear reactor results in the generation of fission products. If the reactor is operated in an orbit about the earth, the ultimate fate of and any hazards associated with these fission products must be determined.

The reactor fission products will undergo natural nuclear decay during the period of the reactor orbital decay, reducing the radioactivity to a nonhazardous level for long-life orbits. For shorter orbital lifetimes, the reactor will re-enter the upper atmosphere with an inventory of fission products remaining in the fuel material. When this is the case, a means of safely disposing of the radioactive products is necessary.

One method of disposing of the reactor fission products is to disperse the fuel material at high altitude. This dispersion can be effected by aerodynamic heating under certain conditions of reentry. The Aerospace Safety Program at Atomics International has undertaken to determine the conditions of reentry which will result in the complete dispersion of the SNAP fuel material.

To determine the conditions of reentry which will cause meltdown and dispersion of a fuel rod, it is necessary to understand the characteristic behavior of the fuel material when it is subjected to a reentry environment. Analytical descriptions have previously been formulated and used to predict the expected behavior of a fuel rod for various reentry trajectories. However, the formulations are complex and require a number of approximations for the physical phenomena involved (i.e., the aerodynamic heating, the material thermodynamics and metallurgy, and the fuel rod dynamics). The refinement and verification of these analytical approaches requires experimental support.

B. EXPERIMENT OBJECTIVE

An ideal experiment would be to observe the behavior of a SNAP fuel rod in an actual or completely simulated orbital-decay reentry environment. However, this is neither technically feasible nor economical with the current state-of-the-art flight capabilities and test facilities. It thus becomes necessary to utilize a partially simulated reentry environment for the experimental studies

of the fuel material behavior. The most complete simulation of the reentry environment (for the time periods of interest for SNAP fuel rods) is obtained with an arc-heated, hyperthermal wind tunnel, commonly called an arc-jet.

The objective of the experiment described in this report is to provide experimental support for formulating an analytical description of the SNAP fuel rod reentry behavior. Since, ultimately, the objective of this program is to determine the behavior of SNAP fuel rods during reentry, it is advantageous to be able to extrapolate the behavior observed in the arc-jet directly to that expected during reentry. Therefore, the direct extrapolation of the behavior in the arc-jet to that reported during reentry is an additional objective of this experiment.

II. TEST DESCRIPTION

A. FACILITY DESCRIPTION

The facility utilized for this experiment was the North American Aviation hyperthermal, electric-arc wind tunnel. This facility is a continuous-running wind tunnel which produces a nominal Mach-3 gas flow at high temperature by passing an electric arc through a gas and expanding it through a contoured nozzle to impinge on a test specimen. The nozzle exit diameter for this facility is 3.5 in. However, due to incomplete expansion of the jet and boundary effects, the effective test section is approximately 2 in.

A simplified schematic diagram of the facility system is shown in Figure 1.* As shown in this figure, the state of the gas is essentially described by: (1) the gas flow rates, (2) the power input (accounting for losses), and (3) a pitot probe reading. From these data, the stagnation enthalpy and the stagnation pressure of the jet stream may be determined. Knowing the properties of air, the Fay and Riddell[†] theory for equilibrium flow (which is the case for the conditions available in the wind tunnel) may be used to obtain a reference heat flux to a unit hemisphere as shown in Figure 2.* It can be seen from this figure that the same heat flux may occur for a number of different combinations of stagnation enthalpy and stagnation pressure.

In addition to the data on the condition of the jet, various data may be used to observe and describe the behavior of the test specimen during a test run. This may include: (1) film data (event or conventional), (2) pyrometer readings recorded continuously during a test run, and (3) thermocouples mounted in the specimens (the leads being brought out from the test chamber through a water-cooled tube in the support post). The test chamber of the facility, as set up for this test series, is shown in Figure 3.

*M. Cohen, "Tests of SNAP 2/10A Reactor Fuel in the North American Aviation Hyperthermal Electric Arc Wind Tunnel," NA-63-1484- PT10 (December 1963)

†J. A. Fay and F. R. Riddell, "Theory of Stagnation Point Heat Transfer in Dissociated Air," Journal of the Aeronautical Sciences, Vol 25, No. 2 (February 1958) pp 73-85

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Figure 1. Simplified Schematic Diagram of NAA Hyperthermal Electric-Arc Facility

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Figure 2. Stagnation Point Heat Transfer (Fay-Riddell equilibrium theory for hemisphere, as evaluated for air)

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Figure 3. Facility Test Chamber and Associated Instrumentation

B. TEST SETUP AND DESIGN

The test series was designed with essentially five groups of tests with objective as follows:

- 1) Series No. 0 tests: Specimens of stainless steel and aluminum were used to check computational methods and data with thermally simpler materials than the SNAP fuel.
- 2) Series No. 1 tests: Fuel material specimens were tested in a helium jet to isolate the effect of surface oxidation on the fuel behavior in an aerodynamic heating environment.
- 3) Series No.2 tests: Fuel material specimens were tested in air, the runs being terminated at various time intervals to study the oxide buildup and internal state of the specimen.
- 4) Series No. 3 tests: Fuel material specimens were clad with Hastelloy-N to study the effect of the cladding on the behavior.
- 5) Series No. 4 tests: Combined phenomena tests were made of fuel material specimens in air to study the overall behavior of the fuel in the simulated reentry environment.

For these tests, two specimen configurations were used and are described in the following paragraphs.

1. Configuration I

In the Configuration I, cylindrical specimens were exposed to the jet with their axes normal (perpendicular) to the jet. The specimens were 1.25 in. in diameter and 2.0 in. long. They were supported by a tungsten rod, the end of which was gripped in the chuck of a rotating device. The exposed portion of the tungsten rod was protected from overheating by a tube of zirconium oxide wrapped with phenolic refrasil. Configuration I-A was as described, with the specimen stationary in the jet. Configuration I-B was as described, with the specimen rotating about its axis at approximately 4 rps. The Configuration I is shown schematically in Figure 4 and shown as it was installed in the tunnel in Figure 5. For the series No. 3 tests, these specimens were clad as shown in Figure 6.

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Figure 4. Specimen Configuration I (cylindrical specimens
with axis normal to jet)

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Figure 5. Specimen Configuration I Installed on Rotator
(extended to test position)

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Figure 6. Clad Arc-Jet Specimen and Holder Assembly (typical)

2. Configuration II

In the Configuration II, cylindrical specimens were exposed to the jet with their axes parallel to the jet. The specimens were 1.25 in. in diameter and 3.0 in. long. They were held in a graphite adapter by means of graphite set-screws. Configuration II-A was flat faced at the leading edge, while Configuration II-B had a hemispherical-tipped leading edge. The Configuration II is shown schematically in Figure 7 and shown as it was installed in the tunnel in Figure 8.

The test material (except for the Series No. 0 tests) consisted of non-irradiated, modified zirconium-hydride - 10 wt % uranium with natural uranium. The material was hydrided to a nominal content of $N_H = 6.34 \times 10^{22}$ atoms/cm³.

Data from Configuration I specimens consisted essentially of color motion picture coverage with a 24-frame-per-sec event camera and, in some cases, a Fastax camera operating at 1000 to 1500 frames per sec, and an equivalent black-body surface temperature as measured with a Therm-dot TD-9H brightness pyrometer. In addition to those data obtained from Configuration I specimens, temperature data were obtained from the Configuration II specimens with internally installed thermocouples (chrome vs alumel and W-5% Re vs W-26% Re).

NOTE:

△ INDICATES THERMOCOUPLE JUNCTION
DIMENSIONS ARE IN INCHES
NOT TO SCALE

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Figure 7. Specimen Configuration II (cylindrical specimens with axis parallel to jet)

Figure 8. Specimen Configuration II-B in Test Position

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In the design of the test procedures, strict attention was given to the problems of health and safety for testing of the radioactive fuel material and to the safeguarding of the classified aspects of the fuel material.

The analysis and planning of the safety procedures was performed by AI Health and Safety personnel. In brief, the procedures utilized were as follows:

- a) In order to guarantee that all radioactive debris be contained within the test chamber, an absolute filter was installed downstream of the heat exchanger inside the test chamber
- b) An absolute filter vacuum cleaner unit was used to remove material from the test chamber after each test. Access to the test chamber through a single port was limited to properly clad AI personnel. Coveralls, gloves, respirator, and cap were used to ensure the safety of the personnel installing new specimens and removing specimen remains
- c) The entire facility was continuously monitored during the test series and the area around the test chamber was roped off, excluding unauthorized personnel from the vicinity of the radioactive fuel material.

Security measures were planned and carried out for the safeguarding of the restricted data associated with the fuel material and cladding. These measures in brief were as follows:

- a) The classified material to be used in a given test day (up to 8 test specimens) was removed from AI headquarters by a designated custodian and remained within the cognizance of this custodian for the entire period of the test day, after which it was returned to AI headquarters and properly stored.
- b) The material was located within a perimeter at the test facility which was within the health safety perimeter. Both perimeters were marked with a waist-level rope which excluded all but designated personnel.
- c) All identifiable material was removed from the test chamber at the conclusion of the test day. The entire test facility was then locked with a key lock supplied by AI.

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III. TEST RESULTS

A. GENERAL RESULTS

The general results of the various test groups (refer to Section IIB) are summarized in this section. A complete test report was compiled* which provides the complete thermocouple and pyrometer data as well as a discussion of the reduction of the basic data. These, being lengthy, are not repeated in this report.

The run numbers were assigned as "X.Y" such that "X" represented the test series group number and "Y" the run within the test group. The results of each of the test groups are summarized in the following paragraphs.

1. Series No. 0 Tests

This group of tests utilized the Configuration II-A (flat-face axial) as shown in Figure 9. The conditions used for these tests are tabulated in Table 1.

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Figure 9. Test Configurations

*M. Cohen, "Tests of SNAP 2/10A Reactor Fuel in the North American Aviation Hyperthermal Electric Arc Wind Tunnel," NA-63-1484-PT 10 (December 1963)

TABLE 1
SERIES NO. 0 TESTS
(stainless-steel and aluminum specimens)

Run No. (Material)	Reference Heat Flux $q_s \sqrt{r}^*$ (Btu-ft ^{1/2} /ft ² -sec)	Stagnation Enthalpy H_s (Btu/lbm)	Pitot Pressure P_T (atm)	Time in Jet Δt (min:sec)
0.1 (SS-304)	110	6840	0.147	1:08
0.2 (SS-304)	112	6990	0.149	1:05
0.3 (SS-304)	117	7400	-	1:05
0.4 (SS-304)	72	4990	0.130	1:44
0.5 (SS-304)	72	5010	0.130	1:46
0.6 (SS-304)	41	4400	0.055	-
0.7 (Al)	38	3910	0.059	2:15
0.8 (Al)	35	3890	0.052	1:59

*For a cold wall in equilibrium flow as determined analytically from the stagnation enthalpy and stagnation pressure reported

The specimens were held in the jet with these conditions until either the leading thermocouple failed due to ablation or a steady temperature was reached for the leading thermocouple. As planned, complete event film coverage was obtained on all runs in this test group. It was noted from the film data that the leading edge assumed a curvature at the initiation of melting and maintained this shape during the recession of the specimen leading edge. This shape was different for the aluminum runs and the stainless-steel runs (Runs No. 0.1 through 0.6 were 304 stainless steel and No. 0.7 through 0.8 were 1100 aluminum). A time sequence of the behavior of a typical stainless-steel run is shown in Figure 10. As can be seen in this figure, melting of the leading edge was initiated at approximately 37 sec for this test run.

2. Series No. 1 Tests

The test conditions and specimen configurations used for this group of tests are shown in Table 2. A helium jet was used for these tests to eliminate surface reactions. In these tests, no ablation of the cross-axial specimens occurred; however, two axial specimens were observed to ablate back slowly from

$t = 0$

$t = 36.6$

$t = 44.5$

$t = 50$

$t = 58$

$t = 70$

$t = 75$

$t = 100$

ARC-JET TEST RUN NO. 0.4

4-29-74

Figure 10. Stainless-Steel Calibration Run

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TABLE 2
SERIES NO. 1 TESTS (helium jet)

Run No.	Configuration (see Figure 9)	Reference Heat Flux $q_s \sqrt{r}^*$ (Btu-ft ^{1/2} /ft ² -sec)	Stagnation Enthalpy H_s (Btu/lbm)	Time in Jet Δt (min:sec)	Comments
1.1	I-B	90	18,500	6:25	No ablation was observed for runs 1.1 - 1.4
1.2	I-B	100	17,000	6:18	
1.3	II-A	106	16,800	4:08	
1.4	II-A	97	17,200	8:45	
1.5	II-B	108	16,600	9:13	Ablation at tip
1.6	II-B	126	21,300	3:28	Ablated back approxi- mately 1 in.

*Measured with water-cooled LAD calorimeter — the value reported is at center of jet

the leading edge. The fuel material appeared to flow in a very viscous manner from the leading edge. This is shown in Figure 11. Several specimens from this group, with similar specimens run in an air jet, are shown in Figure 12 after they had been removed from the test chamber.

3. Series No. 2 Tests

The test conditions and configurations utilized for this group of tests are shown in Table 3. The specimens were exposed for a time interval after which the arc and jet flow were cut, terminating the test run. This provided information on the oxide buildup on the specimen as well as data on the internal state of the specimens at various times during a test run. Specimens from this group are shown in Figures 13 and 14 after they had been removed from the test chamber. Additional discussion of the results from these tests is given in paragraph C of this section.

4. Series No. 3 Tests

The test conditions used and comments on each test run for this group of tests are tabulated in Table 4. The configurations I-A and I-B (see Figure 9) were clad and used for this group of tests with a spectrum of heating rates which are characteristic of different ejection altitudes of the rods from the reactor vessel.

t=0

t=75

t=100

t = 130

t = 200

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Figure 11. Series No. 1 Tests (Run No. 1.6)

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Figure 12. Inert-Jet (helium) and Air-Jet Specimens After Runs

TABLE 3
SERIES NO. 2 TESTS
(preablation oxidation, simulated air jet)

Run No.	Configuration (see Figure 9)	Reference Heat Flux* $q_s \sqrt{r}$ (Btu-ft ^{1/2} /ft ² -sec)	Stagnation Enthalpy H_s (Btu/lbm)	Pitot Pressure P_T (atm)	Time in Jet Δt (min:sec)	Comments
2.1	I-B	73	5000	0.135	2:04	Runs 2.1-2.12 were terminated at a pre-determined time. The time of termination was determined by examination of previous runs. In all three cases (2.1-2.4, 2.5-2.8, 2.9-2.12), a good spectrum of oxidation was obtained.
2.2	I-B	70	4790	0.135	1:41	
2.3	I-B	70	4780	0.135	1:43	
2.4	I-B	72	5000	0.132	1:25	
2.5	II-B	73	5010	0.133	2:18	
2.6	II-B	72	5000	0.130	1:00	
2.7	II-B	72	5000	0.128	0:30	
2.8	II-B	72	4990	0.130	0:45	
2.9	II-B	40	4280	0.056	2:18	
2.10	II-B	38	4130	0.055	1:28	
2.11	II-B	35	4190	0.045	3:59	
2.12	II-B	33	4190	0.041	1:00	

*Reference heat flux calculated from stagnation enthalpy (H_s) and pitot pressure (P_T).

12-4-63

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Figure 13. Preablation Oxidation Test Specimens
(Configuration II-B) After Runs

7-9-64

7611-5417A

Figure 14. Preablation Oxidation Test Specimens
(Configuration I-B) After Runs

TABLE 4
SERIES NO. 3 TESTS
(simulated air jet)

Run No.	Configuration (see Figure 9)	Reference Heat Flux* $q_s \sqrt{r}$ (Btu-ft ^{1/2} /ft ² -sec)	Stagnation Enthalpy H_s (Btu/lbm)	Pitot Pressure P_T (atm)	Time in Jet Δt (min:sec)	Comments
3.1	I-B	123	7590	0.154	1:43	Cladding dispersed, holder failed
3.2	I-B	101	6530	0.142	0:48	
3.3	I-A	100	6460	0.141	0:36	
3.4	I-B	38	4210	0.054	3:06	Explosive dispersal, no ablation
3.5	I-B	95	6120	0.142	1:27	Ablation
3.6	I-A	98	6360	0.142	0:47	Cladding dispersed, holder failed
3.7	I-B	73	5040	0.128	0:51	
3.8	I-B	71	4970	0.129	2:28	Complete ablation
3.9	I-B	94	6180	0.139	1:43	Complete ablation
3.10	I-B	33	3770	0.051	10:18	Cladding remained, no ablation
3.11	I-A	33	3850	0.049	10:47	Cladding burned off, no ablation
3.12	I-B	73	5020	0.130	2:16	Complete ablation

*Reference heat flux calculated from stagnation enthalpy (H_s) and pitot pressure (P_T)

The lowest heat flux used is characteristic of the orbital reentry heating (assuming an equilibrium boundary layer) at an altitude of 280,000 to 290,000 ft. For the nonrotating specimens with this heat flux, the cladding was observed to melt along the stagnation line and eventually disperse. For the rotating case, two test runs were made. In one of these, the specimen was immersed in the jet for a period of over 10 min with no dispersal of the cladding. In the other run (at a slightly higher heat flux), the cladding blew off the end of the specimen, apparently due to a buildup of pressure within the cladding. This test is shown in Figure 15. The specimens from these test runs are shown in Figure 16 after they had been removed from the test chamber.

For the higher heating rates with nonrotating specimens, the cladding was observed to melt along the stagnation line almost immediately. The cladding then melted back and eventually dispersed. This is shown in Figure 17. In these test runs, the holder failed after dispersal of the cladding due to exposure of the tungsten holding rod.

For higher heating rates (characteristic of the heating at altitudes of 240,000 to 260,000 ft) with rotating specimens, the cladding was again observed to fail early in the test run. The remaining fuel material specimen then continued to heat and eventually ablated. This is shown for several runs in Figures 18 and 19. It should be noted that these runs are most characteristic of the actual reentry case, since the specimens were clad and since the test conditions used were similar to those expected for the actual rod trajectories. The residue from several of these tests is shown in Figure 20. In addition to the fuel material residue, the aluminum foil used to shroud the specimen prior to immersion may be seen in this residue. The residue is not, of course, characteristic of reentry, since the material dispersed from the fuel in the arc-jet leaves the jet and lands against the cooled test chamber walls.

5. Series No. 4 Tests

The test conditions used for test Runs No. 4.1 through 4.12 are tabulated in Table 5. These specimens were all of the Configuration I-B (cross-axial, rotating). In general, the specimens were observed to form cracks and eventually melt during the test run. This is shown in Figures 21 and 22 for several typical runs.

$t = 0$

$t = 50$

$t = 75$

$t = 124.3$

$t = 140.3$

$t = 140.34$

$t = 184.2$

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Figure 15. Series No. 3 Tests (Run No. 3.4)

12-4-63

7611-5421A

Figure 16. Clad Specimens (Runs No. 3.4, 3.10, and 3.11) After Runs

$t = 0$

$t = 2$

$t = 4$

$t = 10$

$t = 20$

$t = 25.6$

4-29-64

7611-0316

Figure 17. Series No. 3 Tests (Run No. 3.6)

$t = 0$

$t = 2$

$t = 4$

$t = 8$

$t = 12$

$t = 16$

$t = 40$

$t = 62.2$

$t = 70$

4-29-64

7611-0317

Figure 18. Series No. 3 Tests (Run No. 3.9)
(Sheet 1 of 2)

$t = 80$

$t = 85$

$t = 95.2$

$t = 99.5$

4-29-64

7611-0317-1

Figure 18. Series No. 3 Tests (Run No. 3.9)
(Sheet 2 of 2)

$t = 0$

$t = 4$

$t = 8$

$t = 12$

$t = 15$

$t = 20$

$t = 30$

$t = 40$

$t = 49.4$

4-29-64

7611-0311

Figure 19. Series No. 3 Tests (Run No. 3.12)
(Sheet 1 of 2)

NAA-SR-9779

$t = 66.2$

$t = 85.0$

$t = 100.0$

$t = 115.0$

$t = 120.4$

$t = 130.1$

$t = 132.1$

$t = 132.14$

4-29-64

7611-0312

Figure 19. Series No. 3 Tests (Run No. 3.12)
(Sheet 2 of 2)

12-4-63

7611-5419A

Figure 20. Clad Specimens (Runs No. 3.8, 3.9, and 3.12) After Runs

TABLE 5

SERIES NO. 4 TESTS
(Runs No. 4.1 through 4.12, combined phenomena)

Run No.*	Reference Heat Flux $q_s \sqrt{r}$ (Btu-ft ^{1/2} /ft ² -sec)	Stagnation Enthalpy H_s (Btu/lbm)	Pitot Pressure P_T (atm)	Time in Jet Δt (min:sec)
4.1	98	6220	0.148	1:34
4.2	98	6350	0.150	1:41
4.3	97	6160	0.149	1:52
4.4	97	6170	0.150	1:49
4.5	74	4730	0.144	2:36
4.6	67	4360	0.150	2:18
4.7	65	4360	0.127	2:26
4.8	64	4500	0.129	1:46
4.9	113	6950	0.151	1:37
4.10	110	6820	0.150	1:32
4.11	35	3890	0.053	4:20
4.12	35	3910	0.053	8:05

*Configuration I-B (see Figure 9)

$t = 0$

$t = 40$

$t = 50$

$t = 74.2$

$t = 87.8$

$t = 91.8$

$t = 94.3$

$t = 97.4$

$t = 97.6$

4-29-64

7611-0314

Figure 21. Series No. 4 Tests (Run No. 4.2)

$t=0$

$t=20$

$t=33.9$

$t=60$

$t=65$

$t=82$

$t=85$

$t=88.6$

$t=88.8$

4-15-64

7611-0301

Figure 22. Series No. 4 Tests (Run No. 4.9)

The test conditions and specimen configurations used for test runs No. 4.13 through 4.22 are tabulated in Table 6, with comments on each test run.

TABLE 6
SERIES NO. 4 TESTS
(Runs No. 4.13 through 4.22, combined phenomena)

Run No.	Configuration (see Figure 9)	Reference Heat Flux* $q_s \sqrt{r}$ (Btu-ft ^{1/2} /ft ² -sec)	Stagnation Enthalpy H_s (Btu/lbm)	Pitot Pressure P_T (atm)	Time in Jet Δt (min:sec)	Comments
4.13	I-B	84	5940	-	1:35	Specimen ablated
4.14	I-B	91	5910	-	1:44	Specimen ablated
4.15	I-B	69	4990	-	1:53	Specimen ablated
4.16	I-B	69	4950	-	2:23	Specimen ablated
4.17	II-A	93	6110	0.140	9:23	Oxidized heavily, no ablation
4.18	II-B	94	6160	0.141	1:56	Ablated back
4.19	II-A	94	6150	0.140	6:19	Ablated back ir- regularly
4.20	II-B	94	6100	0.141	2:02	Ablated back
4.21	II-A	91	6040	0.140	2:55	Oxidized heavily, ablated
4.22	II-A	120	7330	0.157	1:55	Ablated back

*Run No. 4.13 - 4.16 - reference heat flux measured with LAD calorimeter

Run No. 4.17 - 4.22 - reference heat flux calculated from stagnation enthalpy and pitot pressure

For the Configuration I-B specimens, the behavior was as observed in the earlier runs. These were repeated, however, due to oxygen flowmeter difficulties in the earlier runs which reduced the confidence in the test conditions for these runs. The behavior is shown in Figures 23 and 24 for these later runs. For the Configuration II specimens, a similar behavior was observed. The specimens heated for a period and then ablated rapidly from the leading edge. This is shown in Figure 25. Although not readily apparent from the single frames shown in this figure, the behavior was quite different for this test run than that for a similar run with the helium jet. For these test runs in air, the flow of the molten material appeared much less viscous, possibly due to higher shear forces on the surface with the air jet. The specimen also ablated much faster

$t = 0$

$t = 25.8$

$t = 35.9$

$t = 52.3$

$t = 65.7$

$t = 71.6$

$t = 71.64$

$t = 91.1$

$t = 91.3$

4-29-64

7611-0318

Figure 23. Series No. 4 Tests (Run No. 4.13)

$t = 0$

$t = 30$

$t = 61.8$

$t = 90$

$t = 120$

$t = 126.1$

$t = 136.3$

$t = 137$

4-29-64

7611-0310

Figure 24. Series No. 4 Tests (Run No. 4.16)

$t=0$

$t=20$

$t=46$

$t=56.4$

$t=65.4$

$t=66.6$

$t=72.1$

4-16-64

7611-0300

Figure 25. Series No. 4 Tests (Run No. 4.18)

(although the measured cold-wall heat flux to the specimens was approximately the same), with some apparent action at the surface (a great amount of sparks issued from the ablating surface in air while no material appeared to issue from the helium-jet specimens). The specimens from several of these test runs are shown in Figure 26 after they had been removed from the test chamber.

12-4-63

7611-5413A

Figure 26. Combined Phenomena (Series No. 4)
Specimens After Runs

B. HEAT FLUX DATA

In order to analyze the test data on the behavior of the fuel specimens in the arc-jet, it is necessary to accurately determine the heat flux to the specimens for the various jet conditions. This is difficult, since limited information is available on the heat flux distribution on even simple specimen geometries in high-speed flow. Also, there are nonuniformities in the jet itself which affect the distribution of heat flux to the specimens. Therefore, water-cooled assemblies in the shape and size of the specimens were fabricated and instrumented with heat flux sensors. The heat flux sensors used were "asymptotic" calorimeters. These consist essentially of a constantan disc with copper leads from

the edge, which thus measures the temperature difference between the center and edge of a disc. It may be shown that the heat flux to the surface of the disc is proportional to this temperature difference and, therefore, the output may be calibrated to determine the heat flux to the disc. These sensors and the assemblies were fabricated by the Hy-Cal Engineering Company.

The three units, as fabricated, are shown in Figures 27, 28, and 29. Figure 27 shows a hemispherical-tipped unit, with a single sensor at the stagnation point, installed in a holder that was adaptable to the facility support post. The data obtained from this unit are compared in Table 7 with other measurements and the theoretical reference heat flux. The same holder was used for the cross-axial and axial assemblies shown in Figures 28 and 29. All three assemblies are shown as they were inserted in the jet in Figure 30.

3-13-64

7611-0273

Figure 27. Hemispherical-Tipped Axial Calorimeter in Holder Assembly

3-13-64

7611-0274

Figure 28. Cross-Axial Calorimeter Assembly

3-13-64

7611-0275

Figure 29. Flat-Faced Axial Calorimeter Assembly

TABLE 7

COMPARISON OF REFERENCE HEATING PARAMETER
MEASUREMENTS FOR TEST CONDITIONS USED
IN THE ARC-JET TEST SERIES

Test Condition	Reference Heating Parameter – Centerline of Jet ($B\sqrt{\text{ft}/\text{ft}^2\text{-sec}}$)		
	$q_s \sqrt{r}$ Theoretical	$q_s \sqrt{r}$ Asymptotic Calorimeter	$q_s \sqrt{r}$ LAD Calorimeter
1	35	24 to 35 [†]	23 to 31 [†]
2	74 and 75*	75 and 78*	76
3	93 and 98 [†]	99 and 103 [†]	99
4	123	127	124

*Measurements from two different test runs

[†]Between centerline and 1 in. from centerline, since the distribution in the jet is poor for this condition.

NOTE:

$q_s \sqrt{r}$ Theoretical

is calculated from the stagnation enthalpy of the jet (as determined from an energy balance of the system) and the measured pitot pressure. It assumes equilibrium boundary layer flow.

$q_s \sqrt{r}$ Asymptotic
Calorimeter

uses an "asymptotic" sensor at the stagnation point whose output is directly proportional to heat flux. This is corrected for a 1/2-in. nose radius.

$q_s \sqrt{r}$ LAD
Calorimeter

uses a watercooled, hemispherical-tipped calorimeter with a 1/4-in. nose radius. An energy balance is made on the nose of this instrument to obtain the average heating on the hemisphere which is then related to the reference heating parameter listed.

The locations of the sensors are shown schematically and numbered in Figure 31. The actual heat flux data from the different assemblies for the nominal theoretical values of the reference heat flux, as reported in the test results for the various runs, are tabulated in Table 8. These data are plotted for the Test Conditions 2, 3 and 4 (see Table 8) in Figure 32.

STAGNATION POINT,
HEMISPHERICAL CALORIMETER

AXIAL, CYLINDRICAL
CALORIMETER ASSEMBLY

CROSS - AXIAL, CYLINDRICAL
CALORIMETER ASSEMBLY

5-8-64

7611-0361

Figure 30. Calorimeter Assemblies
in Supersonic Arc-Heated
Air Jet

NAA-SR-9779

HEMISPHERICAL MODEL

FLAT-FACED MODEL

CROSS-AXIAL MODEL

NOTE:

DIMENSIONS ARE IN INCHES NOT TO SCALE

6-1-64

7611-0404

Figure 31. Schematic Diagram of Calorimeter Assemblies

TABLE 8
CALORIMETER ASSEMBLY TEST RESULTS

Model	Test Condition *	Calorimeter Data (Btu/ft ² -sec)				
		1	2	3	4	5
Flat-Faced Model	1	58.8	48.3	81.2	0	0
	2	218	186	214	21.0	55.8
	3	284	248	256	26.0	82.3
	4	360	365	371	30.0	96.5
	He-1	365	306	294	0	0
	He-2	507	373	416	0	0
Cross-Axial Model	1	109	61.0	0	153	160
	2	239	135	63.8	236	205
	3	353	198	78.3	330	316
	4	456	260	75.5	427	400
	He-1	162	155	46.4	378	405
	He-2	295	205	58.0	351	424

*Test Condition	Nominal Theoretical $q_s \sqrt{R}$
1	40
2	70
3	100
4	125
He-1	70
He-2	100 (Max arc current)

†Calorimeter data number refers to location of sensor shown

For the cross-axial cylinder, it would appear from Figure 32 that the ratio $\frac{q}{q_s} = 0.36$ (previously used in analysis of the fuel rods^{*}) is a reasonable approximation. Examination of the stagnation heating for Test Conditions 2, 3, and 4 (those conditions used in the testing of the fuel) indicates that the stagnation heating is approximately 14% greater than that for an infinite cylinder with uniform flow.

For the flat-face cylinder, it may be seen from Figure 32 that the average heating is approximately 0.65 times the theoretical stagnation heating to a hemisphere with the same radius.

*R. D. Elliott, "Aerospace Safety Reentry Analytical and Experimental Program SNAP 2 and 10A (Interim Report)," NAA-SR-8303 (September 30, 1963)

6-1-64

Figure 32. Calorimeter Assembly Test Data

7611-0405

C. POST-TEST SPECIMEN STUDIES

Select specimens from the various groups of tests were examined after removal from the test chamber. The study of these specimens was in progress at the time of this report; therefore, the discussion here will be brief and include only preliminary conclusions from this effort.

The most significant information was obtained from the Series No. 2 test specimens, since these specimen remains represent essentially the specimens of the other series at particular time intervals during the test runs.

The initial study involved microstructural analysis with conventional metallographic techniques and spot chemical analyses. The metallographic preparation of the samples examined consisted of the following:

- 1) Longitudinal sectioning along a diameter
- 2) Grinding with 600-grit papers
- 3) Polishing, initially with 30-micron diamond paste with polish on micro-cloth, using an abrasive suspension of Al_2O_3 (Line B) in a 10% oxalic acid solution
- 4) Electrolytic oxide tinting, using the specimen as the anode in a 10% oxalic acid solution.

Subsequent to this preparation, the sections were examined and photomicrographs and macrographs of significant structures were prepared. Chemical sampling was then used to provide information on the distribution of elements within the section. Macrographs of four specimens are shown in Figures 33 and 34.

The general observations and preliminary conclusions drawn from this effort are as follows:

- 1) In the sectioned specimens, the concentration of the hydrogen increases with distance from the heated surface and from cracks within the specimen. This is particularly evident in specimen No. 2.4 (See Figure 33), where the apparent islands of material are δ - hydride and the material around these islands contains less hydrogen and the surface is nearly devoid of hydrogen.

RUN 2.4 - $q_s \sqrt{r} = 72$, RUN TERMINATED AT 85 SEC

RUN 2.1 - $q_s \sqrt{r} = 73$, RUN TERMINATED AT 124 SEC

H1 = 0.026 HYDROGEN CONTENT, WEIGHT PERCENT

N2 = 0.040

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7611-0406

Figure 33. Macrographs of Preablation Oxidation
Test Specimens (Runs No. 2.1 and 2.4)

RUN 2.10 - $q_s \sqrt{r} = 38$, RUN TERMINATED AT 88 SEC
 H1 = 1.00 HYDROGEN CONTENT, WEIGHT PERCENT
 N2 = 1.74

RUN 2.11 - $q_s \sqrt{r} = 35$, RUN TERMINATED AT 239 SEC

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7611-0407

Figure 34. Macrographs of Preablation Oxidation
 Test Specimens (Runs No. 2.10 and 2.11)

- 2) The hydrogen is lost such that discrete interfaces are formed between the phases present. This is particularly evident in Figure 34, where it is apparent that the phase interfaces have moved back for the longer test run.
- 3) The zirconium-oxygen reaction at the surface is apparently preferential to the reaction of zirconium to nitrogen.
- 4) The material in the vicinity of a molten surface was always devoid of hydrogen.

In addition to the foregoing observations, cracks were noted in most samples (as evident in Figures 33 and 34). The origin of these cracks had not been definitely determined at the time of this report, although some speculation had been made. Close examination of the specimens revealed essentially three types of cracks. Microcracks were evident in all specimens and are characteristic of the hydrided fuel. These were extremely small and did not appear to be of any significant length (small compared to the fuel dimensions). Very large cracks are also evident in the photos. These in general, appear to originate at the hole for the tungsten rod holder or in the thermocouple holes. These cracks are relatively few in number and extend to the surface in most cases. These cracks appear in the motion picture coverage of the specimens in the tunnel as shown in Figures 21, 22, and 23. The third-type crack appears to originate at the surface of the specimen in the dehydrided region and to extend a short distance from the surface.

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IV. TEST ANALYSIS

A. CALIBRATION SPECIMENS

In order to obtain confidence in the computational techniques and the jet conditions, the first series of test runs was conducted using both stainless-steel and aluminum specimens. These materials are considerably simpler thermally than the fuel material and, therefore, are useful as a check on the computational methods as well as the data reduction and interpretation. The Configuration II-A (flat-face, axial) was used for these specimens, since this best approximates a one-dimensional heat conduction problem within the specimen. The problem is shown schematically with an equivalent thermal network in Figure 35. It is assumed that the radial variations in temperature are small.

This problem was solved for given conditions with the application of the digital thermal analyzer program (TAP). The heat flux to the specimens was determined from the calorimeter assembly measurements as described in Section III. The average face heating was taken as 0.65 times the stagnation heat flux to a hemisphere with the same radius, using the theoretical reference heat flux.

The thermal properties used for the stainless-steel specimens are shown in Figure 36. Calculations were performed with these properties for several test conditions and the results are shown in Figures 37 and 38 as compared to the test data. Since limited data (two positions along the axis) are available on the lateral heating and the data obtained appeared erratic, a band of results are shown, using a lateral heating range of 5 to 10% of the average face heating. The time for the leading edge to begin to melt was determined from the film data and is also shown in Figures 37 and 38. Good agreement between the calculated and measured time for the leading edge to reach the melting temperature was found as seen in these figures.

As a result of these stainless-steel calibration test runs, it may be concluded that the interpretation of the test data is accurate.

Similar calculations were performed for the aluminum test Runs No. 0.7 and 0.8. It was found that the high thermal conductivity of the aluminum made the results extremely sensitive to the lateral heating of the specimens and the losses

$$Q_{\text{FACE}} = (\pi r^2 \times 0.65) \frac{(q_s \sqrt{r})_{\text{TH}}}{\sqrt{r}} = \pi r^2 \bar{q}_{\text{FACE}}$$

$$Q_{\text{radiation, FACE}} = (\pi r^2) \epsilon \sigma T_{\text{surface absolute}}^4$$

$$\Delta q_{\text{LATERAL}} = \left(\frac{\bar{q}_{\text{LATERAL}}}{\bar{q}_{\text{FACE}}} \bar{q}_{\text{FACE}} \right) 2\pi r \Delta x$$

$$\Delta q_{\text{radiation LATERAL}} = (2\pi r \Delta x) \epsilon \sigma T_X^4, \text{ ABSOLUTE}$$

$$R = \Delta x / K \pi r^2$$

$$C = \rho (\pi r^2) \Delta x C_p$$

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Figure 35. One-Dimensional Heat Conduction Within a Calibration Specimen (Configuration II-A)

to the holder (which were neglected for the stainless-steel specimens where the temperature of the rear surface did not become too appreciable). Therefore, no results are given for these runs.

B. CROSS-AXIAL FUEL SPECIMENS (Clad and Unclad)

The cross-axial fuel tests (Configuration I) best simulate the case of re-entry, since the stable attitude of a cylinder is with its axis normal to the velocity vector. Therefore, a reentering rod would either tumble or oscillate about a cross-axial attitude, both of which tend to cause the heating to be distributed along the axis as opposed to end heating. The comparison of the test data for these cross-axial tests to an analytical approach and to the actual re-entry is therefore of most interest.

As discussed in Section III, the data for this configuration specimen consist essentially of: (1) the film data, (2) the calorimeter-assembly data on the heat flux to the specimens, (3) the jet conditions, and (4) a continuous reading of the surface temperature with a Thermodot TD9H pyrometer.

It is thus possible to compare the time for ablation to begin, and the surface temperature transient during this heating period, to an analytical prediction of the same for a given heat flux to a specimen. The assumptions used in this prediction may then be evaluated and the validity of the analytical approach be determined.

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Figure 36. Thermal Properties of 304 Stainless Steel

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Figure 37. Calibration Run Results (Runs No. 0.1 and 0.2)

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Figure 38. Calibration Run Results (Runs No. 0.4 and 0.5)

Consider first the heat flux to the cross-axial specimen. From the calorimeter assembly data, it was determined that a reasonable approximation for the average cold-wall heat flux to a specimen center (where the pyrometer was focused) is:

$$\bar{q}_{\text{center}} = \frac{(1.14)(0.36)q_s \sqrt{r}_{\text{TH}}}{\sqrt{2r}},$$

where

$q_s \sqrt{r}_{\text{TH}}$ = the theoretical stagnation heat flux to a unit radius hemisphere

(1.14) = the factor correcting for the nonuniformity of the jet and the short cylinder effect

(0.36) = the factor relating the stagnation heating to the average heating around the periphery

$\sqrt{2r}$ = the factor relating the stagnation heat flux to a cylinder to that of a unit-radius hemisphere.

For the spinning rods, as used in the test, the problem may be represented schematically and with a simplified equivalent thermal network as shown in Figure 39. It is assumed that the surface heat flux may be effectively averaged around the specimen due to the rotation of the specimen and that the rotational velocity does not affect the value of the heat flux. This would appear to be the case, since the films show no large surface temperature variation and the surface velocity is small compared to the gas velocity. This problem may also be solved with the application of TAP. However, one difficulty with executing a solution is that the specific heat of the fuel material is a function of the temperature and the hydrogen content of the fuel. The equivalent network shown in Figure 39 does not, of course, account for the effects of hydrogen diffusion or dissociation.

A highly simplified thermal approximation to the effect of the hydrogen on the behavior is used for these computations. It is assumed that the hydrogen is dissociated (or activated) at a temperature of 2000°F. The choice of this temperature is not arbitrary. It is chosen because in the vicinity of this

$$\bar{q}_{CL} = 2\pi \bar{q}_{CL} \left(\frac{H_S - H_W}{H_S - H_{300^\circ N}} \right)$$

$$\bar{q}_{CL} = \frac{(1.1 \times 0.375) \eta_s \sqrt{r_{TH}}}{\sqrt{2r}}$$

$$\bar{q}_{rad} = (2\pi r) \epsilon \sigma T_s^4 \text{ ABSOLUTE}$$

$$R = \frac{\ln r_2/r_1}{2\pi K(r_2 - r_1)}$$

$$C = \pi(r_1^2 - r_2^2) \rho C_p$$

WHERE r_1 AND r_2 ARE THE INSIDE AND OUTSIDE RADII OF A NODE.

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7611-0412

Figure 39. Thermal Description of Cross-Axial Specimens (Configuration I)

temperature, the effective time for hydrogen to diffuse from the specimen goes from a long time to a short time compared to the test time. That the actual mechanism of the hydrogen loss occurs over an interval of temperature appears to have only a secondary effect on the specimen behavior. This has been demonstrated by comparing calculations with an assumed constant temperature dissociation to those assuming that the hydrogen is uniformly lost over a span of approximately 400°F in the vicinity of 2000°F.

The problem then becomes as shown in Figure 39 with a moving reaction interface within the specimen at 2000°F (or essentially nodes have a phase change at 2000°F, absorbing the heat of dissociation of hydrogen). This is accomplished with TAP by monitoring the temperatures of each node. When the node reaches 2000°F, the temperature is held constant while the net heat input is integrated. When the integrated heat input to the node equals the heat of hydrogen dissociation, the problem continues. The thermal properties used were:

$$K = 15 \text{ Btu/hr-ft-}^\circ\text{F}$$

$$\epsilon = 0.4$$

$$\rho = 374 \text{ lbm/ft}^3$$

$$C_p = \text{as shown in Figure 40}$$

$$\Delta H = 40.5 \text{ kcal/mole of hydrogen}$$

$$N_{H_{\text{initial}}} = 6.35 \times 10^{22} \text{ atoms/cc,}$$

In order to compare the calculated surface temperature to the pyrometer data, it is necessary to correct the indicated black-body temperature from the pyrometer for the window losses (the pyrometer was focused through a window in the test chamber) and the surface emissivity. The method of correction is discussed in the test report.* A graphical representation of this correction is shown in Figure 41. An emissivity of 0.4 was assumed and this value was used in the computations.

*M. Cohen, "Tests of SNAP 2/10A Reactor Fuel in the North American Aviation Hyperthermal Electric Arc Wind Tunnel," NA-63-1484-PT10 (December 1963).

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7611-0413

Figure 40. Specific Heat Used for Uranium-Zirconium Hydride (0 to 2000°F) and Uranium-Zirconium (2000 to 3400°F)

Comparisons are shown in Figure 42 for two cases of clad runs and two cases of unclad runs, respectively. The cladding was assumed to have been dispersed immediately, since, as seen in the film data, this was generally the case. As can be seen from the graphs in Figure 42, good agreement is found between the analytical results and the reduced data. The test data indicate a faster temperature response than was predicted in the latter part of the test runs. This can be attributed to several possible causes. Comparison of the film data shows that towards the end of the test runs some changes in shape occurred. This would have tended to increase the heating to the specimen. It also is possible that an increased amount of oxidation, which has been neglected in the computations, was occurring, resulting in an increase of heat flux to the specimen.

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Figure 41. Measured Surface Temperature (Thermodot TD-9H Pyrometer) Correction

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Figure 42. Comparison of Calculated to Measured Surface Temperatures
(Sheet 1 of 2)

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Figure 42. Comparison of Calculated to Measured Surface Temperatures
(Sheet 2 of 2)

In general, it would appear that the use of this simple thermal approximation to the fuel material results in good agreement between the predicted behavior and the observed behavior in the simulated reentry environment. The extrapolation of the behavior in the arc-jet to the case of reentry is discussed in Section VI.

The important assumptions inherent in the thermal approximation used herein are reiterated as follows for clarity:

- 1) It is assumed that axial conduction of heat is negligible and calculations are performed on the basis of the center circumference average heat flux.
- 2) It is assumed that the hydrogen is dissociated and lost from the specimen at 2000°F, with no effect other than that of an endothermic constant temperature reaction.
- 3) The aerodynamic heating to the specimen is taken as that to a specimen with no transpiration of material. In particular, the effect, if any, of the hydrogen on the heat flux to the specimen is neglected.
- 4) Oxidation of the specimen surface is neglected.

The development of a more detailed analytical model is currently in progress. The foregoing assumptions are not used and, therefore, their effect on the predicted behavior of the fuel material may be evaluated. This is necessary for the ultimate extrapolation to the general case of actual reentry. The behavior observed in the arc-jet and the test data obtained are useful for this further development in providing both direction and a means of comparing test results with the results of the more detailed analytical model.

C. AXIAL FUEL SPECIMENS

The thermal approximation of the fuel material, as described in the preceding section, was also used for computing the expected behavior of a flat-face axial specimen, Configuration II-A. (The hemispherical-tipped axial specimens are not readily adaptable to one-dimensional computations, making it difficult to utilize these test data for comparison to computations. This configuration is useful primarily for its well defined flow, which may be used for studying surface reactions.) For these specimens, it was possible to compare the calculated internal temperatures to those measured with a thermocouple. The heat flux to

the specimens was as determined from the calibration specimens; and as with those specimens, a range of lateral heating was used. The results of these computations are shown in Figure 43 for the leading thermocouple and the second thermocouple from the leading edge, respectively. The apparent temperature of hydrogen dissociation for the test data is approximately 1600°F. However, as seen by the sectioned specimens, the hydrogen in these specimens may diffuse to the thermocouple holes, thus decreasing the effective diffusion length. Also, the net heating back from the leading edge of these specimens is less than that for the cross-axial runs. These two effects would tend to lower the effective temperature at which the hydrogen is lost. It should be noted that the gross effects for the cross-axial test computations would not change appreciably if the hydrogen were assumed to be lost at the temperature of 1600°F instead of 2000°F. This is the case, since the gross difference would be due to the difference in the thermal radiation losses which are small in both cases.

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Figure 43. Comparison of Calculated to Measured Internal Temperatures

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V. EXTRAPOLATION OF RESULTS TO ORBITAL REENTRY

The extrapolation of the behavior observed in the arc-jet to that expected in a reentry trajectory requires some approximations. Therefore, conclusions with respect to the predicted behavior of a reentering SNAP fuel rod, derived from these test results, must be appropriately qualified.

There are two methods of extrapolating the behavior in the arc-jet to the case of reentry. One is the direct use of the analytical description used in analyzing the test data for the case of reentry heating of typical trajectories. The other is a direct comparison of the heating expected during typical reentry trajectories to that used in the arc-jet and assuming that for the same heat flux the behavior will be the same. The latter method will be used here to indicate what the test results mean to fuel rod reentry, since it is the most direct approach. Both methods, however, involve essentially two types of assumptions.

First, it is necessary to assume that the behavior is a function only of the heat flux to the fuel rod. This is a good assumption for a limited range of heating, since agreement was found using this assumption in analyzing the test data. However, it does not take into account any inhibiting effects of oxidation which in certain cases may be significant.

Second, it is necessary to make assumptions with regard to the expected aerodynamic heating during reentry. In the arc-jet, direct measurements of the heating were made. However, during reentry, analytical correlations are necessary to determine the trajectory and the resulting heating to a free-flight rod. Consider, then, the environment and resulting heating to a reentering fuel rod.

The rods are initially within a reactor vessel which will undergo orbital decay and reentry according to the ballistic characteristics of the entire vehicle. At some altitude within this vehicle trajectory, the rods are expected to be released and begin a trajectory of their own. The initial conditions of the rods will then depend on the trajectory of the reactor vehicle and the trajectory of the rods will depend on their ballistic characteristics and dynamics. It has not been experimentally determined whether the rods will tumble or reenter cross-axial to the velocity vector. This is important since the cross-axial orientation results

in a greater net heating at a given time to the rod than tumbling, while the tumbling orientation increases the weight-to-drag ratio and, therefore, extends the trajectory, increasing the total time period of heating. It is as difficult to determine which is optimum as it is to determine which can be expected to occur. This task of studying the rod dynamics during reentry is to be carefully undertaken in the early part of FY 1965.

The tests in the arc-jet were cross-axial, since this is a stable orientation of a cylinder. It will be assumed here that this is the case during reentry. A vehicle trajectory has been computed for orbital decay, using a weight-to-drag ratio of 132 lbm/ft² as shown in Figure 44. From this trajectory, the initial conditions of the rod (after exposure to the reentry heating from within the vehicle) have been determined. Using a weight-to-drag ratio of 25 lbm/ft²* for these rods, a trajectory has been determined for release from an altitude of approximately 240,000 ft (a predicted release altitude†) as shown in Figure 45. Thus, the velocity and free-stream density are known as a function of time from release. From these, the stagnation enthalpy and a reference heat flux, as used in the test results, may be determined. The reference heat flux was determined with the Detra and Hidalgo§ correlation:

$$q_s \sqrt{r} = 865 \left(\frac{\rho_\infty}{\rho_o} \right)^{1/2} \left(\frac{V}{10^4} \right)^{3.15},$$

where

ρ_∞ = free-stream density of air

ρ_o = sea-level density of air

V = rod velocity (ft/sec)

$q_s \sqrt{r}$ = reference heat flux.

* $W/C_D A = \frac{\pi \rho r}{2 C_D} = 25$, where $C_D = 1.2$, $\rho = 374 \text{ lb/ft}^3$, and $r = 0.605 \text{ in.}$

†R. D. Elliott, "Aerospace Safety Program SNAP 10A Reentry Flight Demonstration (RFD-1) Analysis of Flight-Test Data," NAA-SR-9479 July 15, 1964

§R. W. Detra and H. Hidalgo, "Generalized Heat Transfer Formulas and Graphs for Nose Cone Reentry into the Atmosphere," ARS Journal, Vol 31, No. 3 (March 1961) p 318.

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Figure 44. Trajectory and Heat Pulse for an Orbital Decaying Vehicle
($W/C_D A = 132$) in a Polar Orbit

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Figure 45. Trajectory Parameters for a Rod ($W/C_{DA} = 25 \text{ lb/ft}^2$) Released from an Orbital Decay Trajectory ($W/C_{DA} = 132 \text{ lb/ft}^2$) at an Altitude of 241,400 ft

It should be noted that this correlation is for an equilibrium boundary layer. If the boundary layer is not in equilibrium, it is necessary to determine the effect of the catalytic efficiency of the fuel material on the heating. This correlation also does not take into account any effect of mass injection into the boundary layer. A study of the hydrogen mass loss is currently in progress to determine the effect on the heat flux to the reentering rod. In this comparison here, the effect of the hydrogen injection into the boundary layer will not be included.

The results of these computations for the rod release at an altitude of 241,400 ft are shown in Figures 46 and 47. Superimposed on these plots are the results of two clad specimen runs. The reference heat fluxes used for these runs are as determined from Figure 2. (The factor 1.14 used in the surface temperature calculations is not included, since this applies only at the center of the specimen where the pyrometer was focused. Examination of the calorimeter-assembly data for the cross-axial assembly shows that the value used for this comparison represents the average heating on the stagnation line of the cylindrical specimens.)

Examination of Figures 46 and 47 reveals that the specimens undergo complete meltdown while aerodynamic heating is still available. In the one case, the heating is slightly less than that predicted by equilibrium boundary layer theory and, in this case, the rod has considerable heating still available after meltdown. In the other case, the test heating is approximately 30% less than that predicted for the trajectory using equilibrium boundary layer theory. In this case, the meltdown of the rod occurs with little available heating remaining.

Thus, within the validity of the experimental data and observations, reentry meltdown of a fuel rod released at an altitude of 241,000 ft is feasible and will occur. This would be the case even if the combined effect of the assumptions used in this comparison were in error by 30% of the actual aerodynamic heating during the rod trajectory.

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Figure 46. Comparison of Run No. 3.9 to Heat Flux Transient for a Rod Released at an Altitude of 241,000 ft

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Figure 47. Comparison of Run No. 3.12 to Heat Flux Transient for a Rod Released at an Altitude of 241,400 ft

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VI. SUMMARY AND CONCLUSIONS

In summary, SNAP fuel material specimens of several configurations were tested in simulated reentry environments. The behavior in this environment was observed and is described in this report. Data on this behavior were collected from the tests and compared to computations with a simple thermal approximation to the fuel material. Reasonable agreement was noted and is also presented in this report. It would appear from these results that the simple approximation used is adequate, as a first approximation, to describe the behavior of a fuel rod in a reentry environment. However, additional consideration of the assumptions used in this approximation was in progress at the time of this report and is necessary before definitive conclusions may be complete. Modifications were being investigated and may be made before complete use of an analytical description of the SNAP fuel material can be used for predicting the reentry behavior of fuel rods.

The behavior in the simulated reentry environment was extrapolated directly to that of an orbital reentry (with release of the reactor fuel rods from the vessel at an altitude of 241,400 ft) of SNAP 10A fuel rods on the basis of the theoretical equilibrium boundary layer reference heat flux. This extrapolation requires additional investigation of the rod dynamics and reentry heat flux and, therefore, is not completely conclusive. However, it would appear from this extrapolation that meltdown of the SNAP 10A fuel rods would occur under these conditions, with up to a 30% reduction in the heating to the specimens over that predicted by equilibrium boundary layer theory. That this meltdown occurs more readily than previously predicted for these conditions is attributed to the apparent break-up of the sample at high temperature. This comparison is on the basis of a rod with uniform heat flux around its circumference (accomplished in the tests by spinning the sample). It would be expected that a nonrotating rod with a heat flux distribution would melt down faster due to the initiation of melting along the stagnation line sooner and probably earlier failure of the rod.

The state of and behavior of the melted material is not presented or discussed in this report, although some analysis of the test debris was in progress at this time. In order to completely evaluate the hazard associated with the dispersed fuel material, it is necessary to determine this information.

In conclusion, it has been shown that "burnup" of SNAP 10A fuel rods will occur for release altitudes of approximately 240,000 ft or greater. Additional investigation of the assumptions used in arriving at this conclusion are necessary and were in progress at the time of this report. In addition, a spectrum of reentry conditions (release altitudes, aerodynamic characteristics, etc.) are to be considered in the future to determine the effect of these parameters on the expected behavior.