MASTER

EXPERIMENTAL INVESTIGATION OF
THE THERMOCHEMICAL BEHAVIOR
OF SNAP FUEL MATERIAL IN
A HYPERTHERMAL WIND TUNNEL

AEC Research and Development Report

ATOMICS INTERNATIONAL

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By

J. E. ARNOLD
A. W. BARSELL

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ABSTRACT

Experimental support for SNAP fuel element reentry burnup analytical programs and associated fuel particle disintegration studies was provided by a series of ablation tests on actual fuel material (non-enriched uranium) in a partially simulated reentry environment. Data were obtained on the transient temperature and hydrogen effusion behavior, surface catalycity effects on heat flux, and ablating particle size distributions and compositions. It was found that good temperature correlation was possible for those test conditions in which nonequilibrium flow effects were small. Fuel surface catalycity effects were found to cause significant heating reductions at conditions where departure from equilibrium flow was effected. For ablating particle size determinations, a laser photographic system proved to be a highly valuable tool. The work was performed under the Aerospace Nuclear Safety Program at Atomics International.

I. INTRODUCTION

The SNAP (Systems for Nuclear Auxiliary Power) 10A and SNAP 8 are compact power systems for space applications. Upon termination of their reactor operation in an earth orbit, the reactor fuel material ($\text{ZrH}_{1.8}$ -10 wt % U) will contain fission products. A significant portion of the radioactivity associated with these products will remain when the eventual orbital decay reentry of the reactor occurs if the orbit is not sufficiently long-lived. It has been determined that exposure to the reentry environment may cause the complete burnup of the reactor vessel and the fuel material, causing dispersal of the fission products at high altitude so that no radiological hazard from these products will exist.

The experimental effort to date in support of analytical studies to determine the conditions necessary for burnup and dispersal of the SNAP fuel material under reentry conditions has consisted of two series of arc-jet tests. A pilot test series was conducted, from which certain characteristics of the fuel behavior were observed and experience obtained in the safety and security considerations of arc-jet testing of the fuel material. A second and more advanced test series was then developed and performed. From this second series, data on the fuel behavior were obtained and correlated^{(1)*} with computational methods.

Both previous arc-jet test series were conducted at the NAA/LAD (Los Angeles Division, North American Aviation, Inc.) hyperthermal facility. The data from the second test series consisted of temperature transients for the fuel specimen surfaces as determined pyrometrically, internal temperatures for the specimens as measured with thermocouples, oxide buildup on the fuel surface, filmed observation of the fuel melting (ablation) behavior, metallurgical analysis, and analysis of the particulate matter remaining in the wind tunnel following each test.

As a result of these experiments an analytical description of the fuel material behavior was correlated with the experimental data and the final areas of the investigation requiring experimental support were defined. This analytical description in its present stage of development has recently been delineated in a detailed report,⁽²⁾ and is briefly summarized in the Appendix. Correlations of

*Superscript numbers in parentheses are for References at back of this report.

this analytical description with the past arc-jet test results are presented in Section VII of Reference 2, along with reentry behavior predictions.

The test series described in this report has evolved from the results of the previous experimental program and from the development of the analytical description of the fuel material thermochemical behavior. The testing described herein was necessary to provide data for the use in and verification of a complete description of SNAP fuel behavior during reentry. Specific objectives and a brief outline of the present tests are given in the following section.

The important feature of the most recent test series lies in the large number of specimens tested and the large number of flow conditions and configurations used. By testing over a range of flow conditions, data were provided with which the effect of flow chemistry on the results may be studied. Comparisons of the results for different configurations enable evaluations of the end heating effects, specimen holder effects, and specimen orientation. Finally, the large number of tests performed renders abundant data so that correlations and conclusions may be more confidently made.

II. TEST OBJECTIVES

To meet the needs and specific objectives of the test series described herein, five groups of tests were designed. Each group had a primary objective and most include one or several secondary objectives. A description of these five groups of tests and their objectives are as follows:

GROUP I

The determination of heat flux to a reentering SNAP fuel element is an important factor in predicting the reentry behavior of the element. Since the fuel element may traverse both the frozen and nonequilibrium boundary layer flow regimes, the problem of heat flux determination is further complicated by the heterogeneous catalycity of the surface recombination of dissociated air. Under certain conditions, the theoretical surface heat flux at the stagnation point may be reduced up to 70% for a non-catalytic surface over the heat flux to a catalytic surface.⁽³⁾ The importance of the surface catalycity in interpreting any heat-flux measurements in this case is apparent.

Although the analysis of the effect of surface catalycity on surface heat flux for frozen boundary layer flow has been considerable, the experimental verification of this effect has been limited. A summary of the experimentation to date is given in Reference 4. A very few materials have been used and most measurements have determined only the relative reduction in heat flux for a non-catalytic material over a catalytic material. Little correlation of the results with theory has been accomplished.

The objective of Test Group I of this experimental program was, therefore, to obtain data on the aerodynamic heat flux with catalycity effects considered, to certain materials, emphasis being placed on zirconium and zirconium oxide. These data are to be used in enhancing the predictions of the reentry behavior of SNAP fuel material⁽²⁾ and in correlating the thermal history data obtained in the present tests.

Various methods of instrumenting for the measurement of heat flux with different surface materials were considered for satisfying the objective of Test Group I. Possible methods included: A slug calorimeter with the slug being of the desired surface material, an absolute water-cooled calorimeter with the tip

being of the desired surface material, and an Asymptotic* calorimeter with the face coated with the desired material. It was determined that the latter could best accomplish the test objective since a standardized calibration procedure was available and this type of heat-flux sensor could be used to measure directly the stagnation point heat flux where the major portion of the analyses has been concentrated.

GROUP II

Stationary fuel specimens were designed for testing in cross-axial flow for the purpose of evaluating the radiant heat losses for simulated reentry temperature transients. The method of evaluation was based on a comparison of thermocouple and optical pyrometer measurements. This evaluation was necessary since the surface condition (oxide buildup) is known to affect the fuel emissivity.⁽⁵⁾ The condition of the fuel surface varies for different transients and therefore a spectrum of arc-jet conditions was used. A secondary objective for these tests was to provide an indication of the effect of a non-rotating cylindrical sample on the ablation characteristics.

GROUP III

Various tests were designed to be made on rotating fuel specimens in cross-axial flow for the primary purpose of evaluating the effect of fuel element radius on the reentry behavior. This was necessary since surface phenomena, as well as heat and hydrogen diffusion effects, depend on the specimen radius. Specimen diameters corresponding to those for SNAP 10A and SNAP 8 fuel elements were used.

A second objective in this test group was to evaluate the effects of different types of specimen holders. In the previous test series, a 3/16-in. hole was drilled through the fuel specimens for the insertion of a tungsten rod holder. The hydrogen loss and the observed cracking of the specimens may have been affected by the hole or by stresses resulting from this hole. Therefore, both completely solid specimens and specimens with the tungsten holder rod were made for this group to determine what effects the holes might have on the material behavior.

*Registered trademark of the Hy-Cal Engineering Company

Also designed for this test group, as a secondary objective, was an attempt to photographically record hydrogen effusion from the fuel specimens. An important assumption used in the analytical model calculations is that the hydrogen outflow is reasonably uniform over the surface and is diffusion controlled. Visual observations could lend more rigorous justification for this assumption, enhancing the confidence level of the analytical results. Therefore, to supplement the normal photographic instrumentation, a laser-schlieren system was designed and fabricated.

Monochromatic light from a laser source would be focused on the surface of the fuel specimen in the arc-jet. The specimen image could then be recorded throughout a test run by a camera.

Other objectives in this group of tests included the acquisition of data on fuel integrity, microcracking, and end heating effects. For the latter, configurations were designed and used in which ceramic (Al_2O_3) cylinders of specimen-size diameter were attached to the fuel specimen ends. The resulting behavior would then be compared with other configuration results.

One final objective for the Group III tests was the determination of the state (size, composition, etc.) of the particulate matter just as it leaves an ablating fuel specimen. To meet this objective an aluminum particle catcher was fabricated for use in each of nine test runs out of 36 total test runs in Group III.

GROUP IV

The fourth group of tests was designed to study the possibility of enhancement of ignition and ablation of the fuel material by surface irregularities. It is known that an effective high specific area (causing ignition) may be obtained with a pyrophoric metal by placing wires or small particles on the surface. The fuel material, if ignited, should ablate rapidly. Four specimen configurations were made with smooth surfaces over one-half of the axial length. The other half was grooved or cross-hatched to increase the effective specific area. The behavior of each half would be compared with the other to determine the gross effects of such surface modifications.

GROUP V

The primary objective of the fifth group of tests was to obtain photographic data on particle size distributions during fuel ablation. To accomplish this objective, laser photographic methods were designed to supplement normal film coverage.

III. TEST DESCRIPTION

A. FACILITY DESCRIPTION

The arc-jet test series described in this report was performed in the North American Aviation hyperthermal, electric-arc wind tunnel. This facility is capable of producing nominal Mach-3 gas flows at extremely high temperatures. The power supply can deliver 1 Mw of direct current power for continuously-running periods up to one hour. The flow is produced by passing gases through a high-current dc electric arc and the resultant high-temperature gas is exhausted through a contoured nozzle. The expanding gas, in this case partially dissociated air, leaves the nozzle to impinge upon a test specimen.

A simplified schematic diagram of the test facility is shown in Figure 1. Provision is made for injecting a secondary gas (oxygen) downstream of the arc. By using nitrogen as the primary gas, then postinjecting oxygen in the proper proportion, air may be reconstituted for use as the test medium, while the electrode erosion which would be produced by passing oxygen through the arc is avoided. As shown in Figure 1 an absolute filter was added downstream of the heat exchanger to prevent loss of radioactive material used in this test into the vacuum system. Also, a sheet metal liner was added to the rear walls of the test chamber to collect the test material that strikes the rear baffle plate, rebounds to the chamber walls, and adheres there. This was done to avoid grinding the radioactive test material from the walls at that location. Specimens and flow survey instrumentation are mounted on two (upper and lower) hydraulically retracted water-cooled posts as shown in the figure.

The state of the gas exiting the nozzle is essentially described by the power input, gas-flow rates, and a pitot probe measurement. These data are recorded during each test run. The average stagnation enthalpy is determined from a heat balance on the arc head and the measured flow of gas. The stagnation pressure is a direct measurement made with the pitot probe. Using the recorded flow condition data, the stagnation enthalpy, H_S , is computed with the equation:⁽⁶⁾

$$H_{S(H/E)} = \frac{E_{in} - E_{loss}}{\dot{m}_{prim} + \dot{m}_{sec}} \text{ Btu/lb} \quad \dots (1)$$

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

where

$$E_{in} = 0.948 (\text{volts} \times \text{amperes}) \times 10^{-3} \text{ Btu/sec}$$

$$E_{loss} = 0.1388 (\dot{m}_w)(\Delta T_w) \text{ Btu/sec}$$

$\dot{m}_{prim}$, $\dot{m}_{sec}$ = primary and secondary gas flow rates, lb/sec and $\dot{m}_w$ and ΔT_w are, respectively, the flow rate and temperature rise of the water which cools the anode and cathode. This method of computing stagnation enthalpy assumes that no other significant heat losses occur, and that the arc head is in thermal equilibrium. Most accounted-for losses would be from the boundary layer, which receives relatively little energy from the arc. Therefore, it is felt that this computational method gives a fairly good value for the average enthalpy in the test core.

Another method of determining stagnation enthalpy is by the "sonic throat" method. A plot of $H_{S(S/T)}$ vs $\dot{m}_{air}/P_o A^*$ is presented in Reference 7, which may be used directly. This method assumes uniform mixing and thermal and chemical equilibrium at the nozzle throat.

In general, an average of "sonic throat" and "heat balance" enthalpies is satisfactory for data correlation. It must be noted, however, that as enthalpy increases, and as pressure decreases, the flowing gas gets further and further from equilibrium, reducing the accuracy of the "sonic throat" assumptions. Conversely, at low enthalpy, less heat is rejected to the cooling water, and instrumentation accuracy becomes a limiting factor for "heat balance" measurements. In addition, aerodynamic and thermal non-uniformities in the flow field will determine how well an average enthalpy represents actual conditions at the specimen position.

From the determined values of stagnation enthalpy and pressure, a reference heat flux can be obtained using the theory of Fay and Riddell⁽⁸⁾ for a Newtonian velocity distribution about a hemisphere and using the thermodynamic properties of equilibrium air from References 9 and 10. This is shown in Figure 2. The reference heat flux may be interpreted as the heat flux to a 1-in. radius hemisphere at the stagnation point for equilibrium boundary layer flow. Also plotted in the figure is the reference heat flux to a two-dimensional cylinder and a flat-faced cylinder (end-on orientation in flow stream).

Figure 2. Stagnation Point Heat-Transfer Diagram

Figure 3. NAA Hyperthermal Wind Tunnel Operating Envelope

The operating envelope of the test facility is shown in Figure 3 and is based on the Fay and Riddell equation for heat flux presented 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. The envelope is shown for nozzle exit diameters of 2.5 and 3.5 in. Previous Al fuel arc-jet tests were also conducted in the North American Aviation wind tunnel and the most recent of these tests⁽¹⁾ utilized the nozzle exit diameter of 3.5 in. Since that time, the facility was improved with the installation of a new arc head which offered, with the 2.5-in. nozzle (lower vacuum limit), frozen boundary layer flow conditions extremely important to Test Group I (Section II-B). It is the low-pressure high-enthalpy conditions which result in a frozen boundary layer; therefore, the nozzle exit diameter of 2.5 in. was used throughout this test series. It must be pointed out, however, that due to incomplete expansion of the gas and boundary layer effects, the effective test section (core) was approximately 1.5 in.

B. SPECIMEN CONFIGURATIONS AND MATERIALS

The test configurations designed for the five test groups, as outlined in Section II of this report, are described in the following paragraphs.

Configuration I - Test Group I

Test Configuration I was an Asymptotic calorimeter which consists basically of a thin constantan disc over a cavity in a heat sink of copper. The disc is bonded to the heat sink at the periphery of the disc forming a thermocouple junction. A thin copper wire is attached to the center of the disc thus forming a differential thermocouple with the hot and cold junctions at the disc center and the periphery, respectively. The temperature difference between the center and periphery of the disc (and thus the output) is directly proportional to the heat flux impinging on the surface of the disc, assuming steady state, a constant thermal conductivity, and a radial temperature gradient only, i. e., no gradient between the face and rear of the disc. The principle of this calorimeter is shown with a schematic diagram in Figure 4.

Two standard types of calorimeters of the Hy-Cal Engineering Company were used in Test Group I. The first was a flat-faced, cylindrical water-cooled unit with a diameter of 5/8 in. The sensor (constantan disc) had a diameter of approximately 0.1 in. and is located in the center of the face or at the stagnation

$$\dot{Q} = \frac{4KS}{R^2} \Delta T$$

WHERE $\dot{Q}$ = HEAT FLUX

K = DISC THERMAL CONDUCTIVITY

S = DISC THICKNESS

R = RADIUS OF DISC

ΔT = TEMPERATURE DIFFERENCE BETWEEN
CENTER AND EDGE OF DISC

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Figure 4. Principle of Asymptotic Calorimeter

point. This calorimeter had a heat-sensing range of 0 to 500 Btu/ft²-sec. The second type was also a flat-faced cylinder but was, itself, not water-cooled due to its diameter of only 1/8 in. The sensor disc is of the same diameter as the larger calorimeter and has a heat range of 0 to 400 Btu/ft²-sec.

The coatings selected for Test Group I were applied to the surface of the calorimeters by methods best suitable to each material. The stainless steel and zirconium coatings were applied by plasma-spraying and then lapped for a smooth finish. Stainless steel was sprayed with and without a nitrogen blanket, resulting in oxidation of one coating. The zirconium was sprayed on in an inert (helium) atmosphere to prevent oxidation or nitridation. Zirconia (ZrO₂) and selenium

were plasma-sprayed to the sensor face in an atmospheric environment. The gold and silver coatings were plated to the calorimeters. The zirconia-coated 5/8-in. -diameter calorimeter is shown in Figure 5 as installed in a conical copper adapter for mounting in the holder assembly. Figure 6 shows the gold plated, stainless steel coated and silver plated (left to right) 1/8-in. calorimeters in a small copper adapter which was mounted in a water-cooled conical copper adapter of the size used for the 5/8-in. calorimeters.

The thickness of each coating was approximately 1 to 3 mils and applied to the entire face of the sensor. The effect of the coating on the constantan disc (which is 5 to 8 mils in thickness) is to provide an additional heat-conduction path or heat shunt to the sensor. If the same assumptions are used (steady-state, constant thermal conductivities for the disc and the coating, and no temperature gradient from the face of the coating to the rear of the disc) then it may be shown that the temperature difference will remain proportional to the surface heat flux but will be reduced by the factor: $K_D S_D / (K_C S_C + K_D S_D)$ (see Figure 4). If in either case, coating or no coating, the assumptions are not true, then for steady-state it may be stated that a unique solution of temperature distribution in the sensor disc and coating must exist and, therefore, the sensor may be calibrated and the resulting calibration curve is unique. The procedure described in Reference 11 was used by the manufacturer for the calibration of these sensors.

Configuration II - Test Group II

The material used for Test Group II and all remaining test groups consisted of non-irradiated modified SNAP fuel material, that is, zirconium-uranium hydride (ZrH_x - 10 wt% U). The material was hydrided to a nominal content of $N_H = 6.35 \times 10^{22}$ atoms/cm³ which constitutes a hydrogen-to-zirconium atom ratio, H/Zr, of 1.8. This material has a CRD (Confidential Restricted Data) classification which required security precautions (see Section III-C-2).

Configuration II was a cylinder oriented cross-axially in the jet stream and held stationary. The specimens were 1.25 in. in diameter and 2.00 in. long (SNAP 10A diameter). Each specimen was drilled above and below the transverse centerline to accommodate a solid tungsten rod and an alumina (Al_2O_3) tube. A hole was drilled from the tapped hole for the alumina tube, at an angle,

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Figure 5. 0.625-inch-Diameter Calorimeter Mounted in Copper Adapter

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Figure 6. 0.125-inch-Diameter Calorimeters Mounted in Copper Adapters

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to the center of the specimen and just close enough to the outer surface as possible without breaking through, for mounting a tungsten-rhenium thermocouple (W-5% Re vs W-26% Re). After mounting the thermocouple, an alumina insulation tube was placed over the thermocouple sheath and fitted into the hole in the specimen provided for it. The tube was then cemented in place. The tungsten rod, which provided support for the fuel cylinder, was cemented into the other hole in the specimen. The opposite end of the tube and rod were inserted into a graphite holder and held with graphite setscrews. Figure 7 is a schematic diagram of Configuration II which illustrates the details of its construction. There was a total of eight Configuration II specimens.

Configuration III - Test Group III

The Configuration III fuel specimens consisted of two major classifications, (1) and (2), designating the specimen diameter. The first classification (1) refers to specimens with a diameter of 1.25 in. and the second (2) refers to specimens of 0.562-in. diameter. These diameters correspond to those of the actual SNAP 10A and SNAP 8 fuel elements, respectively. Configuration III specimens were further divided into three sub-categories: A, B, and C. Category A designates a solid fuel specimen with an overall length of 6.62 in. The test length of the specimen was 2.0 in. and the remaining length was ground to a suitable diameter to provide sufficient strength when the test length was exposed to the jet stream and sufficient gripping area for the chuck of a rotating device. The remaining length of the classification (1) specimens was ground to a diameter of 0.5 in. and that of the classification (2) specimens ground to a diameter of 0.38 in. An alumina tube (Al_2O_3) was placed over the non-test length of these specimens, to protect them from overheating, and cemented to the test length. These configurations are shown unassembled in Figure 8.

Category B designates a fuel specimen drilled longitudinally through the center to accommodate a tungsten rod holder. A small hole was drilled in the end of the tungsten rod for a tungsten wire which was fitted into a slot at the base of the fuel piece to hold the assembly together. These fuel specimens were of both diameters (1 and 2) and the tungsten rod holder was protected by an alumina tube cemented to the sample. Configurations IIIB(1) and IIIB(2) are shown unassembled in Figure 9.

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Figure 7. Schematic Diagram of Configuration II

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Figure 8. Arc-Jet Test Configurations
IIIA1 (top) and IIIA2

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Figure 9. Arc-Jet Test Configurations
IIB1 and IIB2

The final category, C, of Configuration III fuel specimens was similar to Category B inasmuch as there were longitudinal holes drilled through the center for a tungsten rod holder. However, the C specimens were assembled with alumina tubing cemented to both ends of the fuel piece (to assure two-dimensional flow and eliminate end effects. Configurations IIIC(1) and IIIC(2) are shown, unassembled, in Figure 10. Configuration III specimens were oriented cross-axially in the jet stream.

Configuration IV — Test Group IV

The fuel specimens of Configuration IV were identical to Configuration IIIC(1) (SNAP 10A diameter) except for the surface of the fuel pieces. One half the length of these specimens was grooved leaving a smooth surface on the other half. There were four degrees of grooving which were categorized as A, B, C, and D. Configurations IVA, IVB, and IVD were grooved circumferentially in varying depths of groove and width of lands. Configuration IVC was first grooved circumferentially and then laterally, creating a cross-hatching of lands and grooves. A visual comprehension of these configurations can be gained from Figures 11 and 12. The orientation of Configuration IV in the jet stream was the same as for Configuration III (cross-axial).

Configuration V — Test Group V

The Configuration V fuel specimens were patterned after those of Configuration II with the exception that no thermocouple was mounted within the fuel. Two tungsten rods were cemented into the fuel pieces (one taking the place of the alumina tube of Configuration II) and the opposite ends fitted into a graphite holder and held with setscrews.

Configuration VI — Test Group V

Fuel specimens of Configuration VI were 0.562-in. diameter (SNAP 8) and 3.0 in. in total length. These specimens were so mounted in a graphite holder for orientation in the jet stream that the longitudinal axis was parallel to the direction of flow. The tips of these specimens were flat-faced. A length of 2.0 in. was exposed to the jet, with the remaining length inserted into the holder and held with a graphite setscrew. An unassembled Configuration VI specimen is shown in Figure 13.

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Figure 10. Arc-Jet Test Configurations
IIC1 and IIC2

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Figure 11. Arc-Jet Test Configurations
IVA and IVB

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Figure 12. Arc-Jet Test
Configurations
IVC and IVD

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Figure 13. Arc-Jet Test Configuration VI

C. DESIGN AND PROCEDURES

1. Test Group Setup and Data Acquisition

Test Group I

The Configuration-I calorimeters were first mounted to the copper adapters and then inserted into a main holder assembly which was mounted to the upper support post of the wind tunnel. The water-cooling tubes were connected on the interior of the main holder and the calorimeter leads drawn up through the support post to be connected to the recording instrument hookup panel on the top of the tunnel. A graphite shield protected the water line connection and the electrical leads. Figure 14 shows the 0.125-in. calorimeter and holder assembly mounted and in test position. Also shown in the figure is the pitot probe mounted on the lower support post of the tunnel.

Following the installation of the calorimeter assembly on the upper support post, the assembly was withdrawn to a position above the nozzle exit. The test chamber was then evacuated and the arc started. When the power input and flow

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Figure 14. 0.125-Inch-Diameter Calorimeter
Installed in Holder and Lowered to
Test Position in Tunnel

conditions became steady, the pitot probe was inserted to the centerline of the jet stream (well within the shock diamond) and the stagnation pressure recorded. Data on the flow were recorded simultaneously. These data included the power input, losses to the cooling water, gas-flow rates, plenum pressure, nozzle exit pressure, and chamber pressure. The same procedure for recording flow data was followed for every test run of all groups of tests in this series.

Upon steady operation of the jet and following complete recording of the flow condition data, the calorimeter was inserted into the center of the jet stream and the millivolt output recorded. The calorimeter was placed always within the jet shock diamond. As the sensor was inserted, a peak heat flux was observed at the edge of the jet or shock diamond. The output then quickly reached a steady reading at the center of the jet stream. When this occurred, the sensor was withdrawn, a typical run-time being approximately 5 to 10 sec for the 5/8-in.-diameter calorimeter and 3 to 5 sec for the 1/8-in.-diameter calorimeter.

Immediately following the completion of each test run, the calorimeter face was examined. In a large portion of the tests the calorimeter face became contaminated by the jet and from the turbulent environment in the test chamber, which may have caused fine debris to coat the sensor. When this was observed, the calorimeter face was carefully cleaned with a liquid soap, which removed the contamination. Each calorimeter was cleaned after a run and retested at all test conditions.

Test Group II

Configuration-II assemblies were mounted to a sting on the upper support post of the test chamber as shown in Figure 15. The thermocouple lead was drawn through the support post to the recorder connection on top of the tunnel. After mounting the specimen, the support post was withdrawn to a point parallel with the cooling air supply. A shroud of heavy foil was then secured from the air outlet tube to aid in covering the specimen in order to maintain the specimen at as low a temperature as possible during the time the jet is being brought to a steady flow condition. As soon as a steady flow condition was achieved and all flow data recorded, the specimen was lowered into the center of the jet stream. The distance between the nozzle exit and the specimen was preset at 5/8-in. since an earlier flow survey indicated this to be a position such that flow blockage was eliminated. The specimen was held in the jet until ablation was complete or until an equilibrium state was evident in the case of non-ablation.

Data obtained during the test runs with Configuration II consisted of full coverage with the 24 frames/sec motion picture event camera, an equivalent black-body surface temperature as measured with a Thermodot TD-9H optical pyrometer, and some temperature data from the output of the thermocouple. The thermocouple failed to operate during all but three test runs of this group. For one test run, high-speed film coverage, taken at 400 frames/sec, was obtained. Three of the Configuration-II specimens were used in conjunction with particle photography; Test Group V.

Test Group III

The Configuration-III fuel specimens were inserted and held in the chuck of the rotating device by gripping the end of the tungsten rod holder (Configurations IIIB and IIIC) or the tip of the turned down length of fuel [Configurations IIIA(1)

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Figure 15. Arc-Jet Test Configuration II Installed on Upper Support Arm and Lowered to Test Position

and IIIA(2)]. The rotating device was water-cooled and installed to the upper support post of the tunnel. The angular velocity of the rotator was preset and held at 120 rpm. A schematic diagram of the rotator and a typical Configuration-III specimen are shown in Figure 16.

The primary test setup for the first ten runs of Test Group III consisted of a double-pass laser-schlieren system. The laser light source used was a Korad K15QP laser which is water-cooled and Q-switched with an output of at least one joule at a firing rate of one pulse/sec. The laser system is comprised of three units: (1) an electronics cabinet which contains the charging and switching electronics, the trigger units, and the oscillator energy storage bank; (2) the laser head, output reflectors, and the switching mechanism which are all mounted to an anodized aluminum rail (I-beam); and (3) a closed-cycle cooling unit which provides sufficient temperature regulation for safe firing at recommended rates. The Q-switch mechanism for this system is a rotating mirror having a wavelength the same as the ruby rod ($6943 \text{ \AA}$) and is operated with air pressure.

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Figure 16. Schematic Diagram of Rotating Device and Fuel Specimens (Axis Normal to Jet Stream)

The diameter of the laser beam is approximately 5/8-in. and its divergence is 10 milliradians. The laser flash duration is approximately 4×10^{-8} sec.

The layout of the schlieren system is shown schematically in Figures 17, 18, and 19. An aluminum tube 15 ft long and 8-1/2 in. in diameter was attached to one viewing port of the tunnel and a spherical schlieren mirror to the viewing port of the opposite side. The entire system was made vacuum tight so that it could be evacuated with the test chamber. In order to accommodate the required length of the tube, it was necessary to cut an opening in the wall separating the plasma tunnel from an adjacent test cell. Figure 20 shows the end length of the tube and the laser system which were located in the adjacent cell. As it was necessary for the tunnel operator to visually inspect the jet stream while bringing the tunnel up to the proper test condition, a mirror was installed inside the tube near the viewing port (Figure 18). This mirror could be swung out of the path of the laser beam when schlieren photographs were to be taken. An auxiliary tube, at an angle of 5° to the main tube axis, was added so that motion picture event coverage could be obtained continuously throughout a test run without disturbing the schlieren system. A third opening with a right-angle view into the tube was provided in order to focus the optical pyrometer on the test specimen, again without causing any interference with the schlieren setup. The movie camera and pyrometer were situated in the cell accompanying the test chamber itself as shown in Figure 21.

The laser light entered the tunnel through a vacuum-sealed quartz lens which focused the essentially parallel beam down to a small spot in its focal plane. A thin aluminum foil was mounted in the focal plane and the laser light generated its own stop by burning a small hole into the foil at its focal point. The laser light was then bent 90° by an uncoated pellicle beam splitter and directed toward the schlieren mirror at the opposite end of the tube. From that point, it was returned upon itself, passed the beam splitter, and came to a focus at the vertical knife edge which was located exactly two focal lengths away from the mirror. The knife edge could be moved parallel and perpendicular to the tube axis by means of a microscopic stage. This movement for final adjustment could be effected from outside the tube by flexible vacuum-sealed cables, even while the tube itself was under vacuum. The laser light was then passed out of the tube at the end window, bent 90° by a small mirror, and let into a modified

Figure 17. Overall Layout of Laser-Schlieren System

Figure 18. Details of Schlieren System at the Test Section Enclosure

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Figure 19. Details of Schlieren System in Adjacent Test Cell

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Figure 20. Laser-Schlieren Setup in Adjacent Test Cell

Figure 21. Schlieren Tube Connection to Test Chamber and Associated Test Instrumentation

large aerial camera (Figure 19). The camera has a 40-in. lens which was covered by a narrow bandpass filter. An electrically operated shutter and a 70-mm film magazine (both taken from a standard Beattie Varitron camera) were added to the aerial camera. The camera operation was actuated by manually pressing a push-button switch and the sync-contact of the shutter triggered the laser. Maximum speed of the camera was one photograph every two seconds.

Following the installation of a Configuration III-specimen into the rotating device, the upper support post was withdrawn to a point where the specimen was aligned with the cooling air supply outlet. A tinfoil shroud was mounted, as in the case of Group-II specimens, from the air outlet line to and covering the test specimen. Once the test condition was reached and all flow data recorded, the specimen was lowered into the jet stream. Laser-schlieren photography was initiated at this time and was continued throughout the entire test run. Additional data included motion picture coverage (24 frames/sec) and pyrometer surface temperature recordings. The specimens were held in the jet stream until either ablation was complete or until equilibrium was established. During a test run, the knife edge of the schlieren system had to be repeatedly readjusted. This was due to the heat radiated from the jet stream to the schlieren mirror causing it to shift continuously.

A particle catcher was used in conjunction with nine test runs of the remaining 18 runs of Group III. The catcher assembly main shaft was inserted into the face of the test chamber through an opening already provided. A lever handle was fixed to the outside end of the shaft for operation of the catcher in and out of test position. A movable linkage assembly was attached to the interior end of the main shaft. The particle catcher itself was a solid aluminum block, 1-1/2 in. (thickness) by 2-1/2 (height) by 2-1/2 (width) with a concave front face. An aluminum rod was welded to the back of the catcher block off center to allow for rotational adjustment above and below the specimen ends and of sufficient length to adjust forward to and beyond the specimen and aft of the specimen a distance of approximately two in. Figure 22 shows a Configuration-III specimen and the particle catcher in test position.

The schlieren system was removed from the test chamber and the viewing windows replaced during the remainder of Test Group III and all of Test Group IV. A Configuration-III specimen was mounted as previously explained, and

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Figure 22. Arc-Jet Test Configuration IIIA2 on Rotator and Lowered to Test Position

upon reaching proper flow conditions, was lowered into the jet stream. At the initiation of ablation, which was observed visually through the viewing window, the particle catcher was inserted to full test position aft of the specimen until a sufficient amount of ablating material was deposited on the concave face of the block and then withdrawn. Other data obtained consisted of motion picture coverage (24 and 400 frames/sec) and pyrometer surface temperature recordings.

Test Group IV

Configuration-IV fuel specimens were mounted in the test chamber in the same manner as Configuration-III specimens. The test run procedure was also the same as for Test Group III. An additional optical pyrometer (Thermodot TD-9H) was used during all Group IV test runs. One pyrometer was focused on the smooth surface of the specimen at approximately 1/4-in. below the specimen traverse centerline, and the other was focused on the grooved surface at the same distance above centerline. Temperature recordings were taken throughout each test run along with 24 frame/sec motion picture coverage. Two of the Group-IV test runs were also film-recorded at 400 frames/sec.

Test Group V

To perform particle photography during Test Group V runs, the schlieren tube was replaced in position on one viewing port of the test chamber. The other window was left in place so that pyrometer and film data could be obtained simultaneously. The aluminum tube length for this portion of the test series was decreased to 9 ft; the tube extended into the adjacent test cell containing the laser system. An ordinary window glass plate, as used in the viewing ports of the test chamber, was fastened to the end of the tube and sealed for vacuum. The position of the laser head with respect to the tube is shown in Figure 23. The laser beam was aimed through the glass plate directly at the test specimen or just slightly above it (approximately 1/8 in.). Due to its own divergence, the laser beam expanded to approximately 1 in. in diameter at the center of the test chamber. A slit-type diaphragm was made and attached to an inner metal plate (in place of the viewing window) so that the beam was only 1 in. in width and 1/8 in. in height. Thus, only particles which were caught by the laser light inside this narrow beam would be illuminated and become visible on the photograph. This precaution had to be taken since the photographic depth of field was

Figure 23. Laser Head and Laser Beam Entrance Window to the Test Chamber for Particle Photography

only 0.1 in. for this particular test setup. Otherwise, particles which would be out of focus could also show up and would appear larger than they actually were.

To obtain a slightly magnified image of the particles on the film, it was necessary to have the specimen as close to the camera as possible. To do this, an open well with a pyrex window installed at the bottom had to be inserted into the test chamber through the top viewing port. A camera was placed inside the well and was air-cooled from an air line outside the test chamber. The camera used for this purpose was a modified Beattie Varitron employing an 8-1/2 in. Kodak Anastigmat F/4.5 and the same bandpass filter (Perkin Elmer type interference filter for 6943 Å wavelength and 0.25% HWB 1-1/2-in. diameter) that was used in the schlieren photography. The film used in both cases was 70-mm Kodak Linograph Shellburst. The entire experimental setup for particle photography is shown schematically in Figure 24.

Two primary fuel specimen Configurations were used in Test Group V, V and VI. In addition, three Configuration-II specimens were used in this group since it provided additional specimens for particle photography and did not interfere with temperature data acquisition as required from the Group-II test

Figure 24. Schematic Diagram of Overall Test Setup for Particle Photography

sequence. Mounting of Configuration V and VI specimens to the sting on the upper support post was the same as that for Configuration II. Figure 25 shows a Configuration-VI specimen in test position. The camera well and the slit-type diaphragm for laser light passage can also be seen in the figure. Before making a test run, each specimen was withdrawn to a position parallel to the cooling air supply inside the chamber but was not shrouded with foil so as not to obstruct the view of the camera from above.

The procedure for obtaining a flow condition and the associated data was followed, as in all test runs, after which each specimen was lowered into the jet stream. Just prior to entry of the specimen into the stream, particle photography was initiated. Photographs were taken at the rate of one every two seconds throughout the entire test run, the speed being limited by the time it took to advance the film in the magazine. Other data obtained consisted of motion picture coverage (24 frames/sec), pyrometer recordings, and thermocouple (Configuration II) output.

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Figure 25. Interior View of Test Chamber with a Configuration VI Specimen Lowered to Test Position

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2. Health, Safety, and Security Procedures

The SNAP fuel tested in this test series was a natural-uranium-bearing material which presented a health hazard and contamination problem. The health hazard was primarily associated with the inhalation of dust particles inside the test chamber following a run. The contamination problem occurred inside the test chamber and in the downstream heat exchanger.

Procedures for specimen handling, monitoring of radioactive levels, and facility decontamination were previously developed and implemented by AI personnel and equipment for a recent arc-jet test series.⁽¹⁾ These procedures were applied to the test series described herein.

Since the test material was classified CRD (Confidential Restricted Data) it was necessary to maintain appropriate security measures approved by AI Security personnel. The procedures used throughout the test series for maintaining these security measures were the same as those used in the previous test series.

IV. TEST CONDITIONS AND HEAT-FLUX DATA

A. TEST CONDITION DATA

The present series of arc-jet tests was designed to simulate typical stagnation pressures, stagnation enthalpies, and heating rates encountered by a reentering SNAP fuel element following release from a disintegrating SNAP reactor. Originally, it was planned to conduct these tests at only a few sets of conditions along typical trajectories. As the initial tests were conducted, however, it became evident that substantial heating reductions were occurring at particular test conditions, both for the fuel specimens and for various materials used in the coated calorimeter (Group I) tests. In order to provide data for a comprehensive evaluation of these heating effects, tests with actual fuel specimens were made over a broad spectrum of stagnation-pressure, enthalpy combinations.

The actual test conditions used throughout all tests in the current series are shown graphically on a stagnation-pressure, enthalpy, heat-flux diagram in Figure 26. The stagnation-pressure and enthalpy values corresponding to these conditions were taken from calibration measurements made for each test condition at the time when cross-axial calorimeter heat-flux measurements were made (see Section B following). The heating rates along the ordinate in Figure 26 are based on evaluations of the Fay and Riddell equation, assuming equilibrium flow. A tabular listing of each measured stagnation pressure, stagnation enthalpy, and calculated reference heat flux is presented in Table 1. A comparison of these theoretical heating values with the corresponding measured cross-axial calorimeter values is given in the next section.

Typical SNAP fuel element reentry trajectories are also shown in Figure 26. These trajectories were calculated using the RESTORE computer code developed and used at Atomics International for reentry trajectory and aerodynamic heating calculations.⁽²⁾ As far as possible the arc-jet flow conditions were selected at particular points along these trajectories. The higher altitude conditions could not be simulated due to the performance capability limitations of the arc-jet (see Figure 3).

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Figure 26. Stagnation-Pressure, Enthalpy, Heat-Flux Diagram Based on the Fay and Riddell Equation

TABLE 1
SUMMARY OF FLOW CONDITION DATA

Test Condition	Stagnation Pressure (atm)	Stagnation Enthalpy* (Btu/lb of air)	Reference Heat Flux† (Btu- $\sqrt{\text{ft}}/\text{ft}^2\text{-sec}$)
I	0.0475	4611	39
J	0.0511	5432	48
H	0.0732	7908	87
C	0.0750	7641	82
M	0.0809	6480	74
K	0.1056	5704	73
D	0.0959	5205	63
P	0.1036	4425	55
G	0.1360	5140	74
U	0.2560	4603	90
F	0.3579	3974	90
T	0.3185	2563	52
R	0.1444	7198	110
S	0.1374	10440	159

*Average value using sonic throat and heat balance methods (Section III-A)

†Stagnation-point, cold-wall heat rate to a 1-ft radius sphere

B. HEAT-FLUX MEASUREMENTS

1. Calorimeter Assembly Description

In order to analytically evaluate the behavior of the fuel specimens in the arc-jet stream, it was necessary to accurately determine the heat flux to the specimens at each test condition. This is a difficult parameter to determine confidently from the test condition data since there are nonuniformities in the jet itself which affect the distribution of heat flux to a particular specimen geometry. Also, flow blockage by the specimen and gas mixing problems, which may create a "hot core" in the jet stream, would affect the heat flux distribution. Therefore, a water-cooled assembly was fabricated in the shape and size of a Configuration-II specimen (SNAP 10A diameter, oriented cross-axially and held stationary) and instrumented with heat flux sensors. The heat flux sensors

used were Asymptotic calorimeters of the same type used in Configuration I. There were five sensors mounted in the assembly. The location of each of these is shown schematically in Figure 27.

Figure 27. Cross-Axial Calorimeter Assembly Diagram

2. Heat-Flux Data

Heat-flux measurements, using the cross-axial calorimeter, were made at each of the fourteen conditions used for testing of the fuel specimens. For each condition the flow was allowed to stabilize, a centerline pitot reading was taken, and all tunnel parameters were recorded. The calorimeter was then inserted into the flow stream. Data from its five sensors were recorded for approximately 5 sec during each run. The resulting data are tabulated for all fourteen cases in Table 2. Note that these are local heating rates, in units of $\text{Btu}/\text{ft}^2\text{-sec}$, and appropriate for the SNAP 10A diameter size assembly.

From the measured readings of Sensors No. 2 (stagnation line center), 4 (45° back from stagnation line), and 5 (90° back from stagnation line), local-to-stagnation line heating ratios were calculated around the periphery of the calorimeter assembly. The calculated values for each test condition are plotted in

TABLE 2
CALORIMETER ASSEMBLY TEST RESULTS FOR CROSS-AXIAL FLOW

Test Condition	Measured Heating Rates (Btu/ft ² -sec)				
	1 Stagnation Line Bottom	2 Stagnation Line Center	3 Stagnation Line Top	4 45° Back	5 90° Back
I	150	192	142	119	17
J	167	226	153	139	17
H	298	293	269	193	23
C	303	279	245	179	23
M	290	274	253	170	23
K	336	534	292	319	41
D	286	463	241	282	38
P	249	404	217	236	37
G	338	596	321	368	64
U	362	581	387	330	48
F	300	523	335	309	44
T	185	311	203	177	30
R	356	442	385	276	41
S	587	596	526	379	45

Figure 28 as a function of angle from the stagnation line. Good agreement may be noted among the values for the different test conditions. For Sensor No. 4, all values fall within a ± 0.05 deviation range about the mean value, 0.61 and for Sensor No. 5, all values fall within a ± 0.02 deviation range about the mean value, 0.09.

These results are compared, in Figure 28, with the corresponding peripheral heating ratios used in previous analytical studies.⁽²⁾ The present results indicate somewhat lower heating ratios around the backside of the cylinder than those expected for an infinitely long cylinder on the basis of past analytical and experimental investigations.^(1, 12, 13) The lower values may be due, however, to flow irregularities (flow blockage, hot core, etc.) inherent in the jet stream. It seems unlikely that they are due to the low length-to-diameter ratio (1.6) of

Figure 28. Local-to-Stagnation Point Heating Ratio Around the Periphery of the Cross-Axial Calorimeter

the fuel specimens and calorimeter assembly, since Baughn's results⁽¹⁾ are higher for the same size specimens. A trend was noted for the calculated ratios in that the values for those test conditions, characterized by pronounced axial heating profiles (see following discussion), tended to be lower than mean values. Conversely, the ratios were higher for those test conditions characterized by uniform axial heating.

A smooth curve was drawn, in Figure 28, through the mean (for all fourteen test conditions) peripheral heating ratios. The shape of this curve was assumed to be roughly parallel to the corresponding (dashed) curve which was used in Reference 2. The area under the curve drawn through the present data was then evaluated from 0 to 180°. Knowing this area, the average-to-stagnation point heating ratio may, for a rotating cylinder in cross-flow, be calculated. This parameter, generally noted by F_Q , was calculated to be 0.31. For comparison, the corresponding value previously assumed in fuel element reentry statistical analyses is 0.36.^(2, 14) It should be noted that the present lower value, although appropriate for the particular arc-jet test conditions and not necessarily for free flight (reentry), was derived from measurements made apparently in the complete absence of end heating effects.

The measured calorimeter readings from Sensors No. 1, 2, and 3 indicate the axial heating distributions to the SNAP 10A size specimens for each test condition. It can be seen, from Table 2, that the heating was a maximum almost invariably at the axial center (Sensor No. 2). Measured heating rates for the top and bottom sensors were generally in fair agreement with each other. Test conditions H, C, M, and S exhibited relatively uniform heating along the axial length. It is interesting to note that these conditions are also those with high stagnation-enthalpy values. For these four conditions, the three stagnation-line heating rates were summed and an average value calculated. These average values were then used in analytical computations, assuming uniform surface heating, performed to correlate the experimental temperature response data. The average heating values are listed in Table 3.

For the remaining test conditions, the measured heating was not uniform along the axial length. For these, the heating rates for the top and bottom sensors were averaged and normalized to the center (peak) heating rate. The results are shown graphically in Figure 29 for the various test conditions used for cross-axial test runs with SNAP 10A size diameter specimens. Curves drawn through the data points were assumed to have a chopped cosine shape. It is

Figure 29. Axial Heating Distributions for SNAP-10A-Size Fuel Specimens Under Various Test Conditions

TABLE 3
FUEL SPECIMEN AVERAGE* SURFACE HEATING RATES
(COLD WALL)

Test Condition	Theoretical Heat Rate (Btu/ft ² -sec)	Measured Heat Rate (Btu/ft ² -sec)	Peak-to-Average Heating Ratio
SNAP 10A Diameter Size Specimens			
F	86	114	1.41
U	86	130	1.36
D	60	98	1.46
G	71	121	1.52
K	70	114	1.44
C	78	85	1.00
H	83	90	1.00
M	70	83	1.00
R	105	118	1.15
S	151	170	1.08
SNAP 8 Diameter Size Specimens			
I	55	72	1.22
J	69	82	1.25
D	90	144	1.46
C	117	127	1.00
P	78	124	1.45
T	74	102	1.39

*Based on $F_Q = 0.31$

apparent from Figure 29 that a hot core existed for these test conditions. Relative heating rates are seen to taper off drastically at the specimen ends.

A comparison is made, in Table 3, for both theoretical (based on the Fay-Riddell equation) and measured (average over the axial length) surface heating rates. The average measured values were evaluated by integrating under the axial heating profile curves in Figure 29. In every case, these measured values

were higher than the corresponding heating values computed using the Fay-Riddell equation. Moreover, the degree of deviation seemed to be directly proportional to the severity of the axial heating profile. That is, for large axial peak-to-average heating ratios, the measured heating rates exceeded the theoretical by substantial amounts. For those test conditions in which the axial heating was relatively uniform, the measured heating rates were, consistently, only slightly (about 8%) higher.

V. TEST RESULTS AND ANALYSIS

A. GROUP I: COATED CALORIMETER TESTS

The first group of tests was conducted with coated Asymptotic calorimeters (Configuration I) for the purpose of determining the effect of surface catalycity on heat flux. Many tests runs were made for initial data and for repeatability. The test conditions for each run were set and although small deviations in conditions occurred from run to run, the repeatability of a test condition was such that the reference heat flux deviated by only 5%. If a larger deviation occurred, the run was considered questionable. The test conditions used for Group I were chosen to correspond to near-frozen boundary layer flow. Care was taken to determine in advance the recombination rate parameter, C_1 , (see Section V-C-3) for the test conditions being used. The operating envelope of the North American Aviation wind tunnel is shown in Figure 30. Each condition used is shown on the envelope along with the recombination rate parameters, determined according to the defining equations given in Section V-C-3. As can be seen from these equations, the recombination rate parameter is inversely proportional to the velocity gradient, du_e/dx , and directly proportional to the radius of the model.

Figure 30. Operating Envelope with Test Conditions and C_1 for Test Group I

Thus, to determine C_1 for a flat-faced cylinder the ratio $C_{1FF}/C_{1hemi} = (du_e/dx)_{hemi}/(du_e/dx)_{FF}$ is used, yielding, $C_{1FF} = 4R_n C_{1hemi}$.⁽¹⁵⁾ For reference, an additional value of the recombination rate parameter is shown in Figure 30 for a 1-ft radius hemisphere.

The lower test condition, I, was chosen for the 1/8-in. diameter calorimeters so as not to exceed their maximum heat-flux rating. The nominal output of each calorimeter ranged from 0 to 10 millivolts which corresponds to a heat-flux range of 0 to 500 Btu/ft²-sec for the 5/8-in. diameter calorimeters and 0 to 400 Btu/ft²-sec for the 1/8-in. diameter calorimeters. The recorded output was reduced to measured heat flux using the calibration curve for each sensor. The jet conditions were then used with Figure 2 to obtain a reference heat flux. In Figure 2, the reference heat flux ($q_S\sqrt{R_n}$) is to a hemisphere of 1-in. radius. This was related to the theoretical stagnation point heat flux to a flat-faced cylinder in equilibrium boundary layer flow [$q_{S(FF)}$] by the relationship⁽¹⁶⁾

$$q_{S(FF)} = \frac{0.55 (\dot{q}_S \sqrt{R_n})}{\sqrt{R_n}} \quad \dots (2)$$

The measured heat flux, q_m , was then ratioed to $q_{S(FF)}$. The results are shown in Figure 31 for the materials and test conditions considered. As seen in the figure, the ratio $q_m/q_{S(FF)}$ varies from 0.44 to 1.35 depending on material and test condition. That a ratio greater than 1.0 was obtained for a catalytic material (silver) is consistent with theory. In equilibrium flow the air recombines in the boundary layer and a portion of the heat of dissociation is lost, while a catalytic wall in frozen flow will obtain a greater portion of the energy tied up in the heat of dissociation since the recombination occurs nearer the wall. In addition, second order effects tend to increase the heat flux from equilibrium boundary layer theory.⁽⁴⁾

The order of the test data, at each condition, in Figure 31, is highly significant with respect to the catalytic efficiency of the test materials. Silver is known to have a high catalytic efficiency for oxygen atom recombination, while selenium and oxides have a low catalytic efficiency.⁽¹⁷⁾ Table 4 presents the catalytic efficiency of several materials including some that were tested in Group I. It can

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Figure 31. Measured-to-Theoretical Heat Flux Ratio for Coated Asymptotic Calorimeter Tests

TABLE 4
CATALYTIC EFFICIENCY OF SOME MATERIALS⁽¹⁷⁾

Material	Catalytic Efficiency (γ_A)* $\times 10^4$	Material	Catalytic Efficiency (γ_A)* $\times 10^4$
Silver	2400	Selenium	1.7
Copper	1700	Copper Oxide	200
Iron	360	Nickel Oxide	77
Nickel	280	Aluminum Oxide	26
Gold	52	Pyrex	1.2
Antimony	8.2	Potassium Chloride	2.8
Arsenic	4.6	Cesium Chloride	3.0

*Catalytic Efficiency (γ_A) = $\frac{\text{Atomic Collisions Effective in Recombination}}{\text{Total Number of Atomic Collisions}}$

be seen from the table that gold has a much lower catalytic efficiency, γ_A , than silver. Stainless steel appears to be relatively low in catalytic efficiency and oxidized stainless steel should be even lower, according to the trends in Table 4. However, it would be expected that when the major portion of the heat flux is due to molecular conduction, a further reduction in γ_A will not affect the surface heat flux. The similarity in the measured heat flux to stainless steel and oxidized stainless steel may be attributed to the above or to only a small real difference in their catalytic efficiencies.

A determining factor of the chemistry of boundary layer flow is the recombination rate parameter, C_1 , defined quantitatively in Section V-C-3. The effect of C_1 on the aerodynamic heat-transfer rate (expressed as the Nusselt number, Nu , divided by the square root of the Reynolds number, i.e., $(Nu/\sqrt{Re})$ was calculated by Fay and Riddell⁽⁸⁾ and is shown in Figure 32 for a given set of conditions. Two conclusions can be drawn from the figure: (1) there is no significant variation of heat-transfer rate with the parameter, C_1 , if the wall is catalytic to atom recombination; and (2) if the wall is noncatalytic, a significant reduction in the heat-transfer rate accompanies a decrease in the recombination rate parameter, C_1 . Therefore, to substantiate the data received from the calorimeter measurements as following this trend of heat-transfer reduction with decreasing C_1 , the data is shown in Figure 33 as a function of C_1 . At each

Figure 32. Heat-Transfer and Recombination-Rate Parameters for Boundary Layer Flow

Figure 33. Coated Asymptotic Calorimeter Heat-Flux Measurements and Recombination-Rate Parameter for a Flat-Faced Cylinder

test condition, the data for each material was averaged for that condition. It can be seen in the figure that the heat-transfer reduction is significant with lower values of the recombination rate parameter. It is necessary to point out, however, that Figure 32 is based on one particular set of conditions and since the test data represent several conditions, only a qualitative comparison can be made.

The hyperthermal wind tunnel simulates the conditions of reentry by arc-heating air and expanding it through a contoured nozzle to a nominal Mach-3 jet. Unlike reentry, however, the free stream of the arc-jet is partially dissociated and so only part of the dissociation occurs in the shock layer. For the test conditions used here, approximately 40% of the air is dissociated in the plenum prior to expansion through the nozzle. Some recombination will occur in the nozzle and in the jet itself. However, behind the shock at the stagnation point the gas will, if in equilibrium, return to a condition of approximately 40% dissociation. The effect of catalycity would then be expected to be significant since the recombination rate parameter indicates essentially a frozen boundary layer for these conditions ($C_1 \ll 1$). Since the major portion of the dissociation has occurred prior to the shock, the problem of the nonequilibrium shock layer, a formidable one in the case of reentry, provides only a secondary effect in the hyperthermal wind tunnel. Other secondary effects, such as external vorticity, will be considered in Section V-C-3 where correlation of the data is made in terms of the Reynolds number, the amount of dissociation in the free stream, and the "effective" catalytic efficiency.

The data presented in Figure 31 are those obtained with a clean sensor face and with no apparent damage to the sensor. Data obtained with contaminated sensors or after apparent damage to the coating had occurred, were excluded. As a result, only one data point was obtained with the selenium coating and only at test Condition C, and one data point with the zirconia coating at Condition I. It was found difficult to maintain the coating on the 1/8-in. diameter calorimeters, which were tested only at Condition I, and only one data point was obtained for zirconium and silver along with zirconia. Therefore, due to the lack of repeatable data, these were considered questionable data points. However, these are consistent with other data and indicate proper proportionality according to the flow condition.

In summary, the conditions of flow in a hyperthermal wind tunnel and those of orbital reentry in which body surface catalycity has a significant effect on the heat flux have been discussed. It is important to consider this effect since large errors in heat-flux measurement may occur if it is neglected.

The methods used in this test series for measuring the heat flux to surface materials of zirconium, zirconia, stainless steel, gold, silver, and selenium were described. The Asymptotic calorimeter was used with surface coatings of these materials. The major problem in making measurements with a significant catalycity effect is surface contamination and material adherence to the calorimeter. Surfaces must be carefully examined prior to and after each test run.

A significant variation in heat flux with these materials of different surface catalycity was observed. The ratio of the measured heat flux to a reference heat flux (the theoretical heat flux for an equilibrium boundary layer) varied from 0.44 to 1.35. The lower value occurred with zirconia but was considered questionable. A value of 0.71 was obtained for selenium which is known to have a relatively low catalytic efficiency. The high value of 1.35 was obtained for silver which has a high catalytic efficiency.

B. GROUP II: STATIONARY CROSS-AXIAL TESTS

The primary objective of this second group of tests was the determination of the fuel surface emissivity throughout typical reentry temperature transients. In addition, the acquisition of data on the ablation characteristics of the fuel specimens in a nonrotating cross-axial orientation was a secondary objective.

The specimen configuration with data instrumentation is schematically shown in Section III-B. Eight test runs were made in this group using five different test conditions (K, G, R, F, and S). A summary of the results and data obtained from these eight tests is given in Table 5.

In the first five tests (Runs 2-01 to 2-05), two optical pyrometers were utilized to record surface temperatures. These pyrometers were trained on opposite sides of the fuel specimens, at the axial center, 90° back from the stagnation line. In Run No. 2-04, additional thermocouple data were obtained, recording temperatures just beneath the surface at a location monitored by one of the optical pyrometers. By comparing, at each time, the thermocouple

TABLE 5
SUMMARY OF TESTS ON STATIONARY SPECIMENS
IN CROSS-AXIAL FLOW

Run No.	Test Condition	Data Obtained			Time to Initial Ablation (sec)	Time to Complete Ablation (sec)
		Pyrometer No. 1	Pyrometer No. 2	Thermocouple Data		
2-01	K	X	X		Equilibrium	
2-02	G	X	X		Equilibrium	
2-03	R	X	X		Equilibrium	
2-04	F	X	X	X	Equilibrium	
2-05	S	X	X		21.5	170.0
2-06	S		X		53.2	90.2
2-07	S		X	X	57.2	103.9
2-08	S		X	X	40.4	88.3

readings with equivalent black-body pyrometer temperatures and knowing the temperature difference across the surface crust, one can determine the emissivity of the fuel surface for whichever gray-body conversion of the pyrometer data correlates best with the thermocouple data.

An important prerequisite for the success of these emissivity determinations is that the temperature difference between the thermocouple junction and the adjacent surface remain small. If this is the case, uncertainties in this temperature difference will not cause undue uncertainties in emissivity determinations.

In the last three tests (Runs 2-06, 2-07, and 2-08) made in Group II, only one optical pyrometer was used, which, of course, was trained on the thermocouple location. No thermocouple data were obtained for Test Run 2-06. However, good data were obtained in Test Runs 2-07 and 2-08 up to the time of ablation of the fuel material immediately surrounding the thermocouple junction.

The transient temperature data for all the test runs were plotted vs time using special computer programs. It became evident from these plots that large differences exist between the readings of the two pyrometers throughout some of these tests (Runs 2-02 and 2-03, for example). These may be attributed to

uneven oxide layer growth, as was evident from the photographic data in which the temperature of the surface is thought to increase at spots covered by the growing oxide layer. This heavy oxide buildup can be seen in Figure 34, which is a post-test photograph of the first three nonablated specimens, and in Figure 35. Also, at later times, the flowback of molten material from the stagnation line is viewed by the pyrometers, drastically increasing temperatures. This molten flowback is shown in Figure 35 (note the outgassing of hydrogen at $t = 1.5$ and $t = 2.17$ sec).

Comparisons of the thermocouple data with the corresponding pyrometer data, corrected for an assumed constant emissivity of 0.4, may be made from Figures 36 and 37. In addition, the pyrometer data are compared with the analytical calculations (using the model outlined in the Appendix) for Condition S in Figure 38. These figures indicate a much larger temperature difference between thermocouple and pyrometer readings than was anticipated. Since the

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Figure 34. Group II Test Specimens After Runs
(Configurations II)

Figure 35. Arc-Jet Test Run No. 2-07
(24 frames/sec Motion Picture Film)

Figure 36. Measured Surface and Thermocouple Temperatures for Arc-Jet Test Run No. 2-04

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Figure 37. Measured Surface and Thermocouple Temperatures for Arc-Jet Test Runs No. 2-07 and 2-08

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Figure 38. Comparison of Calculated to Measured Surface Temperatures (Arc-Jet Test Runs No. 2-05, 2-06, 2-07, and 2-08)

total amount of temperature correction going from black-body (black-body pyrometer temperature traces are given in Reference 6) to gray-body pyrometer readings ranges from 100 to 350° through each run, for a gray-body emissivity of 0.4, there can be no doubt that large temperature differences existed between the thermocouple junction and the surface. In Figure 37, fair agreement is noted in surface temperatures for Runs 2-07 and 2-08, whereas the thermocouple data indicate a response lag for the thermocouple in Run 2-08.

Finally, convincing evidence that large temperature differences existed between the thermocouple junction and the surface comes from the post-test macrographic data presented in Section V-C-5. In a cross-section macrograph of the fuel specimen used in Run 2-04, the thermocouple tip is seen to be about 1/16 in. from the surface. This is somewhat deeper than was planned. More important, the thermocouple tip is seen to lie within a void space or hole in the specimen which may be due, in part, to the original size of the drilled hole with respect to the thermocouple diameter. It also appears evident that the thermocouple hole developed during heating as the fuel material cracked due to the strong hydrogen outgassing. The resulting poor thermocouple contact would thereby be consistent with the recorded data.

In view of these results, quantitative data on the surface emissivity could not easily be obtained. It appears possible that with further study some estimations of the emissivity values could be determined. One could take into account heat conduction across the oxide layer and across the 1/16-in. depth of fuel material, in addition to heat radiation across the void space to the thermocouple junction. An appropriate temperature difference could then be determined. With this, the magnitude of the surface emissivity could be approximated. Such results, however, would be compromised by the uncertainties inherent in the calculations of the temperature difference.

It is important to note that the Group-II tests demonstrate a definite difference in overall ablation characteristics as compared to tests made on rotating specimens. The times observed for complete ablation (Table 5) were found to be substantially longer for the stationary cross-axial orientation. Analytical calculations indicate that a rotating specimen would be completely ablated at about 60 sec for flow condition S. Observed ablation times for the stationary tests

were correspondingly higher. Moreover, the stationary specimens did not ablate for test conditions K, G, and F, whereas rotating specimens tested at these same conditions ablated completely (see Section C following). Further careful investigation is needed to understand fully the underlying causes for this gross behavior difference.

C. GROUP III: ROTATING CROSS-AXIAL TESTS

The third and largest group of tests had the primary purpose of evaluating the effect of radius on the fuel material behavior over a wide range of test conditions. A total of 28 tests was made using 12 different test conditions. The specimens were held in the jet and rotated in cross-axial flow until ablation or equilibrium was achieved. Specific configuration details are given in Section III-B. SNAP 8 size diameter specimens were used in 12 of these tests; the remaining tests were performed for SNAP 10A size diameter specimens. Overall, 20 specimens were ablated, 7 reached equilibrium, and 1 was prematurely withdrawn. Ten runs were made with completely solid specimens; the rest had tungsten rod holders. A detailed summary of all Group III tests is given in Table 6.

1. Photography

a. Motion Picture Film Data

Each test run, from the time of specimen insertion into the jet until withdrawal of the sting, was filmed with a 24-frame/sec color motion picture camera. The film was reviewed in detail with a frame-counting projector and the events were recorded for each entire test run. A listing is given in Table 7 of the significant events which were observed and recorded. The quality of the 24-frame/sec film was quite good throughout the tests.

In addition to the normal event film, high-speed (400-frame/sec) color motion picture film was utilized to record the sequence of events during actual ablation for nine selected test runs (see Table 6). The quality of the 400-frame/sec film was also found to be quite good and sufficient to fulfill its intended purpose.

Detailed analysis of all of the film data showed that, qualitatively, the fuel thermochemical behavior was consistent from test run to test run within the

TABLE 6
SUMMARY OF TESTS ON ROTATING CROSS-AXIAL
SNAP 8 AND 10A SIZE SPECIMENS

Run No.	Configuration (Section III-B)	SNAP Type Size	Time to Initial Ablation (sec)	Test Condition	Special Instrumentation
3-01	III-B-1	10A	86.1	F	Laser-schlieren photography
3-02	III-B-1	10A	46.5	U	Laser-schlieren photography
3-03	III-A-1	10A	81.3	U	Laser-schlieren photography
3-04	III-A-1	10A	87.1	U	Laser-schlieren photography
3-05	III-B-1	10A	Equilibrium	C	Laser-schlieren photography
3-06	III-B-2	8	53.0	T	Laser-schlieren photography
3-07	III-B-2	8	52.9	T	Laser-schlieren photography
3-08	III-C-2	8	39.8	P	Laser-schlieren photography
3-09	III-A-2	8	59.5	T	Laser-schlieren photography
3-10	III-A-2	8	59.5	T	Laser-schlieren photography
3-11	III-A-1	10A	Equilibrium	C	400 frame/sec film
3-12	III-A-1	10A	Equilibrium	D	None
3-13	III-A-2	8	42.5	C	400 frame/sec film
3-14	III-A-2	8	33.8	D	None
3-15	III-B-1	10A	Withdrawn	G	None
3-16	III-B-1	10A	93.3	G	400 frame/sec film
3-17	III-B-2	8	Equilibrium	I	None
3-18	III-B-2	8	84.1	J	400 frame/sec film
3-19	III-C-2	8	96.8	J	None
3-20	III-C-1	10A	165.1	H	400 frame/sec film
3-21	III-C-1	10A	166.7	K	400 frame/sec film
3-22	III-C-1	10A	Equilibrium	H	None
3-23	III-C-2	8	36.3	D	400 frame/sec film
3-24	III-C-2	8	Equilibrium	J	None
3-25	III-A-1	10A	130.8	G	400 frame/sec film, second optical pyrometer
3-26	III-A-1	10A	118.5	K	Second optical pyrometer
3-27	III-C-1	10A	105.3	K	400 frame/sec film, second optical pyrometer
3-28	III-B-1	10A	Equilibrium	H	Second optical pyrometer

TABLE 7
MOTION PICTURE FILM EVENT DATA
(24 Frames per Second)

Run No.	Test Condition	Time (sec)					
		Initial Hydrogen Detection	Initial Cracking	Initial Oxide Formation	Hydrogen No Longer Detectable	Initial Ablation	Final Ablation or Withdrawal
2-01	K	1.5	-	8.8	10.2	-	296.2
2-02	G	1.4	64.7	-	7.4	-	293.8
2-03	R	-	-	5.4	-	-	297.3
2-04	F	-	-	15.0	-	-	261.8
2-05	S	-	-	-	-	21.5	170.0
2-06	S	-	-	1.2	-	53.2	90.2
2-07	S	-	-	2.1	-	57.2	103.9
2-08	S	-	-	1.4	-	40.4	88.3
3-01	F	-	18.8	58.4	-	86.1	90.3
3-02	U	-	8.2	36.5	-	46.5	74.5
3-03	U	-	14.3	47.7	-	81.3	90.3
3-04	U	-	37.2	48.8	-	87.1	96.4
3-05	C	6.6	26.9	110.9	71.1	-	261.5
3-06	T	-	-	-	-	53.0	63.5
3-07	T	-	-	-	-	52.9	70.0
3-08	P	5.4	2.3	-	12.3	39.8	55.6
3-09	T	-	21.5	-	-	59.5	83.0
3-10	T	-	13.8	-	-	59.5	131.8
3-11	C	9.8	33.9	76.2	100.0	-	227.4
3-12	D	19.5	26.2	84.9	79.2	-	241.2
3-13	C	15.1	2.3	-	35.0	42.5	180.4
3-14	D	17.0	-	-	32.6	33.8	119.7
3-15	G	-	1.7	-	-	-	46.8
3-16	G	23.0	10.6	60.9	46.4	93.3	146.0
3-17	I	-	-	225.1	-	-	244.0
3-18	J	-	-	-	-	84.1	176.0
3-19	J	-	124.8	-	-	96.8	174.9
3-20	H	23.1	23.3	82.4	95.8	165.1	210.5
3-21	K	16.0	22.0	80.9	69.9	100.7	140.0
3-22	H	26.5	35.6	121.3	87.6	-	264.6
3-23	D	7.3	-	-	20.3	36.3	65.3
3-24	J	-	-	157.2	-	-	300.3
3-25	G	20.0	19.6	61.6	59.2	130.8	238.9
3-26	K	14.2	-	63.9	60.3	118.5	238.8
3-27	K	13.0	21.6	67.3	63.3	105.3	145.0
3-28	H	37.8	34.7	132.3	102.6	-	241.8
4-01	H	20.1	15.7	87.6	77.5	-	298.7
4-02	K	5.9	10.8	54.4	50.0	109.5	141.1
4-03	M	-	-	89.4	-	-	360.2
4-04	K	4.3	24.5	52.4	47.8	100.2	126.0
4-05	K	13.4	3.3	39.6	30.1	46.6	113.3
4-06	K	16.5	30.4	55.7	47.2	142.2	189.1
4-07	K	12.8	40.2	69.3	27.8	100.0	107.8
4-08	K	-	1.1	-	-	56.7	104.6

Group III series. Comparisons with previous tests of this kind⁽¹⁾ evidence some dissimilarities attributable to specific arc-jet characteristics and test conditions used. The fuel thermochemical behavior in the present tests may be specifically outlined by the following film observations which summarize the results of the motion picture film analysis:

1) Heavy zirconium-oxide buildup occurred at the surface of all specimens. Except for those tests in which ablation occurred relatively soon after insertion, this oxide buildup resulted in flaking and spalling of the oxide at high temperatures. Such flaking is immediately apparent in Figure 39 and in the post-test photograph in Figure 40. Since little or no flaking was observed in the previous arc-jet test series, the increased oxidation and flaking in the present tests appears to be due to the particular arc-jet gas composition and flow characteristics. The arc-jet facility at NAA/LAD has recently been improved, before the tests described in this report, by the installation of a new arc head. This improvement makes it possible to obtain higher enthalpy values with low stagnation pressures. The nozzle diameter for the present test was 2.5 in. compared to the 3.5-in. diameter nozzle used previously. Accompanying these changes is a modification of the gas mixing procedures before expansion of the gas out the nozzle. Increased oxidation could be the direct result of these modifications. It should be noted that a correlation between the amount of oxidation attained and the test condition used could not be drawn from the motion picture film data. It is conceivable that, in going from an equilibrium boundary layer flow to frozen flow, the amount of oxidation (and/or heat of oxidation) might change with an increasing preponderance of oxygen atoms over oxygen molecules at the surface.

2) Hydrogen outgassing was visually evidenced in the 24-frame/sec film data for many of the test conditions used (C, P, D, G, H, K, and M). It could not be observed with certainty in tests run at other test conditions. The hydrogen outgassing, although not as apparent in the black-and-white still photographs as in large, running projections of the color motion picture film, can be faintly noted in many of the photographs shown in this report. As in the Group-II test runs, the outgassing appeared for the most part to

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Figure 39. Arc-Jet Test Run No. 3-25 (400 frames/sec Motion Picture Film)

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Figure 40. Group III Test Specimens After Runs (Configuration IIIA1)

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be uniform and continuous along the stagnation line. The occurrence of large radial cracks in the fuel provided exceptions to this observation, as strikingly evident in film data for Runs 3-13 and 3-27. For these runs, the hydrogen may be seen emitting profusely from one or several open cracks in the fuel material (see, for example, Figure 41).

3) The occurrence of large, radial cracks appeared to be confined to configurations with tungsten rod holders. Completely solid specimens developed a fine network of microcracks but were rarely noted to incur large, radial cracks. (The one exception was Test Run 3-13, Figure 41.) This observation lends support to Baughn's⁽¹⁾ previous finding that these large cracks appear to originate at the hole for the tungsten rod holder. The large cracks, which in some cases developed into splits, in the configurations containing the tungsten holder influenced the manner in which the specimens ablated. These specimens usually ablated in a piecemeal fashion as evidenced from Figure 42 and in the previous arc-jet test series,⁽¹⁾ while the integrity of the solid fuel specimens was maintained up to ablation through the center of the specimen as shown in Figure 43. Nonablated specimens are shown in post-test photographs in Figures 40 and 44 for both types of configurations and the difference in cracking can easily be seen.

4) The oxide layer was found to be tenacious enough to inhibit fuel ablation until a substantial portion of fuel material became molten underneath the oxide layer. Most noteworthy examples were Test Runs 3-06 and 3-07 (Figure 45) in which the molten fuel was seen to spew out the bottom at the initiation of ablation. Figure 46 is a post-test photograph showing the resolidified fuel material at the base of the specimen used in Run 3-07. Ablation sequences, filmed with the 400-frame/sec film, were always characterized by the expulsion of molten fuel material out of cavities or gaps in the oxide layer (see, for example, Figure 47). This effect was more pronounced in these tests than in previous ones due to the increased oxide layer thickness.

5) An uneven distribution of heating along the axial specimen length was evident in many test runs as indicated by distinct differences in incandescence

Figure 41. Arc-Jet Test Run No. 3-13 (24 frames/sec Motion Picture Film)

Figure 42. Arc-Jet Test Run No. 3-27 (24 frames/sec Motion Picture Film)

Figure 43. Arc-Jet Test Run No. 3-03 (24 frames/sec Motion Picture Film)

Figure 44. Group III Test Specimens After Runs (Configuration IIIC1)

Figure 45. Arc-Jet Test Run No. 3-07 (24 frames/sec Motion Picture Film)

Figure 46. Group III Test Specimens After Runs (Configurations IIIB2, IIC2, and IIIA2)

Figure 47. Arc-Jet Test Run No. 3-16
(400 frames/sec Motion Picture Film)

along the axis. In all such cases, the heating was greater at the axial center and tapered off at both ends. Ablation was consistently initiated at the center. The heating at the axial ends was often insufficient to completely ablate the remaining specimen end portions. Some of the specimens, however, exhibited relatively uniform surface heating, notably those for test conditions C and H. The complete absence of corner heating effects is a marked characteristic of the present arc-jet test series. It strongly contrasts with the observed behavior in the previous arc-jet test series, in which the flow shock diamond of the 3-in. nozzle completely enveloped the length of the 2-in. specimens. This resulted in higher heating rates at the specimen ends, as well as higher overall stagnation-point-to-average heating ratios. As a consequence, ablation usually initiated at the ends of the specimens in these tests (see Pages 31 through 42 of Reference 1). This difference in fuel behavior between the two test series may be attributed to differences in test design and facility modifications. Specifically, the smaller 2-in. nozzle used in the recent tests, the distance of the specimens from the nozzle, and the method of gas injection and mixing may be cited (see Section III-A).

6) The 400-frame/sec motion picture film was found to be highly effective in recording the details of the ablation sequence. The events appear clearly in slow motion action with high resolution. Particles of molten fuel material extruded from the specimens are seen, in still photographs (Figure 47), in mid-motion, often undistorted and unblurred. The fact that some of the particles are distorted while most are not (in the same focus range) points to the difference in velocities of the extruded particles. It is felt that these photographs can be usefully applied in future work as a supplementary source of data (in addition to laser photography, Section V-E) for determinations of fuel particle size distributions. Such information is essential for fuel particle formation and disintegration studies.

b. Laser-Schlieren Photography

A secondary objective of Test Group III was to photograph hydrogen escape from the fuel specimens by means of a laser-schlieren system. This was attempted during the first 10 runs of Group III (see Table 6). The results were inconclusive and did not establish definite photographic evidence of hydrogen outgassing. However, Figure 48 shows an example of one of the better quality photographs taken during Test Run No. 3-09, and from observation there appears to be the images of two shock waves in front of the specimen (these are definitely not due to a misalignment of the double-pass system, as otherwise, they would be symmetrical to the last detail, in which case the model itself would also appear with double contours). Tentatively, they have been identified as the usual bow shock wave and the boundary of the hydrogen gas escaping from the specimen. Comparison of this appearance with the hydrogen outgassing as seen in the motion picture film data seems to substantiate this assumption.

Laser-schlieren photography was started at the beginning of a test run, carried through to its completion, and although the exact timing is not known, the sequence number is indicated. Those photographs in the sequence that were over- or underexposed, and therefore not resolvable, were eliminated.

Laser-schlieren photographs taken during Test Run No. 3-10 are shown in Figures 49 and 50. Figure 49 is a similar photograph to Figure 48 in that, here again, the two faint "waves" in front of the specimen can be seen. Also, in this particular photograph, there appears to be an eruption of gas at one distinct point

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Figure 48. Laser Schlieren Photography for
Arc-Jet Test Run No. 3-09
(Film Frame No. 6)

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Figure 49. Laser-Schlieren
Photography for Arc-Jet
Test Run No. 3-10
(Film Frame No. 2)

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Figure 50. Laser-Schlieren
Photography for Arc-Jet
Test Run No. 3-10
(Film Frame No. 5)

on the surface which could be from either a crack in the fuel specimen or from a breach in the oxide layer as witnessed in the motion picture film. However, this photograph is Sequence No. 2 and taken just after the specimen was lowered into the jet stream and no cracks or oxide layer are evident in the early stages of the test run from film observation.

The "speckled" appearance in Figures 49 and 50 is due to particles of ablated fuel material from previous runs which have adhered to the schlieren mirror. All of the more legible photographs shown clearly display a bright line along surface boundaries, which is quite typical of schlieren photographs in general. However, they seem to be more pronounced in laser-schlieren systems. Also, when comparing the figures by sequence, it could be seen how the adjustment of the system changed. The bright areas (seen at the right in Figure 48) vary in intensity from a grey background (proper exposure) to a fully illuminated background. This was attributed to the slightly varying output of the laser coupled with the fine adjustments required of the system, particularly when the temperature of the specimen was quite high.

The photographs shown in Figures 48 through 50 were taken during those particular test runs for which no protection was provided for the schlieren mirror and are very close to the sensitivity limits of the schlieren system. Under similar test conditions, but with a protecting 1/4-in. glass plate in front of the mirror, the shock wave pattern did not show. This corroborates the claim that maximum schlieren sensitivity can only be obtained with all windows removed from the light path.^(18,19) Figure 51 is a photograph taken during Test Run No. 3-03 with a 1/4-in.-thick protective plate glass in front of the schlieren mirror. An irregular crack in the glass, caused by the environment, can be seen quite clearly and the background is far more "grainy" than in the previous photographs. Although the model size is larger in this case (1.25-in. diameter), no shock wave is visible.

Figures 48 through 50 showing schlieren photographs for Test Runs 3-09 and 3-10, were taken under the following approximate test conditions: airflow at a Mach number (M) of 3.4 with a stagnation enthalpy (H_S) of 2600 Btu/lb at a reservoir pressure of 2 atmospheres. The free stream density (ρ_∞) (equilibrium conditions) was calculated to be 2.4×10^{-4} lb/ft³. The photograph, Figure 51, for Run No. 3-03 was taken under the conditions $M = 3.35$, $H_S = 4600$ Btu/lb, and $\rho_\infty = 1.23 \times 10^{-4}$ lb/ft³.

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Figure 51. Laser-Schlieren Photography
for Arc-Jet Test Run No. 3-03
(Film Frame No. 10)

Before making any test runs, a check was made with a small continuous light source in the schlieren system, to observe the limits of the visibility of hydrogen escaping from a small orifice (about 0.006-in. width) into air at decreasing pressures and at room temperature, without flow from the plasma jet. This orifice was mounted in place of a test specimen inside the test chamber. From atmospheric pressure down to about 2 psia, trial photographs did not change appreciably in contrast, but below that pressure the contrast and contours of the hydrogen jet faded out rather quickly, so that at 0.5 psia the jet was invisible. This sudden loss of sensitivity was somewhat striking and is usually not expected; therefore, an explanation is suggested as follows:

From the theory of schlieren optics, it is well known that a disturbance in the light path is detectable due to a refraction (bending) of the light rays passing through such a disturbance. The larger the refraction angle, the more clearly the disturbance will appear (up to a certain limit depending on the range of the system). This deflection angle depends on various parameters: (a) the gradient of the refractive index (which is proportional to the density gradient) of the

disturbance, and (b) the length over which this gradient exists which is related to the actual size of the test object. The magnitude of the gradient also depends on the absolute value of the refractive index, n , itself (more precisely on $n - 1$). Unfortunately, this value is quite low for hydrogen, namely $n - 1 = 9 \times 10^{-5}$, compared with 29×10^{-5} for air at atmospheric conditions. This illustrates the magnitude of the problem of hydrogen detection. It would be much easier to detect a heavy noble (inert) gas, for example, under otherwise equal conditions.

In the case of the actual fuel test runs, the gradient obviously decreases with decreasing pressure or density as the refractive index itself decreases with pressure. Furthermore, the escaping hydrogen will spread out rapidly over a wider and wider angle with decreasing pressure of the surrounding air. This also reduces the gradients, but in this case in a much stronger fashion than a merely linear relationship would indicate. Therefore, the combined effects of lowering the refractive index and the lateral spreading of the hydrogen will generate something like a third or even higher order dependence of the schlieren sensitivity on the pressure in the test chamber.

In the event that the preliminary experiments had shown that hydrogen could be detected down to a pressure of about 0.5 psia at room temperature, the limiting pressure would probably be quite different under the conditions of a hot plasma jet. Even if the pitot pressure within the jet itself indicated higher than 0.5 psia, the corresponding density at the high temperatures of the jet is an order of magnitude lower than it would be under room temperature conditions. As the schlieren effect depends on the density, and not the pressure, it is obvious that hydrogen under the hot plasma jet conditions would be much less visible than at room temperature.

In summary, the successful adaptation of a laser-schlieren system to a hyperthermal wind tunnel has been described. The performance, however, was marginal with respect to the intended objective, namely, photographing the outgassing of hydrogen from the SNAP fuel material. This was mainly due to the following special circumstances of this particular test series that hindered high quality schlieren photographs:

- 1) Low pressures and high temperatures of the plasma jet which resulted in very low gas densities.

- 2) Low refractive index of hydrogen.
- 3) Small size of test specimens.
- 4) Nonuniformities in the laser output.
- 5) Impossibility of maintaining perfect alignment due to thermal shifting of the schlieren mirror.

Under more favorable conditions, it is felt that higher quality photographs with a schlieren system could have been obtained.

2. Correlation of Pyrometer Data

During each run in the Group-III tests, the optical pyrometer was used to monitor the temperatures of the specimen surface, usually at the axial center. The actual data readings obtained were values of the "uncorrected" temperature at particular times along the temperature transient. To reduce the pyrometer output to useful data, it was necessary to apply appropriate corrections.⁽⁶⁾

The optical pyrometer readings were converted, for an assumed surface emissivity of 0.4, and plotted as functions of time with the use of special computer programs. All Group-III test run data were grouped according to test condition. That is, the data for all tests run at any particular test condition were converted and plotted on the same graph for the same specimen size. The results are shown in Figures 52 through 64 for all tests run in the Group-III series. Data reproducibility is seen to be good, within any test condition, at low and intermediate temperatures. As expected, the data scatter is a maximum at high temperatures where the oxide layer effects dominate.

Correlations of the pyrometer data were made using the analytical computer models which simulate the thermochemical behavior of the fuel specimens. These models are summarized in the Appendix. Two model types or versions were employed. The one-dimensional model, which simulates radial heat and hydrogen flow, was used for all runs in which uniform heating may be assumed on the cylindrical surface. For test runs in which a definite axial distribution of heating was noted, the two-dimensional model simulating radial and axial heat and hydrogen flow was utilized. It is important to note that the processes simulated and the parameter values used were identical in both cases. Moreover, these

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Figure 52. Comparison of Calculated to Measured Surface Temperatures (Arc-Jet Test Run No. 3-01)

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Figure 53. Comparison of Calculated to Measured Surface Temperatures (Arc-Jet Test Runs No. 3-02, 3-03, and 3-04)

Figure 54. Comparison of Calculated to Measured Surface Temperatures (Arc-Jet Test Runs No. 3-06, 3-07, 3-09, and 3-10)

Figure 55. Comparison of Calculated to Measured Surface Temperatures (Arc-Jet Test Run No. 3-08)

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Figure 56. Comparison of Calculated to Measured Surface Temperatures (Arc-Jet Test Run No. 3-12)

Figure 57. Comparison of Calculated to Measured Surface Temperatures (Arc-Jet Test Runs No. 3-14 and 3-23)

Figure 58. Comparison of Calculated to Measured Surface Temperatures (Arc-Jet Test Runs No. 3-15, 3-16, and 3-25)

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Figure 59. Comparison of Calculated to Measured Surface Temperatures (Arc-Jet Test Runs No. 3-21, 3-26, and 3-27)

Figure 60. Comparison of Calculated to Measured Surface Temperatures (Arc-Jet Test Runs No. 3-05 and 3-11)

Figure 61. Comparison of Calculated to Measured Surface Temperatures (Arc-Jet Test Run No. 3-13)

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Figure 62. Comparison of Calculated to Measured Surface Temperatures (Arc-Jet Test Run No. 3-17)

Figure 63. Comparison of Calculated to Measured Surface Temperatures (Arc-Jet Test Runs No. 3-18, 3-19, and 3-24)

Figure 64. Comparison of Calculated to Measured Surface Temperatures (Arc-Jet Test Runs No. 3-20, 3-22, and 3-28)

models were consistent with and equivalent to the SNAP fuel element analytical model used for atmospheric reentry statistical analyses.⁽²⁾

Application of the appropriate model version for each cross-axial test condition was made after analysis of the results of the calorimeter-measured heating distributions (see Section IV). The calorimeter assembly data showed that pronounced axial heating distributions for a SNAP 10A size specimen occurred under test conditions F, U, G, D, and K. At the same time, the data showed that relatively uniform heating was achieved for test conditions C and H. Consequently, the two-dimensional model for radial and axial flow simulation was employed in analyzing the pyrometer data for all tests run on SNAP 10A size specimens for test conditions F, U, G, D, and K. Axial heating profiles according to Table 2 and Figure 29 were input into the model. An average-to-stagnation point heating ratio of 0.31 (see Section IV) was used for each axial increment in the model network. The measured heating rates input to the model were not corrected to account for noncatalytic wall effects, since the magnitude of the proper correction was uncertain. The obtained analytical predictions are thus appropriate for a surface that is fully catalytic. Hot-wall correction factors are, of course, made continuously by the analytical model according to the specified stagnation enthalpy and calculated surface temperatures.

The pyrometer data for all other test runs (all SNAP 8 size specimen runs and runs with test conditions C and H for SNAP 10A size specimens) in Group III were correlated using the one-dimensional model. Measured average surface heating rates given in Table 3 were input to the model in all cases. Thus, the axial heating profiles measured by the SNAP 10A size calorimeter assembly for test conditions I, J, D, P, and T were not applied to calculations for SNAP 8 size specimens, the reason being that these distributions are believed to be highly dependent on the test specimen diameter. The assumption is that the flow blockage would not be as great for the smaller size specimens. Therefore, in lieu of special and costly SNAP 8 size calorimeter assembly measurements, it was decided to apply the averaged heat flux values given in Table 3. As before, hot-wall corrections were made to these cold-wall heating values and the specimen surface was assumed to be fully catalytic.

The resulting analytical calculations for all test conditions are shown as solid curves in Figures 52 through 64. It is interesting to note that good correlation with the computer-plotted experimental data points was obtained for several test conditions (U, F, and T), while the correlation for other test conditions was notably poorer. In all of these latter cases (except for the one run at condition P) the calculated thermal response is sharper; the measured thermal response lags behind the analytical. The deviations are worst for test conditions I, J, and H. At these test conditions, however, heating reductions due to noncatalytic wall effects may be expected on the basis of the coated calorimeter test results (see Section V-A). Since such heating reductions result in slower experimental thermal responses, this effect offers a reasonable explanation for the observed deviations. On the basis of past extensive parametric studies,⁽²⁾ no other input parameter can be reasonably changed in such a manner so as to achieve good correlation for all test conditions.

As a first step toward determining quantitatively the effect of flow chemistry on the results, the amount of heating reduction was evaluated for each test condition. This was done by first constructing families of analytical temperature response curves (one for each model) for different heating rates. The corresponding experimental data for each test condition were then superimposed, and the analytical curve (and corresponding heating rate) was chosen which gave the best correlation. Particular attention was focused on the earlier (low-temperature) portions of these curves for the following reasons: (1) to eliminate uncertainties caused by severe oxide layer buildup and hydrogen outgassing; and (2) to obtain correlation where experimental data reproducibility was best. In this manner, values of the deviations between the analytical (based on a fully catalytic wall) and experimental results were estimated for each test condition and for each specimen size. The results are presented in Table 8. Included also in this table is the estimated reduction for flow condition M used in the fuel burnup enhancement tests discussed in the next section.

3. Extrapolation to Reentry Conditions

It is significant to note that, in the preceding analytical correlations of the fuel thermal response data, good correlation was obtained for those conditions (high stagnation pressure) for which little or no heating reductions due to surface

TABLE 8
ESTIMATED HEATING REDUCTIONS FOR
EACH TEST CONDITION

SNAP 10A Radius		SNAP 8 Radius	
Test Condition	Percentage Reduction	Test Condition	Percentage Reduction
F	0	I	28
U	0	J	21
D	18	D	6
G	15	C	15
K	12	P	0
C	24	T	0
H	28		
M	22		

catality were measured in the coated calorimeter (Group-I) tests. That is, on the basis of the Group-I test results, surface catalytic effects are small for these conditions. Correlations of the fuel data with the analytical model calculations (which assume no heating reductions) are consequently fully appropriate for these conditions. The good agreement observed for these conditions increases considerably the confidence in the analytical predictions.

Since analytical investigations for SNAP fuel element ablation probabilities have been made using this same model, an evaluation must be made of the effects of flow chemistry for those flight conditions in which noncatalytic wall effects may be significant. For, although the model may simulate accurately the thermochemical behavior, it is necessary to provide the appropriate cold-wall aerodynamic heat rates as input to the model. In previous reentry studies the net amount of heating reduction due to catalytic over the trajectory transient was assumed to be small — about 5% of the total heating. This value was based on the theoretical work of Inger⁽²⁰⁾ and Chung.⁽³⁾ Figure 65 shows the transient nonequilibrium heating reductions for various catalytic efficiency values and for SNAP 10A and SNAP 8 size diameters, calculated from Inger's reference values using binary scaling. A value of 10^{-2} was assumed for the fuel surface catalytic

efficiency, which was arrived at after reviewing typical literature values for metal oxides. It was recognized, however, that considerable variation in values exist even among metal oxides. Consequently, the need for experimental data appropriate for the actual fuel material in a reentry environment was recognized.

The results of the present tests show that surface catalycity effects are highly important for the fuel material under certain conditions. To help determine the extent of these effects under the specific conditions of reentry, a preliminary analysis was performed here in which the observed effects were correlated with the governing boundary layer flow parameters.

For a given surface catalytic efficiency, the heat transfer to a blunt body is partially dependent on the gas-phase recombination rate parameter, C_1 , and the Reynolds number, Re . The parameter C_1 determines the chemical state of the gas (degree of deviation from equilibrium) and the flow regime about the body can be described as a function of the Reynolds number. Similar flows possess similar C_1 values and similar Re values. The NAA/LAD hyperthermal wind tunnel used in these tests produces flow conditions in the continuum boundary layer regime.

Hypersonic boundary layer flow theory^(8,21) is well developed and recognized for flight at high altitudes where the mechanism of heat transfer includes both the molecular conduction of heat and the atomic diffusion of dissociated nitrogen and oxygen atoms. This occurs when the shock wave ahead of a body converts the kinetic energy into both the temperature increase of the air and the heat for dissociation of the molecular species. A considerable portion of this energy may be tied up in the heat of dissociation of the air. If this process occurs in the shock layer then the importance of heat conduction and atomic diffusion to the surface heat flux will be determined by the conditions in the boundary layer and at the body surface.

The dissociated gas will tend to recombine in the boundary layer since the wall temperature is normally low relative to the temperature required for dissociation. If the conditions in the boundary layer are such that the characteristic time for recombination (the reaction rate) is much shorter than the time required to diffuse across the boundary layer, then an equilibrium boundary

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Figure 65. Nonequilibrium-to-Equilibrium Heating Ratio for a Reentering Body with Non-catalytic Surface

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layer occurs. In this case the species of atoms and molecules in the boundary layer are described simply by the pressure and temperature in the boundary layer and the Mollier diagram for air. The concentration of atoms or dissociated air at the surface will then be essentially zero since the wall temperature is limited by the melting point of the wall material which is lower than the dissociation temperature. However, if the characteristic time for recombination is much longer than the time required to diffuse across the boundary layer, then the boundary layer is considered "frozen," that is, the reaction does not go to completion in the boundary layer. In this case, dissociated atoms will avail themselves to the surface and there they will be affected by the catalytic efficiency⁽²²⁾ of the wall. The surface may act as a catalytic wall promoting the recombination of these atoms and thus obtaining the heat tied up in dissociation, or it may act as a noncatalytic wall with no effect on the recombination, thus losing the heat tied up in dissociation. The catalycity of the surface may in this case have a significant effect on the surface heat flux.

The flow regimes of high-speed high-altitude flight have been described by Probstein⁽²³⁾ and are shown in Figure 66. As seen in this figure, boundary layer flow is divided into an equilibrium boundary layer, for which $C_1 \gg 1$, a nonequilibrium boundary layer, for which $C_1 \approx 1$, and a frozen boundary layer ($C_1 \ll 1$) where C_1 is defined as the ratio of the characteristic diffusion time to the reaction lifetime of an atom in the boundary layer. Specifically, C_1 , is given, according to Fay and Riddell,⁽⁸⁾ by the equation,

$$C_1 = k_r P_S^2 T_S^{-3.5} R^{-2} \left(\frac{du_e}{dx} \right)_S^{-1} \quad \dots(3)$$

where

$$\frac{du_e}{dx} = \frac{1}{R_n} \sqrt{\frac{2(P_S - P_\infty)}{\rho_S}} \quad \dots(4)$$

for modified Newtonian flow.

The flow regimes shown in Figure 66 are based on a nose radius of 1 ft, but may be drawn for any radius by proper scaling ($\lambda_\sigma/R = \text{constant}$). Also shown in Figure 66 is an orbital reentry trajectory, superimposed on the flow regimes.

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Figure 66. Aerodynamic Flow Regimes

Ideally, it would be desirable to determine the exact flow chemistry parameters of each test point and calculate the corresponding theoretical heat transfer. Since this procedure would require a considerable time investment, only an approximate approach could be undertaken in this report. The evaluated heating reductions were examined qualitatively in the light of the governing parameters of boundary layer flow. Both nonequilibrium and completely frozen flows are considered, since the uncertainties in the calculated values of C_1 are deemed to be too large to enable a definite identification of boundary layer regime. Each of these cases is listed and discussed in the following paragraphs.

(1) Nonequilibrium Thin Boundary Layer with Equilibrium Gas at the Edge of the Boundary Layer

For this flow regime, the reduction in heat transfer from equilibrium flow is a function of the wall temperature, T_w , the degree of gas dissociation at the edge of the boundary layer, α_s , and the recombination rate parameters for the boundary layer and the surface, C_1 and ϕ , respectively. Methods for calculating the heating reductions for arbitrary values of these parameters have been given

by Inger.⁽²⁰⁾ Instead of performing these calculations, which are extensive, a correlation of the estimated heating reductions obtained in the previous section were sought with the parameters α_S , ϕ , and C_1 . The effect of wall temperature in the correlations was neglected since the heating reductions represent gross effects throughout the entire temperature transients.

Calculations of C_1 were made for each test condition using the equation

$$C_1 = k_r \frac{P_S^2}{R^2 T_S^2} R_n \sqrt{\frac{\rho_S}{2P_S}} \quad \dots (5)$$

which results from Equations 3 and 4 after assuming $P_\infty \ll P_S$. To assist in solving Equation 5, curves of C_1 as a function of stagnation pressure and enthalpy were drawn up and normalized to agree with Wahlen's values⁽²⁴⁾ (see Figure 67). Resulting C_1 values were found to agree well with corresponding values calculated using the equation given by Vaglio-Laurin and Bloom.⁽²⁵⁾

Figure 67. Fay and Riddell Recombination Rate Parameter for Air, C_1

The amount of gas dissociation for each test condition, α_S , may be set proportional to the ratio of the specific dissociation energy to the total stagnation enthalpy, h_D/H_S . Values of h_D were obtained from calculations of the static pressure and temperature behind the shock and standard dissociation energy diagrams.

The parameter ϕ is commonly called the effective catalytic efficiency. Its value is unity for a perfectly catalytic surface and is zero for a perfectly non-catalytic surface. For a nonequilibrium or frozen boundary layer, a decrease in ϕ will cause a decrease in heat transfer. According to Goulard,⁽²⁶⁾

$$\phi \propto \frac{K_w \rho_w}{\left[\left(\frac{du}{dx} \right)_S \rho_S \mu_S \right]^{1/2}} \quad \dots (6)$$

Here, K_w is the velocity of atom recombination at the surface which is proportional to the product of the catalytic efficiency times the wall temperature and may be assumed constant. Also, $(du/dx)_S$ is the stagnation point velocity gradient and μ_S is the viscosity coefficient. Using the following boundary layer theory relationships,

$$\rho_w \mu_w = \rho_S \mu_S = \text{constant}$$

$$\left(\frac{du}{dx} \right)_S \propto \frac{u_\infty}{R_n} \left(\frac{\rho_\infty}{\rho_S} \right)^{1/2},$$

and neglecting variations in the stagnation-point-to-free-stream density ratio ρ_S/ρ_∞ , and variations in the air density at the wall, ρ_w , for the arc-jet conditions, one obtains

$$\phi \propto (H_S)^{-1/4} \left(\frac{R_n}{m} \right)^{1/2} \quad \dots (7)$$

where m is the mass flow rate ($m = \rho u_\infty$). Equation 7 was used to calculate values of ϕ at each test condition. Corresponding values of the product $\phi C_1 \alpha_S$ were calculated for all test conditions and arbitrarily normalized to the specific

value for test condition I. The estimated heating reductions were then plotted as a function of these normalized products in Figure 68. A basic trend of the data seems evident within the limits of the approximate method employed. Changes in the degree of energy tied up in dissociation have a small effect on the correlation as can be seen in Figure 69 where the reduction in heat transfer was correlated with ϕC_1 only.

Using this same approach, correlations of the heating reductions measured for gold, stainless steel, zirconium, and silver (in the Group I tests) were made with the product ϕC_1 . The results are shown in Figure 70. The basic trend of these data are consistent with that obtained for the fuel material.

According to developed theory, the reduction in heat transfer decreases with the effective catalytic efficiency, ϕ , and the gas phase recombination parameter, C_1 . This trend is also indicated by both the experimental data for the fuel specimen (Figure 69) and the data for the differently coated calorimeters (Figure 70). The obtained heating reduction data correlates, therefore, with the controlling parameters of nonequilibrium boundary layer theory.

(2) Completely Frozen Thin Boundary Layer with Equilibrium Gas at the Edge of the Boundary Layer

In this regime, the ratio of the heating at a surface of arbitrary catalytic efficiency to the equilibrium heating can be approximately expressed as follows:⁽²⁶⁾

$$\frac{q_{cw}}{(q_{cw})_{eq.}} = 1 + (\phi - 1) \frac{h_D}{H_S} \quad \dots (8)$$

where h_D and ϕ are obtained as previously described.

It was found that the experimental data did not reasonably correlate with Equation 8.

Based on the foregoing analysis, the experimental heating reductions appear to correlate with the controlling parameters of nonequilibrium boundary layer theory. The fact that the observed heating reductions for the fuel occur only at those conditions for which similar heating reductions for noncatalytic surfaces were measured (in the coated calorimeter tests), by itself establishes the

Figure 68. Correlation of Heating Reduction to Fuel Specimens with the Nondimensional Parameter, $\phi C_1 \alpha_S / (\phi C_1 \alpha_S)_I$

Figure 69. Correlation of Heating Reduction to Fuel Specimens with the Nondimensional Parameter, $\phi C_1 / (\phi C_1)_I$

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Figure 70. Correlation of Heating Reduction to Coated Asymptotic Calorimeters with the Nondimensional Parameter, $C_1/(C_1)_I$

noncatalytic surface effects as the likely cause of these reductions. The preceding correlations show that the basic trend of the data is consistent with catalycity theory in nonequilibrium boundary layer flow. Considerable substantiation is thereby rendered in associating the observed heating reductions with surface catalycity. In addition, a basis has been established on which more quantitative analyses may be pursued, the importance of which is obvious.

It is important to point out that the magnitude of the reduction in heating as observed in the arc-jet experiments is not necessarily the same as in free flight. This is because the arc-jet facility does not provide exact simulation of free-flight conditions. The essential difference between free flight and arc-jet environments is that, in contrast to the former, the ambient gas in the arc-jet is highly dissociated (10 to 70%). This has a significant effect on the nonequilibrium air properties behind the shock.

The large reduction in heating observed in the experiments described here (up to 30%) suggests the need for quantitative information on the surface catalycity of the fuel material. Since similar reductions in heating were observed for other materials of interest, such as stainless steel, it is recommended that the feasibility of performing bench type experiments on surface catalycity be investigated. This information would be useful to various facets of SNAP reactor reentry studies.

4. Particle Catcher Analysis

An additional secondary objective for Group-III tests was to investigate the state of particulate material just as it leaves an ablating fuel specimen. This was done by means of an aluminum particle catcher as described in Section III-C-1 of this report. A different catcher was used in each of nine test runs of Group III, listed in Table 9. A tenth catcher was used throughout Test Run No. 3-26 but was held in a retracted position, thus providing a monitor of the amount of particles picked up from the backwash along the walls of the test chamber. It was noted that this was negligible as shown in Figure 71, a photograph of the monitor catcher taken after its removal from the test chamber. The material adhering to the concave surface of this catcher was identified as foil used in shrouding the model prior to insertion into the stream.

TABLE 9

SUMMARY OF TEST GROUP III RUNS UTILIZING PARTICLE CATCHERS

Run Number	Specimen Configuration	Test Condition (See Table 1)	General Results	Δt , sec (Time Particle Catcher held in Test Position)
3-13	IIIA2	C	Specimen ablated. Material adhered to catcher.	5.80
3-14	IIIA2	D	Ablation. Material adhered to catcher.	2.08
3-16	IIIB1	G	Ablation. Large amount of material adhered to catcher.	12.87
3-18	IIIB2	J	Partial ablation from bottom of specimen. Little material "caught."	6.88
3-19	IIIC2	J	Partial ablation. Little material.	22.79
3-20	IIIC1	H	Partial ablation. Lower half split and broke away from holder.	11.50
3-21	IIIC1	K	Ablation. Material adhered to catcher.	8.21
3-23	IIIC2	D	Heavy ablation at center. Catcher caught most material ablated.	1.67
3-25	IIIA1	G	Heavy ablation. Most material caught in short time period.	1.62
3-26	IIIA1	K	Ablation. Monitor catcher used.	—

Figure 71. Monitor Particle Catcher Used
During Arc-Jet Test Run No. 3-26

After the specimen was inserted into the jet stream, it was carefully observed for the start of ablation at which time the particle catcher was lowered to test position using the external lever. When it was determined, visually, that a sufficient amount of particles or ablated metal had adhered to the concave surface of the catcher, it was withdrawn and the specimen allowed to ablate to completion. For Test Runs 3-13, 3-14, 3-18, 3-19, and 3-21, involving fuel configurations of SNAP 8 diameter (0.562 in.), the catcher was located approximately 2-1/2 in. behind the specimen when in test position. The catcher location for Test Runs 3-16 and 3-20 using configurations of SNAP 10A diameter (1.25 in.) was 2 in. behind the specimen. The particle catcher used with Test Run No. 3-23 (SNAP 8 diameter specimen) was retracted to a distance of approximately 3 in. behind the specimen which was as far rearward as the assembly design would allow. The catcher used in conjunction with Test Run No. 3-25 (SNAP 10A diameter specimen) was located forward to within approximately 1/4-in. of the specimen. The reason for these various positions was to provide information in regard to the variation of the state of the material with distance behind the specimen and, in the case of Run No. 3-25, to collect as much particulate material as possible.

Following the tests, the particle catchers were photographed (see Figures 72, 73, and 74). The catchers used with Test Runs 3-13, 3-14, and 3-16 are shown in Figure 72; these catchers had a significant amount of fuel material adhering to their surfaces. The same is true for the catchers used during Runs 3-21, 3-23, and 3-25 (Figure 74). This is not the case, however, for the catchers used in Test Runs 3-18, 3-19, and 3-20 (Figure 73) and is due to the fact that these particular specimens did not fully ablate (melt). Also, the time period of catcher insertion was found to be critical since the start of ablation was difficult to judge, as was its duration. The length of time (ΔT) each catcher was held in test position was determined from the motion picture film data, and is tabulated in Table 9.

Three of the aluminum catcher blocks were selected for chemical analysis of the material adhering to the concave face. These were catchers from Runs 3-16, 3-23, and 3-25. The results of the analysis are given in Table 10. It should be pointed out that SNAP fuel material is initially 90 wt % Zr H_x and 10 wt % U and it is interesting to note that the analysis of some small pieces from the catchers yield a higher percentage of uranium content. This would

Figure 72. Particle Catchers After Group III
Test Runs (Arc-Jet Test Runs No. 3-13,
3-14, 3-16)

Figure 73. Particle Catchers After Group III Test Runs
(Arc-Jet Test Runs No. 3-18, 3-19, and 3-20)

Figure 74. Particle Catchers After Group III Test Runs
(Arc-Jet Test Runs No. 3-21, 3-23, and 3-25)

TABLE 10
CHEMICAL ANALYSIS RESULTS FROM PARTICLE CATCHERS

Test Run and Catcher Number	Relative Size and Location of Samples	wt % U in Sample	Compounds Observed
3-16	1. Large piece. Top of catcher face.	10.4	α Zr only
	2. Large piece. Bottom of catcher face.	11.4	α Zr plus a small amount of monoclinic ZrO_2
	3. Small pieces. Taken at random.	10.4	α Zr plus an unidentified compound
3-23	1. Large piece. Top of catcher face.	10.5	α Zr plus appreciable tetragonal ZrO_2 plus some monoclinic ZrO_2
	2. Large piece. Bottom of catcher face.	10.0	α Zr plus some ZrN
	3. Small pieces. Taken at random.	—	α Zr plus unidentified compound (same as 3-16)
3-25	1. Large piece. Top of catcher face.	8.6*	Some oxides* of Zr
	2. Large piece. Bottom of catcher face.	9.7	α Zr plus ZrN and a small amount of tetragonal ZrO_2
	3. Small pieces. Taken at random.	10.1	α Zr

*Questionable due to geometry of sample surface

indicate that the surface of the fuel specimens becomes slightly enriched with uranium prior to or during ablation. The unidentified compound listed in the analysis would be either contamination from the jet stream (Cu and W from the electrodes) or protective foil which was used in precooling the specimens. It is significant that the major material in the analysis was alpha zirconium, being void of hydrogen, and the minor compound zirconium oxide. Also, the compound zirconium nitride was observed even though the oxidizing reaction is much more dominant than a nitriding reaction with zirconium.

In addition to a chemical analysis, three catcher blocks were selected for the determination of the size distribution of particles emitted from the ablating

fuel specimens. The catchers selected were those from Test Runs 3-14, 3-16, and 3-18. The catcher for Run No. 3-16 is shown in Figure 75, which was photographed at approximately 2.5X magnification. Areas indicated on the low magnification photograph were also photographed at 19X magnification and enlarged to 40X for evaluation and analysis. These areas are shown in Figures 76 through 78. Examination of the enlarged photographs yielded particles of four general types: (1) small well-defined spheres which appear to have been solidified at the time of impact with the catcher; (2) large particles with craters in the center which appear to have been partially solidified upon impact; (3) large irregular-shaped particles; and (4) splatter from the larger particles and from large pieces of molten mass. On the basis of the above examination of the photographs, the ablative particles from Areas 2-2 and 2-3 of Catcher No. 3-16 were measured and counted. Particles below approximately 50 microns could not be measured due to the roughness of the catcher block surface.

Assuming spherical geometry and using a density ($\rho_{H/Zr=0}$) of 6.95 gm/cc,⁽²⁷⁾ the mass was computed for the total number of particles counted at each diameter measured. The distributions, resulting from data taken from the two areas of Catcher No. 3-16, are plotted in Figures 79 and 80. To the extent of the data obtained from Area 2-2, the maximum distribution occurs at 650 microns and the maximum for Area 2-3 occurs at 375 microns with a lower limit in each distribution occurring at 50 microns.

The data obtained from these particle catchers were limited due to the splattering of molten material, the craters created upon impact causing irregularities in particle shape, and the piling up of material on large portions of the surfaces. It was originally anticipated that aluminum would be a soft enough material to allow particles to imbed in the concave surface of the catchers, thus minimizing particle distortion.

5. Post-Test Studies

Because of the large amount of oxide formation on the fuel specimens that did not ablate, as observed in the motion picture film and in post-test examination, some of these specimens were selected for metallurgical analysis. The emphasis of the analysis was placed on oxide thickness and the state of the material behind the oxide formation. The specimens from Test Runs 3-05, 3-11,

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Figure 75. Particle Catcher No. 3-16

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Figure 76. Catcher No. 3-16, Area 2-1
(19X Enlarged to 40X)

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Figure 77. Catcher No. 3-16, Area 2-2
(19X Enlarged to 40X)

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Figure 78. Catcher No. 3-16, Area 2-3
(19X Enlarged to 40X)

Figure 79. Particle Distribution from
Catcher No. 3-16
(Area 2-2, Figure 77)

Figure 80. Particle Distribution from
Catcher No. 3-16
(Area 2-3, Figure 78)

3-12, 3-24, 3-28, and 2-04 were cross-sectioned at the center of each specimen. To prevent the oxide from spalling off, the specimens were mounted in Hysol Epoxy prior to sectioning. The steps taken in preparing the samples for examination were as follows:

- 1) Grinding; 180 through 600-grit silicon carbide papers.
- 2) Polishing; 30-, 14-, and 6-micron diamond paste followed by Linde B and water.
- 3) Chemical polish and etching; 100-ml H_2O ,
45-ml HNO_3 ,
5-ml HF .

Macrographs were taken of the prepared samples and are shown in Figures 81 through 87. As can be seen in the figures, the outer layer of oxide in most cases is of considerable thickness. Oxide thickness was measured for each sample at 100X with a micrometer eye piece. The results are given in Table 11 with an average for the five readings around the circumference of each specimen.

In addition to the oxide layers, cracks were observed in the samples. In Figure 81, which was a Configuration-IIIB1 specimen (tungsten rod holder through the center), the cracks radiate from the central hole while those in Figures 82 and 83 (Configuration IIIA1, solid) appear to have initiated at the outer circumference and extend inward. These samples may have cracked upon cooling because during heating the temperature distribution would cause tensile forces at the center and compression at the surface. This would be reversed on cooling. The cracking in Sample No. 2-04 (Figure 86) has no significant pattern but it should be pointed out that this specimen was held stationary in the jet stream while the other specimens considered here were rotated. In addition to cracking, several void areas were observed in the solid specimens (see Figures 82, 83, and 86). The specimen for Test Run No. 3-28 (Configuration IIIB1) has literally split away from the central hole as shown in Figure 85. The specimen tested in Run No. 3-24 (Configuration IIIC2) became molten under the oxide layer around the tungsten holder which could not be removed from the sample and was therefore cross-sectioned with the fuel material (Figure 84).

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Figure 81. Macrograph of Specimen Configuration IIIB1 (Arc-Jet Test Run No. 3-05)

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Figure 82. Macrograph of Specimen Configuration IIIA1 (Arc-Jet Test Run No. 3-11)

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Figure 83. Macrograph of Specimen Configuration IIIA1 (Arc-Jet Test Run No. 3-12)

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Figure 84. Macrograph of Specimen Configuration IIIC2 (Arc-Jet Test Run No. 3-24)

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Figure 85. Macrograph of Specimen Configuration IIIB1 (Arc-Jet Test Run No. 3-28)

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Figure 86. Macrograph of Specimen Configuration II (Arc-Jet Test Run No. 2-04)

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Figure 87. Macrograph of Sample 2-04 Cross-Sectioned at Center (Configuration II)

TABLE 11
OXIDE THICKNESS MEASUREMENTS

Run and Sample Number	Configuration	Metallurgy Lab Number	Measurements (mils)					Average Thickness (in. $\times 10^{-3}$)
3-05	IIIB1	7009-1	10	8	19	18	12	12.4
3-11	IIIA1	7009-2	25	14	18	7	15	15.8
3-12	IIIA1	7009-3	34	35	35	26	30	32.0
3-24	IIIC2	7009-4	31	31	30	28	32	30.4
3-28	IIIB1	7009-5	32	23	16	1	2	14.8
2-04	II	7009-6	68	62	39	30	60	51.8

The solid Configuration-II specimen (Run No. 2-04) was first sectioned just above the centerline, and the thermocouple is clearly visible as shown in Figure 86. A second cross-sectioning of the sample was made at approximately the center where the tip of the thermocouple should come as close as possible to the outer surface as was requested in fabrication. Figure 87 shows the position of the thermocouple tip which is approximately 1/16-in. from the outer surface.

D. GROUP IV: BURNUP ENHANCEMENT TESTS

A small series of tests, comprising the Group-IV tests, were conducted within the arc-jet test program to determine whether SNAP fuel ablation would be enhanced by surface irregularities such as grooves or cross-hatches. Eight specimens of SNAP 10A diameter size were fabricated, each with grooves or cross-hatches over half of the axial length and a smooth surface over the other half. (Configuration details are noted in Section III-B.) These specimens were then tested, at different test conditions, in a rotating cross-axial orientation. Pyrometer measurements of the surface temperatures were made in each case for both axial halves. The specimen behavior was recorded with 24 frame/sec motion picture film. In addition, the ablation sequences were filmed with the special 400 frame/sec film in five of the eight test runs. A summary of the test runs made in this test group is given in Table 12.

TABLE 12
SUMMARY OF GROUP IV TEST RUNS

Test Run	Test Condition	Configuration	Time to Ablation (sec)	Type of Surface Irregularity	Special Instrumentation
4-01	H	IVA	Equilibrium	Large grooves	400 frames/sec film
4-02	K	IVA	109.5	Large grooves	
4-03	M	IVB	Equilibrium	Small grooves	
4-04	K	IVB	100.2	Small grooves	
4-05	K	IVC	46.6	Cross-hatches	
4-06	K	IVC	142.2	Cross-hatches	
4-07	K	IVD	97.0	Large grooves	
4-08	K	IVD	56.7	Large grooves	

The results of the film data indicate that fuel ablation was not enhanced by the surface irregularities. This may be inferred from the motion picture data and from the still photographs taken from the 24 and 400 frame/sec films. In all cases but one (Test Run 4-07), ablation was observed to begin either at the axial center or on the smooth-surface half. The film data show that the smooth surface definitely ablated first in Test Runs 4-02, 4-04, and 4-06. Also seen in the early frames of the film was the effusion of hydrogen as discussed in Section V-C-1-a.

A typical ablation sequence is shown in Figure 88, taken from 400 frame/sec motion picture film. In addition, the usual heavy, spalling oxide coating on the specimen is evident, especially on the smooth-surface halves. This heavy oxide coating can also be seen in post-test photographs of the specimens that did not ablate. The oxide on the grooved portion was observed to be smooth and relatively intact as compared to that on the smooth surface.

Surface temperature pyrometer data for three representative test runs are presented in Figures 89 through 91. Two sets of pyrometer readings are given for each test specimen; one pyrometer was trained at the smooth-surface half while the other monitored the temperatures of the grooved portion. Each pyrometer was trained at the specimen radial center, 1/4-in. off the axial centerline.

Figure 88. Arc-Jet Test Run No. 4-02
(400 frame/sec Motion Picture Film)

In addition to the pyrometer data, corresponding analytical thermal behavior solutions are shown as solid curves in Figures 89 through 91. These solutions were obtained in the identical manner as described in Section V-C and in the Appendix. They are appropriate for a smooth-surface specimen and they assume that surface catalytic effects are not important. Comparisons of these analytical solutions with the corresponding smooth-surface pyrometer data show basically the same trends noted in Section V-C.

It is of interest to note that the measured surface temperatures for the smooth surface were equivalent with or higher than the corresponding temperatures for the grooved surface in every case but one. The exception was Test Run 4-07. Comparisons of the pyrometer data for specimens run at the same test condition indicate that the temperatures for the grooved half in Run 4-07 appear abnormally high. The reason for this is not entirely clear.

The basic behavior of the specimens used in this test group, as indicated by both the film and pyrometer data, demonstrates that fuel ablation is not enhanced by the surface grooves or cross-hatches. In fact, little difference was noted in the overall ablation characteristics. It is felt that the increase in effective surface area in the grooved specimen halves increased the radiative heat losses by at least as much as it amplified the net surface heat input.

Figure 89. Comparison of Calculated to Measured Surface Temperatures (Arc-Jet Test Run No. 4-02)

Figure 90. Comparison of Calculated to Measured Surface Temperatures (Arc-Jet Test Run No. 4-03)

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Figure 91. Comparison of Calculated to Measured Surface Temperatures (Arc-Jet Test Run No. 4-06)

E. GROUP V: PARTICLE PHOTOGRAPHY TESTS

Throughout Test Group V, the laser was used in the photographic determination of the size distribution of incandescent liquid particles coming off ablating fuel specimens. This group utilized three fuel configurations – Configurations V, VI, and II, in a total of thirteen test runs. As shown in Figure 15, Configurations V and II were mounted cross-axially in the jet stream and Configuration VI was mounted with its axis parallel to the stream (Figure 25). Table 13 presents the runs and the conditions at which they were tested.

TABLE 13
SUMMARY OF GROUP V TESTS
(Particle Photography)

Run Number	Configuration	SNAP Type Size	Test Condition (Refer to Table 1)	Time to Ablation (sec)	Instrumentation
5-01	V	10A	S	60.5	Laser particle photography, 24 frames/sec motion picture coverage, pyrometer and thermocouple (2-07, 2-08) output.
5-02	V	10A	S	57.0	
5-03	V	10A	S	74.2	
5-04	V	10A	S	79.4	
6-01	VI	8	P	Nonablation	NOTES: Foil shroud blocked camera view for Runs 6-01, 6-02, and 6-03. Foil not used thereafter. Thermocouple for Run 2-06 failed.
6-02	VI	8	K	Nonablation	
6-03	VI	8	R	Nonablation	
6-04	VI	8	S	13.5	
6-05	VI	8	S	10.3	
6-06	VI	8	S	11.2	
2-06	II	10A	S	53.2	
2-07	II	10A	S	57.2	
2-08	II	10A	S	40.4	

The initial test run (5-01) was made with a Configuration-V fuel specimen and was unsuccessful for particle photography. This was due to the manner in which the specimen ablated, causing severe pitting of the original camera well window (quartz). For all following test runs the quartz window was replaced

(after each run) with pyrex windows. The three remaining test runs, with Configuration-V specimens, were made with each specimen so placed in the jet stream that the laser beam path was parallel with the longitudinal axis of the specimen and approximately 1/8-in. above it (camera was focused perpendicular to the longitudinal axis). Figure 92 illustrates the focus planes of the camera and laser beam for each set of tests. Due to improper focus locations of the laser beam and camera, particle photography was not obtained for these three test runs. Because of the manner in which these configurations were placed in the stream and the erratic ablation of the specimens, it was difficult to determine proper focus locations.

Particle photography was not obtained during the initial three test runs of Configuration-VI fuel specimens simply because they did not ablate. The test condition for the latter three Configuration-VI runs was changed to insure ablation. The proper focus location of the laser beam was again found to be critical and for Test Run 6-04, it was focused at the center of the specimen (see Figure 92). This produced too much illumination along with the incandescence of the ablating specimen; consequently, the photographs were overexposed.

Figure 92. Particle Photography Focus Positions

The final tests for obtaining particle photography were made with Configuration-II fuel specimens. For the first two runs (2-06 and 2-07) a camera replacement was made in order to improve the data. This camera was a modified aerial camera with a factor of ten greater shutter speed (1/250-sec) than the original camera (1/25-sec) which would enable a larger number of particles to be in focus on the film. However, the particle photography for these two runs was not successful due to the fact that even though the shutter speed was greater, this particular aerial camera was limited to a photograph rate of one every three seconds. Therefore, since the first camera used could photograph every two seconds, the final test run with a Configuration-II specimen (Run 2-08) was made utilizing the original camera.

Of the total number of test runs, the particle photography taken during three runs - 6-05, 6-06, and 2-08 - was sufficiently successful to provide meaningful data. Figure 93 is composed of sequence particle photographs taken during Test Run 6-05. As observed in the figure, the specimen is under ablating conditions being struck end-on by the jet stream. The continuous traces of many particles can be seen as well as discrete particles of various sizes whose flight has been stopped by the short laser flash. Unfortunately, no details can be seen in the bright area around the front face of the specimen due to overexposure. It should be pointed out that on the back portion of the cylinder numerous cracks and splattered droplets are clearly distinguishable. The particle photography sequence for Run 6-06 is shown in Figure 94. These photographs are very similar to those of Run 6-05 but yield a smaller total number of particles in clear focus. Note the recession of the front face as ablation proceeds from photograph to photograph and also the formation of small cracks receding back through the specimen. For comparative purposes, the ablation of Test Run 6-05 is shown in Figure 95 which was taken from the motion picture film data (24 frames/sec).

The particle photography taken during Test Run 2-08 is shown in Figure 96. The laser beam for this case was focused perpendicular to the longitudinal axis of the specimen and through its center (see Figure 92). The ablation of this configuration and of Configuration-V specimens was quite unlike that of Configuration-VI in that they ablated in a "stop and go" manner while the Configuration-VI specimens ablated smoothly and without hesitation. Again for comparison, Figure 97 shows the ablation event sequence from motion picture film taken during Run 2-08.

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4-28-67 UNC

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Figure 93. Laser Particle Photography for
Arc-Jet Test Run No. 6-05
(Film Frames No. 3-8)

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4-28-67 UNC

7611-4578

4-28-67 UNC

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4-28-67 UNC

7611-4580

4-28-67 UNC

7611-4581

Figure 94. Laser Particle Photography for
Arc-Jet Test Run No. 6-06
(Film Frames No. 5, 6, 8-11)

Figure 95. Arc-Jet Test Run No. 6-05
(24 frames/sec Motion Picture Film)

The particles from each useful photograph taken during Test Runs 6-05, 6-06, and 2-08 were carefully measured and counted. To insure proper size determination on the film, a post-calibration test was made on several spherical steel ball bearings of known diameters. The diameter of the bearings used was 1/32-in. and 1/16-in. (780 and 1560 μ). The laser and camera setup were used just as was done during the test runs. Examination of the resulting photographs indicated true diameters for each bearing size passed through the laser beam. From the total number of particles counted and measured for each test run, the mass was computed assuming spherical geometry and a density ($\rho_{H/Zr=0}$) of 6.95 gm/cc.⁽²⁷⁾ The resulting distribution is plotted in Figure 98 for Test Runs 6-05 and 6-06 and in Figure 99 for Run 2-08. The peak of the distribution for the axis-parallel Test Runs 6-05 and 6-06 occurs in the approximate particle diameter range of from 575 μ to 650 μ and that for the cross-axial Test Run 2-08 occurs from 410 μ to 490 μ . This difference can be attributed to the manner in which each of these two configurations ablated. The ablation of the Configuration-II specimen, as previously pointed out, was erratic and particles would tend to break away from the molten metal formations as well as from

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Figure 96. Laser Particle Photography for Arc-Jet Test Run No. 2-08
(Film Frames No. 17, 28, 29, 33-35)

Figure 97. Arc-Jet Test Run No. 2-08 (24 frames/sec Motion Picture Film)

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Figure 98. Particle Distribution for Arc-Jet Test Runs No. 6-05 and 6-06

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Figure 99. Particle Distribution for Arc-Jet
Test Run No. 2-08

the specimen itself. The ablation of the Configuration-VI specimens proceeded uniformly and did not form significant amounts of molten metal "flowback." The majority of the particles in this case was, therefore, formed at the front surface of the specimen as indicated by the particle photographs. The total mass at the peak of the distribution for Run 2-08 was much less than that for Test Runs 6-05 and 6-06, due to the limitation of the number of particles photographed in the former case.

As the volume element around the specimens, which was illuminated by the laser beam, was rather small, the number of particles that appeared in any picture was correspondingly small. This rather low yield in photographed particles was restricted even more by the fact that particles would tend to come away from the ablating surface in bursts. This was especially true in the case of Configuration-II and -V specimens, and it was just a matter of coincidence to catch such a burst on instantaneous exposures which were 2 sec apart. Furthermore, the ablation process was quite rapid since the test condition for the majority of the test runs of Group V was one of extremely high heat flux (Test Condition S), sometimes lasting only 34 sec. Therefore, the total number of potentially useful photographs was rather limited.

VI. SUMMARY AND CONCLUSIONS

In summary, SNAP fuel specimens of various configurations were tested in the NAA/LAD arc-jet facility under various test conditions. Both rotating and nonrotating configurations were employed.

Surface heat-flux measurements were made with a special cylindrical calorimeter assembly for each of the fourteen test conditions used. The test 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 with 24 and 400-frame/sec 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/sec 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).
- 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 the 400 frame/sec motion picture film and with instantaneous photographs from a laser system. 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 by, at least in part, 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 identifiable. Surface oxide layer thicknesses measured from 13 to 32 mils for specimens which had been rotated in cross-axial flow. A corresponding frontface 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.

The gross effect of surface catalycity on the heat flux was scanned, over various test 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 test condition was observed for these materials.

Fuel surface temperature history calculations, using the current analytical model, were found to correlate well with the pyrometer data for those test conditions in which surface catalycity effects were found in the coated calorimeter tests to be small. This was true for specimens of both SNAP 8 and SNAP 10A size diameter.

By comparing the fuel pyrometer data with the analytical calculations, the heating reductions due to the noncatalytic fuel surface were evaluated for each test 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 test conditions. The heating reductions were found to correlate well with the controlling parameters of nonequilibrium boundary layer theory. It may be concluded that the oxidized surface of the fuel is a poor catalyst to atom recombination and, as a result, the effects of nonequilibrium chemistry on fuel burnup predictions cannot be ignored. Additional, more rigorous correlations of the observed heating reductions are recommended, as are future experiments designed to quantitatively determine the fuel surface catalycity.

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APPENDIX

ANALYTICAL MODELS FOR THERMOCHEMICAL BEHAVIOR CALCULATIONS

To correlate the pyrometer measurements of the fuel surface temperatures, analytical computer models were utilized which describe the material response of the zirconium-uranium hydride fuel under the environmental heating. These models incorporate all known processes occurring at or near the fuel surface and within the fuel material. Specifically, the models generate simultaneous heat and hydrogen transport solutions considering: (1) temperature and hydrogen concentration dependent material properties; (2) material phase changes and moving phase boundaries; and (3) variable surface heating additions due to oxidation, hydrogen combustion, and transpiration cooling. In addition, fusion and ablation of the fuel material are simulated. The fundamental development and description of an analytical model with these capabilities is given in Reference 2, in which application is made for SNAP fuel element reentry studies. Three variations of this same basic model were used to correlate the pyrometer data in the arc-jet test series described in this report. These are enumerated and briefly described in the following paragraphs.

A. ONE-DIMENSIONAL (RADIAL) MODEL

This model assumes uniform heating over the entire cylindrical surface. The fuel specimen is treated as an infinitely long cylinder with radial heat and hydrogen transport. The heat and hydrogen transport processes within the fuel and at the fuel surface are illustrated in Figure A-1. The equations describing these processes are given in Figure A-2. Details regarding these equations and their solutions are included in Reference 2, Sections III through VII.

In applying this model to arc-jet test conditions, the effect of the cladding material (the model accounts for the fuel element cladding in reentry computations) is omitted. Initial fuel temperatures are taken to be 80°F. Equations expressing the heating permutations due to hydrogen combustion and transpiration cooling are identical to those given in Reference 2. The fraction of completion for hydrogen combustion, F_c , may be evaluated from test condition boundary layer pressures and temperatures. For most test conditions, F_c was found to

Figure A-1. Illustration of Heat and Hydrogen Transport Phenomena

ENERGY
$$\rho C_p \frac{\partial T}{\partial t} = \frac{1}{A} \frac{\partial}{\partial r} \left(kA \frac{\partial T}{\partial r} \right) + \bar{C}_p D \frac{\partial N}{\partial r} \cdot \frac{\partial T}{\partial r} - H_{diss} \frac{\partial N}{\partial t}$$

HYDROGEN CONSERVATION
$$\frac{\partial N}{\partial t} = \frac{1}{A} \frac{\partial}{\partial r} \left(DA \frac{\partial N}{\partial r} \right)$$

BOUNDARIES

$$0 = q_{aero} + q_{oxid} + q_{tran} + q_{comb} - k \left(\frac{\partial T}{\partial r} \right)_{r=R_f}$$

$$- \bar{C}_p D \left(\frac{\partial N}{\partial r} \cdot \frac{\partial T}{\partial r} \right)_{r=R_f} - \sigma \epsilon T_s^4$$

AND

$$D \left(\frac{\partial N}{\partial r} \right)_{r=R_f} - \frac{D_F N_S}{\Delta X} = 0$$

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Figure A-2. Heat and Hydrogen Transport Equations

be approximately 0.15. The rate of heat release due to surface oxidation is taken, at each time step, to be the minimum of the values given in Figure A-3 (appropriate for a kinetics-controlled reaction) and the values given by the equation (appropriate for an oxygen supply-limited reaction)

$$q_{\text{oxid}} = \Delta H_{\text{oxid}} \left(\frac{0.2 q_{\text{aero}}}{H_S - H_W} \right) \quad \dots A-1$$

where

$$\Delta H_{\text{oxid}} = 14,625 \text{ Btu/lb of O}_2 \quad .$$

Figure A-3. Heat of Oxidation for a Kinetics-Controlled Reaction

Other parameter values were chosen identical to those used as the standard set of parameter values in Reference 2. These are as follows:

$$\epsilon = 0.40$$

$$(H/Zr)_i = 1.80$$

$$k = 13.3 \text{ Btu/hr-ft-}^\circ\text{F}$$

$$H_{\text{diss}} = -36,000 \text{ Btu/lb of } H_2 \text{ (}\beta \text{ phase)}$$

$$= 45,000 \text{ Btu/lb of } H_2 \text{ (}\beta + \delta \text{ phase)}$$

$$= f(H/Zr) \text{ according to Figure A-4 in the } \delta - \epsilon \text{ phase region}$$

$$\rho = 380.2 \text{ lb/ft}^3$$

$$C_p = 0.1 (H/Zr - 1.073) + 0.711 \times 10^{-4} T \text{ }^\circ\text{F Btu/lb-}^\circ\text{F in the } \delta - \epsilon \text{ phase region}$$

$$= 0.085 + 0.05 H/Zr \text{ Btu/lb-}^\circ\text{F (}\beta \text{ phase)}$$

$$= (C_p M_F)_\beta + (C_p M_F)_{\delta, \epsilon} \text{ (}\beta + \delta \text{ phase)}$$

$$D = f(H/Zr, T) \text{ according to Figure A-5}$$

$$R_f = 0.625 \text{ in. for SNAP 10A size specimens}$$

$$= 0.281 \text{ in. for SNAP 8 size specimens.}$$

Finally, the simulation of the ablation or mass removal process is achieved, in the arc-jet calculations, in an identical manner to that done for reentry analysis (Reference 2, Section III-C). The heat of fusion was taken to be 90 Btu/lb. As before, the nodal network consists of seven radial nodes, six with nonzero capacities and one zero-capacity surface node (Reference 2, Section VI).

B. TWO-DIMENSIONAL (RADIAL AND AXIAL) MODEL

For many of the tests in which the fuel specimen was rotated in cross-axial flow, sufficient heating variation existed along the axial length to render the one-dimensional model version inappropriate. In these cases, use was made of a two-dimensional model version which takes into account radial and axial heat and hydrogen flows. The basic heat and hydrogen transport equations are similar in this case to those listed before (Figure A-2), except that the partial

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Figure A-4. Heat of Hydrogen
Dissociation in the Delta-
Epsilon Region

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Figure A-5. Hydrogen Diffusion Coefficients
in SNAP Fuel Material as a Function
of Reciprocal Temperature

derivative signs with respect to the single variable are replaced by gradient operators. The surface heating is assumed uniform around the circumference at any point along the axial length. Axial heating profiles are assumed symmetrical about the axial center. The corresponding nodal network is shown in Figure A-6. As in the one-dimensional version, seven nodes (six increments) are used to simulate radial heat and hydrogen flow. For the half axial length, three increments are used to describe axial heat and hydrogen flow. All parameter values are identical to those used in the one-dimensional version.

C. TWO-DIMENSIONAL (RADIAL AND ANGULAR) MODEL

The material behavior of those fuel specimens held stationary in cross-axial flow may be computed using the analytical model described in Appendix B of the cited reference. This model computes radial and angular heat and hydrogen transport for a specified cold-wall heating distribution around the periphery of the fuel specimen. Uniform heating along the axial length is assumed. As described and illustrated in the cited reference, the model nodal network corresponds to four radial increments with 4, 8, and 16 increments, respectively, in the concentric cylindrical rings. For reasons of symmetry, a cross-axial half-slice need only be considered in the model.

Approximations are made in this model after the melting temperature is reached at the stagnation line, ablation begins, and the surface contour changes. These may be listed as follows:

- 1) Aerodynamic heat flux changes due to changes in shape of the ablating specimen are neglected.
- 2) Oxidation heating during melting is assumed constant and equal to the oxidation heating at the melting temperature.
- 3) An approximate increment-wise procedure is used to simulate melt-down and ablation of fuel.

Parameter values used throughout the model computations are identical to those used in the one-dimensional version, except that some simplification is effected (averaging) for those parameters which are temperature- and/or

Figure A-6. Analytical Model Nodal Network for Radial and Axial Heat and Hydrogen Flow

concentration-dependent in a complicated manner. These simplifications, plus the approximations made during ablation (as listed above), introduce some uncertainties in the resulting solution, especially after heavy ablation occurs. For this reason, the use of this current model version is confined to situations where approximate correlation suffices.

NOMENCLATURE

- A = cross-sectional area perpendicular to flow (ft^2)
- C_p = specific heat of the fuel material ($\text{Btu/lb-}^\circ\text{F}$)
- $\bar{C}_p$ = specific heat of hydrogen ($\text{Btu/lb-}^\circ\text{F}$)
- D = hydrogen diffusion coefficient in the fuel material (ft^3/sec)
- D_F = hydrogen diffusion coefficient through the oxide film (ft^2/sec)
- $(\text{H/Zr})_i$ = initial hydrogen-to-zirconium atom ratio
- H_{diss} = heat of hydrogen dissociation (Btu/lb of H_2)
- H_S = enthalpy of the air in the stagnation region (Btu/lb of air)
- ΔH_{oxid} = heat of reaction for zirconium oxidation (Btu/lb of O_2)
- k = fuel thermal conductivity ($\text{Btu/sec-ft-}^\circ\text{F}$)
- M_F = material phase mass fraction
- N = hydrogen concentration ($\text{lb of H}_2/\text{ft}^3$)
- N_S = hydrogen concentration at the surface ($\text{lb of H}_2/\text{ft}^3$)
- q_{aero} = average aerodynamic heat flux for a hot wall ($\text{Btu/ft}^2\text{-sec}$)
- q_{comb} = heat of hydrogen combustion ($\text{Btu/ft}^2\text{-sec}$)
- q_{oxid} = heat of fuel oxidation ($\text{Btu/ft}^2\text{-sec}$)
- q_{tran} = transpiration cooling ($\text{Btu/ft}^2\text{-sec}$)
- R_f = outer radius of the fuel slug (ft)
- T = temperature ($^\circ\text{R}$)
- t = time (sec)
- ρ = density (lb/ft^3)
- σ = Stephan-Boltzmann constant