SNAP REACTOR ABLATION - DISINTEGRATION
EXPERIMENT (RADE) IN A HYPERTHERMAL
WIND TUNNEL

AEC Research and Development Report

ATOMICS INTERNATIONAL

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By

J. E. ARNOLD
L. D. MONTGOMERY

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ABSTRACT

Experimental support for current SNAP reactor reentry burnup analytical programs was provided by a series of ablation tests on half-scale reactor models exposed to a partially simulated reentry environment. Measurements of the aerodynamic heat flux to the complicated geometry of SNAP reactors were obtained with gold-plated calorimeter models. Data were also obtained on the transient temperature response of the reactor models and on the mode of disintegration of the forward components of the reactor, thus satisfying these primary test objectives. Application of the measured heat flux data to the analytical model resulted in good correlation of the analytical calculations with the experimental temperature response of the models. These tests did fail to demonstrate, however, the mode of fuel element release from the vessel since ablation of the reactor models terminated long before the fuel element bundle was exposed to any great extent; even after long exposure to the flow stream. Even though this objective was not satisfied, the results have rendered valuable information to the SNAP reactor reentry burnup program.

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I. INTRODUCTION

A. PROGRAM OBJECTIVE

A study program to investigate the disintegration and dispersion of a SNAP reactor upon reentry has been pursued in detail by the Aerospace Nuclear Safety Program at Atomics International since 1960. The study of reactor reentry behavior (temperature response to aerodynamic heating, mode of failure of the vessel, and release of the fuel rods) has consisted essentially of an analytical approach, using thermal networks to describe the temperature response of the reactor when subjected to aerodynamic heating. Preliminary studies⁽¹⁾ led to the conclusion that the available reentry heating during orbital decay was adequate to effect complete reactor meltdown and fuel ablation. This conclusion was based on theoretical aerodynamic calculations. Since that time, experimental data have been obtained on the aerodynamic force and heating coefficients for the system. Wind tunnel tests were run to determine local heating coefficients at various angles of attack and at various simulated altitudes.^(2,3) A flight test (RFD-1) of a full-scale mockup of the SNAP 10A reactor was conducted in an actual reentry environment to obtain aerodynamic data and confirm the theoretically predicted response of the reactor to reentry.⁽⁴⁾ In addition to these experimental data, the analysis was improved through the use of more refined methods for calculating aerodynamic heating rates to the reactor. Based upon these experimental data and on the improved analysis, the conclusion was made⁽⁵⁾ that the reactor vessel walls will melt away allowing the fuel rod core assembly to fall free at an altitude of not less than 237,000 ft. The mode of burnup and disintegration of the fuel elements after their release and exposure to the reentry environment has been thoroughly analyzed in another analytical study⁽⁶⁾ and in experimental investigations.^(7,8)

B. EXPERIMENT OBJECTIVE

The behavior of a SNAP reactor vessel during reentry is important for safety considerations, as previously discussed; and therefore, confidence in the analytically predicted behavior is essential. The analysis has been complex and required a number of approximations. The flight test (RFD-1) data were, of

necessity, limited. Therefore, experimental investigation of the reentry disintegration of a SNAP reactor was necessary if the reentry behavior was to be accurately predicted. This experimental support must accurately define the heating to the reactor in a reentry environment and must demonstrate the mode of fuel rod release. The objective of the experiment described in this report is to provide this experimental support. Data were to be obtained on the aerodynamic heating to a reactor vessel, on the response of the reactor vessel to this heating, on the meltdown and mode of disintegration of the vessel, and on the release of the fuel rods.

An ideal experiment would be to observe the behavior of a SNAP reactor in an actual or completely simulated orbital-decay reentry environment. However, this is neither technically feasible nor economical with the current state-of-the-art flight capabilities and test facilities. It thus becomes necessary to utilize a closely simulated reentry environment for the experimental studies of reactor behavior. The most complete simulation of the reentry environment is obtained with an arc-heated, hyperthermal wind tunnel. Recent developments have resulted in such facilities capable of partially simulating the orbital reentry environment of a SNAP reactor. The simulation capabilities of these facilities were studied with the primary parameters investigated being:

- 1) Stagnation Pressure
- 2) Heat Flux
- 3) Aerodynamic Shear
- 4) Flow Regime
- 5) Flow Chemistry.

It was concluded from the investigation that the primary parameters which affect the behavior of a reentering SNAP reactor could be simulated in a hyperthermal wind tunnel. Following a survey of facilities, it was ascertained that these parameters could be adequately obtained in the facility located at Ames Research Center, Moffett Field, California.

The experimental program was designed for the testing of SNAP reactor models in the above facility and was given the official designation as the Reactor Ablation and Disintegration Experiment (RADE). These models were planned to be statically tested at 0° and 30° angles of attack (α) under constant and continuous heating until complete disintegration had occurred.

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II. TEST CONDITIONS

A representative trajectory for the orbital reentry of a SNAP system is shown in Figure 1. It has been predicted that the aerodynamic heating produced by such a reentry will cause breaching of the reactor vessel of the SNAP 10A at an altitude of approximately 240,000 ft.⁽⁵⁾ Simulation of the environment at this altitude requires simulation of the hypersonic flow and of the free-flight deceleration (inertial) forces. The deceleration at this altitude is approximately 0.2 g and will not be considered here since this is not expected to have a primary effect on the behavior of the vessel.

The hypersonic Flow ($M \geq 5$) of reentry and that of a hyperthermal wind tunnel can be described by the air stagnation enthalpy (H_s) and the stagnation pressure (P_s). As shown in Figure 2, the altitudes at which significant heating of a re-entering reactor system occurs have a near constant stagnation enthalpy and an increasing stagnation pressure (thus an increasing heat flux as the reentry progresses). Ideally, this value of stagnation enthalpy and the stagnation pressure at the desired test altitude would be used on a full-scale model and the simulation of the reentry environment exactly duplicated. A review of facility capabilities revealed that ground wind tunnel test facilities do not currently exist which can obtain this high stagnation enthalpy with a full-scale model (diameter of approximately 9 in.). Therefore, it was necessary to consider a scaled model for simulation of the parameters which determine the behavior of the reactor vessel. Fortunately, it was found that a half-scale model could be used with test conditions which result in the simulation of the primary parameters and which were available in the Ames Research Center test facility. It was determined that this half-scale model, with the simulated primary parameters, would behave identically as the full-scale reactor in flight. The primary parameters considered were:

- 1) Stagnation Pressure (P_s)
- 2) Aerodynamic Heat Flux (q_s)
- 3) The Flow Regime (determined by the order of the ratio
$$\lambda_s / R = \frac{\text{mean free path behind shock}}{\text{body radius}})$$
- 4) The Recombination Rate Parameter (C_1)
- 5) Aerodynamic Shear (τ).

Figure 1. Representative SNAP Orbital Reentry Trajectory

Figure 2. Stagnation Conditions for a Representative SNAP Orbital Reentry Trajectory

The stagnation pressure influences the reaction rates on the surface and strongly affects the flow chemistry. Therefore, this parameter must be exactly simulated in the test environment. Consider then, the relationship of the other parameters for the half-scale model. The heat flux is related to the stagnation pressure and stagnation enthalpy by the simplified relationship:⁽⁹⁾

$$q_s = 0.0417 \sqrt{\frac{P_s}{R_n}} (H_s - H_{300^\circ K}) \quad \dots (1)$$

where

$$\begin{aligned} H_{300^\circ\text{K}} &= \text{Enthalpy level of the gas at } 300^\circ\text{K } (80^\circ\text{F}), \\ R_n &= \text{Nose radius (ft)}. \end{aligned}$$

Equation (1) was derived from the Fay and Riddell analysis⁽¹⁰⁾ with a Lewis number of 1.0 and a Prandtl number of 0.72; and neglects the wall enthalpy (H_w). If the test conditions are denoted by the subscript (t) and reentry conditions by the subscript (r), it is seen from Equation (1) that for the test heat flux to be equal to the reentry values, the following relationships must hold. If:

$$R_{n_t} = \frac{1}{2} R_{n_r}, \quad \dots (2)$$

and

$$P_{s_t} = P_{s_r}, \quad \dots (3)$$

then

$$q_{s_t} = q_{s_r}, \quad \dots (4)$$

and

$$H_{s_t} = \frac{1}{\sqrt{2}} H_{s_r} \quad \dots (5)$$

Therefore, for the stagnation enthalpy of 12,000 Btu/lb_m experienced during reentry a test value of approximately 8,500 Btu/lb_m should be used. A maximum value of 8,000 Btu/lb_m can be readily obtained in ground facilities. This results in only a 6% decrease in the test heating over that of reentry and was deemed acceptable. The effect of the above scaling on the other parameters must be considered.

The aerodynamic shear in the vicinity of a blunt body is related to the heat flux and stagnation enthalpy in the following manner. Using Reynold's analogy:

$$\frac{\tau_x}{R} \propto q_s / \sqrt{H_s} \quad \dots (6)$$

where

x = distance from stagnation point (ft).

From Equations (4), (5), and (6) it can be seen that the shear at a given position is increased by approximately 20% ($\sqrt[4]{2}$) in the test simulation. It was felt that this deviation in the shear would not significantly affect the model behavior over that of reentry.

The flow regime is determined by the order of the ratio (λ_s/R). For the conditions of interest here this ratio is approximately 6×10^{-3} , and results in boundary layer flow.⁽¹¹⁾ Since the mean free path (λ_s) depends primarily on the stagnation pressure this ratio is increased by a factor of approximately two by scaling of the model size. This is a small change in the order of this parameter and the flow regime remains the same.

The flow regimes of high-speed, high-altitude flight have been described by Probstein⁽¹¹⁾ and are shown in Figure 3. The flow chemistry is described by

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Figure 3. Aerodynamic Flow Regimes

the recombination rate parameter, C_1 . As seen in Figure 3, boundary layer flow is divided into an equilibrium boundary layer, for which $C_1 \gg 1$, a non-equilibrium 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 time of an atom in the boundary layer. Specifically, C_1 is given, according to Fay and Riddell,⁽¹⁰⁾ by the equation:

$$C_1 = k_1 P_s^2 T_s^{-3.5} \Re^{-2} \left(\frac{du_e}{dx} \right)_s^{-1} \quad \dots (7)$$

where

$$\frac{du_e}{dx} = \frac{1}{\Re_n} \sqrt{2 \frac{(P_s - P_\infty)}{\rho_s}} \quad \dots (8)$$

for modified Newtonian flow. In the previous equations:

k_1 = chemical rate constant,

T_s = stagnation temperature ($^{\circ}\text{R}$),

$\Re$ = universal gas constant,

P_∞ = free stream pressure (lb/ft^2),

ρ_s = density behind shock wave (stagnation region) (lb/ft^3).

The flow regimes shown in Figure 3 are based on a nose radius of 1 ft, but may be drawn for any radius by proper scaling ($\lambda_s/R = \text{constant}$). Also shown in the figure is an orbital reentry trajectory (from Figure 1), superimposed on the flow regimes.

The recombination rate parameter is shown in Figure 4 as a function of the stagnation pressure and enthalpy.⁽¹⁰⁾ It is evident from this figure that the diffusion time is short compared to the lifetime of an atom for the proposed conditions ($C_1 \ll 1$) which is the characteristic of frozen flow. It should be pointed out here that a reduction in heat transfer due to the catalycity of the wall will occur at this condition since it also is a function of the degree of dissociation behind the shock and the wall temperature. As shown in Figure 4,

the recombination rate parameter is increased by a factor of approximately $\sqrt{2}$ when the stagnation enthalpy is decreased by this scaling factor. Therefore, noting that the recombination rate parameter is proportional to the radius;

$$C_{1_t} \approx \frac{1}{\sqrt{2}} C_{1_r} \quad \dots (9)$$

This may be considered a small change in the characteristic chemistry of the flow, and will not change the condition of frozen flow for the test case.

It has been shown that the scaling of Equations (2), (3), (4), and (5) results in close simulation of the primary parameters which affect the behavior of the reentering reactor vessel. Therefore, the test behavior will be representative of the reentry behavior and thus, will provide the necessary experimental support.

Figure 4. Fay and Riddell Recombination Rate Parameter for Air, C_1

III. TEST DESCRIPTION

A. FACILITY DESCRIPTION

The test described in this report was performed in the hyperthermal wind tunnel of the Gasdynamics Branch Facility at NASA Ames Research Center, Moffett Field, California. This facility is capable of producing nominal Mach 5 gas flow at extremely high temperatures. The flow is produced by injecting air into the plenum of a Linde arc-heater, used in conjunction with a 10-Mw power supply. The arc-heated air is expanded through a conical, supersonic nozzle to a 24-in. -diameter exit plane.

The Linde arc-heater consists, basically, of two hollow cylindrical copper electrodes separated by an air inlet plenum chamber assembly. The conical nozzle is attached to the heater at the exit of the electrode. The electrodes and nozzle are surrounded by water-coolant passages.

A simplified schematic diagram of the test facility is shown in Figure 5. The gas exiting the nozzle passes into a 48-in. -diameter water-cooled diffuser attached to the rear wall of the test section which is a 10-ft by 8-ft chamber with walls of 1-ft thickness. The jet passes through the diffuser to a gate valve which opens into a settling chamber and is then discharged to the atmosphere. A five-stage steam ejector vacuum system downstream from the settling chamber provides the low test chamber pressures required for testing. The entire system can produce constant flow for a continuously-running period of approximately 15 min.

The test chamber has three viewing ports for observation of tests and for photographic coverage. A port is located on each side wall between the nozzle exit and the diffuser entrance. The third port is located at the top of the chamber. A television camera is mounted to the top port for continuous visual monitoring of a test from the control room. The control room is separate from the main test facility housing. A distilled water supply provides cooling to components in the chamber, the arc-heater and the nozzle. Four pumps produce water flow under 1200 lb-per-in.² pressure. Figure 6 is an overall view of the test chamber.

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Figure 5. Simplified Schematic Diagram of the NASA Ames Hyperthermal Wind Tunnel

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Figure 6. Overall View of the NASA Ames Test Chamber

B. MODEL DESCRIPTION AND INSTRUMENTATION

1. Reactor Ablation Models

This experiment was designed to provide data on the response of a SNAP reactor to aerodynamic heating upon atmospheric reentry, on the meltdown or failure mode of the vessel and on the release of the fuel rods from the vessel. It was planned that these data be applicable to the design of reactor vessels, and be particularly applicable to the SNAP 8 and SNAP 10A reactor configurations. In order to satisfy these objectives, four stainless steel reactor models were fabricated. These RADE models were half-scale replicas of the SNAP flight reactor configurations, restricted basically to the external geometry (other components were scaled as required to insure duplication of the thermal characteristics). The ablation model complement included two SNAP 10A and two SNAP 8 configurations classified for this test as RADE A and RADE B models, respectively, one each to be tested, at 0° and 30° angles of attack.

The RADE A model consisted of a NaK pipe and simulated thermoelectric pump assembly welded to the head of a cylindrical vessel enclosing the reactor core components. Three NaK tubes protruded forward from the transverse section of the NaK pipe; the central tube is a fill tube and the other tubes are overflow tubes. Six simulated thermoelectric switches extended through the transverse pipe normal to the NaK fill and overflow tubes. The pump assembly, positioned between the vessel head and transverse NaK pipe, consisted of a pump housing containing the central NaK outlet pipe, one pair of Alnico magnets, two pump fixtures, and four plane radiator surfaces (pump fins). The exterior dimensions of the NaK piping were half-scale with full-size wall thickness as was the case for the pump fins. The pump itself was half-scale and, although void areas were duplicated by extensive simplification of parts, the general assembly concept was maintained. The pump and NaK pipe assemblies were secured to the vessel head at its center by two pump support brackets and four support legs. The NaK downcomer pipes were secured to the outer periphery of the vessel head by two spacer blocks.

The cylindrical vessel shell of the models housed 2 grid plates, 6 internal reflectors, and 37 fuel elements. The vessel shell was one-half the scale of a SNAP 10A flight reactor with full-scale wall thickness. The upper and lower

grid plates positioned the fuel elements and internal reflectors inside the vessel. The upper grid plate (located under the top head) was half-scale with full-scale thickness and its installation conformed to the SNAP 10A configuration. The lower grid plate was the half-scale concept of the SNAP 8 configuration with the half-scale SNAP 10A fuel rod hole pattern. The internal reflectors were half-scale to the SNAP 10A internal reflectors. The fuel elements were of the full-scale SNAP 8 configuration (0.56-in. diameter) reduced to a length of 6.3 in. With the core assembly in place, a stopring-nut assembly was threaded into the bottom of the reactor vessel to secure the components and to serve as an attachment fixture to the support equipment. The RADE A model major components are shown in Figure 7 and the assembled model (not welded) is shown in Figure 8.

The RADE B model consisted of a U-shaped NaK pipe, a hemispherical-shaped vessel head, and a cylindrical reactor vessel, all half-scale to the SNAP 8 configuration in external dimensions with full-scale wall thicknesses. The NaK pipe was welded to the head which in turn was welded to the reactor vessel. The core components were identical to those of the RADE A model with the exception of the upper grid plate which was half-scale to the upper grid plate of the SNAP 8 configuration with full-scale thickness. The RADE B model major components are shown in Figure 9 and Figure 10 shows the assembled model.

The individual model components were fabricated from like materials of their actual counterparts. This, for the most part, was Type 316 stainless steel, except for the fuel elements, internal reflectors, and RADE A pump components. The fuel rods were zirconium-hydride ($H/Zr = 1.75$), containing no uranium as does the actual fuel, clad with Hastelloy-N which was internally coated with a nonclassified ceramic. The internal reflectors were made of a commercial grade Monel in place of beryllium since it closely duplicates the thermal properties of the actual reflector material and is not toxic. These substitutions of core materials eliminated the health safety hazard associated with nuclear and toxic materials. The pump radiator surfaces (pump fins) were aluminum, the magnets were Alnico, and the pump fittings were a titanium-aluminum-vanadium alloy.

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Figure 7. Disassembled RADE A Model Showing Major Components

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Figure 8. RADE A Model

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Figure 9. Disassembled RADE B Model Showing Major Components

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Figure 10. RADE B Model

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The RADE A and RADE B models were instrumented with 0.02-in. OD chromel-alumel thermocouples located in the NaK pipe, head, grid plates, fuel rods, radiators, and vessel wall. The thermocouples were welded into the various surfaces, with the stainless steel sheathing routed internally through the vessel core to the base of the model, where 10 ft of flexible lead per thermocouple was spliced to the sheaths. The flexible lead bundle was braided to prevent possible capacitive pickup and connected to two electrical plugs. A total of 30 thermocouples were mounted in the RADE A model, and 25 in the RADE B model. The locations of these thermocouples are shown in Figures 11 and 12.

Temperature-sensitive paints were applied to the grid plates, fuel rods, and internal reflectors of both RADE A and RADE B models to supplement the thermocouple instrumentation. Strips of different temperature levels were used to cover a range of maximum anticipated temperatures since the exact mode of disintegration was difficult to predict.

Paint was applied in radial, 1/8-in. wide strips to the upper and lower grid plates on the side facing the fuel rods (top plate lower surface and bottom plate upper surface). A total of six different temperature level paints were applied to the top grid plate at 60° radial locations from the outer edge of the plate to its center. Similarly, four paints were applied to the bottom grid plate at 90° locations. The temperature level paints and corresponding locations on the grid plates are shown in Figure 13 and can also be seen in Figure 7.

Temperature sensitive paints were applied in circumferential bands around four adjacent fuel rods, located on a radius, approximately 3 in. below the top fuel element pin. Four different paint bands were used on each rod and were separated by a space of 1/8-in. The paint levels and locations on the fuel rods are shown in Figure 14. The paint scheme as applied to the outermost rod was also applied to the nearest internal reflector with respect to that rod.

2. Calorimeter Model

In order to analytically evaluate the behavior of the RADE models exposed to the arc-jet stream, and thereby satisfy the objective of the test, it was necessary to accurately determine the heat flux to the complicated geometry of these reactor configurations. This is a difficult parameter to determine confidently from

Figure 11. RADE A Model Thermocouple Installation

Figure 12. RADE B Model Thermocouple Installation

PAINT BAND	TEMP. LEVEL - °F
A	2500
B	2400
C	2300
D	2200
E	2100
F	2000
G	900
H	800
I	700
J	500

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Figure 13. Temperature Sensitive Paint Schemes on RADE Model
Grid Plates

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Figure 14. Temperature Sensitive Paint Schemes on RADE Model Fuel Elements and Reflectors

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theoretical correlations of simple body shapes and from the flow condition data since nonuniformities in the jet stream affect the heat flux distribution. Therefore, to determine the heat flux to the ablation models, a calorimeter (calibration) model was fabricated. This model consisted of one copper vessel, the outside diameter of which was a mean average of the RADE A and B diameters, and three interchangeable copper heads. Two of the heads simulated the RADE A and RADE B ablation model head configurations and the third was a hemispherical (dome) head used for the measurement of a standard reference heat flux. The entire copper calorimeter model was water-cooled to prevent failure during sustained periods of heating in the jet stream. The system was designed to maintain the wall temperatures below 400°F.

The model and its coolant loops are shown in Figures 15 and 16, respectively. The RADE A pump fins were not included on the calorimeter head since they could not be practically cooled and would have quickly failed during a test run, thus rendering possible damage to the calorimeter model. (Analytical predictions indicated that the fins disperse at high altitudes upon reentry and have little effect on the vessel behavior.)

The flow regime required by the test criteria for enthalpy and pressure levels simulating reentry heating results in a condition described by Probst⁽¹¹⁾ as frozen boundary layer flow. Therefore, the surface catalycity of the copper calorimeter model had to be considered with respect to the aerodynamic heating rates to these surfaces. Surface catalycity effects on heat flux have been determined and are presented in Reference 8 for simulated reentry conditions very close to those of these tests. These data show that both gold and stainless steel have the same reduction (approximately 10 percent) in heat flux due to surface catalycity. Therefore, the four components of the copper calorimeter model were gold-plated for the measurement of heat flux.

The requirements of this test prescribed continuous readings of the local heat flux to the calorimeter configurations over a sustained period of time at a relatively high jet stream heat flux. Therefore, the Asymptotic* calorimeter was selected for use in the calorimeter model, since a standard calibration

*Registered trademark of the Hy-Cal Engineering Company.

Figure 15. RADE Calorimeter Model and Head Configurations

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Figure 16. Coolant Flow Schematic for Calorimeter Models

procedure was available and this sensor could be used to measure the heat flux directly. The principle of this calorimeter is explained in detail in Reference 8.

The RADE A and RADE B calorimeter head configurations were each instrumented with 7 Asymptotic calorimeters with a heat flux range up to $400 \text{ Btu/ft}^2\text{-sec}$. The dome head configuration contained three calorimeters of this same heat flux range capability. The vessel was instrumented with 7 calorimeters with a heat flux range of up to $200 \text{ Btu/ft}^2\text{-sec}$. The calorimeters located in the model were gold-plated by the manufacturer prior to their installation. An epoxy bonding material was used to seal each heat sensor unit into the model components flush with the surface.

The stainless steel sheathed sensor leads from each of the interchangeable model heads were attached to an electrical connector. A common electrical connector was located in the vessel which mated with each of the plugs in the heads. Flexible copper leads from the common plug and the calorimeters located in the vessel wall were braided and connected to an electrical plug 10 ft from the base of the model.

The location of each calorimeter in the calibration model is identified in Figures 17 and 18. These Asymptotic calorimeters were selected to withstand a maximum body temperature of 450°F with a response time on the order of 60 msec. The overall accuracy of the calorimeters is $\pm 2\%$ of full-scale. The output is in millivolts and each calorimeter was calibrated by the manufacturer prior to delivery.

C. TEST DESIGN AND SETUP

1. Model Support System

The RADE model support system served to position the calorimeter and disintegration models in the jet and provided a rigid support for the models in the flow stream during testing. The support system consisted of a fixed tubular steel tripod mounted to the sidewall of the test chamber, and a movable water-cooled assembly to which the models were attached. The movable assembly was composed of a foot, leg, and arm which were joint-welded into a Z-shaped fixture. This assembly was joined to the tripod at the apex by a pin joint and the entire assembly was position controlled by a double-acting pneumatic cylinder.

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Figure 17. Calorimeter Model Heat Sensor Installation - Hemispherical Head Configuration

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Figure 18. Calorimeter Model Heat Sensor Installation - RADE A and RADE B Head Configurations

Two separate movable assemblies were attached to the tripod for positioning of the forward part of the model in the core of the jet at the zero and 30° angles of attack.

The model support system is shown schematically in Figure 19. The foot, the first component of the arm assembly, was a 2-in. -diameter steel pipe hinged through teflon inserts to the apex of the tripod support. The purpose of the teflon inserts was to electrically isolate the arm assembly. The leg served as the support member between the foot and the arm and engaged a teflon insert located in the water-cooled diffuser, which provided additional support in the vertical direction and electrical isolation from the diffuser when the assembly was in test position. The arm of the assembly was attached to the opposite end of the leg. A pipe flange was welded to the forward end of the arm for model attachment.

All water-cooling lines for the support system were routed, using flexible tubing sheathed with asbestos, from the arm assembly to a manifold supply and exhaust assembly (see Figure 19) located in the floor of the test chamber. The manifold assembly was equipped with valves, flowmeters, and a pressure regulator for controlling the coolant flow to the models and support system. Due to the pressure limitation of the calorimeter model and safety considerations, an ordinary tap water supply was brought into the manifold, thus eliminating the use of the 1200-lb pressure water supply of the test facility.

The air supply lines for the double-acting pneumatic cylinder were routed through fixtures provided on an instrumentation lead receptacle plate and to an air supply line outside the test chamber. Also, leads from a timing contact switch, located at the apex of the tripod, were routed through the receptacle plate. Figures 20 and 21 show the model support system as installed in the test chamber.

2. Model Installation

The calorimeter model vessel was first mounted to the arm end flange. The electrical calorimeter leads were drawn through the arm, down the leg and out to a plate assembly containing insulated receptacles. This plate was mounted in an existing port in the side wall of the test chamber and sealed for vacuum. Copper coolant lines for the vessel were then extended through the leg. Flexible lines were attached from the ends of the copper tubes down to fittings on

Figure 19. Schematic Diagram of RADE Model Support and Cooling Systems

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Figure 20. RADE Model Support System as Mounted in the Test Chamber

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Figure 21. Leg and Arm Assembly Withdrawn from Test Position

the manifold. Following the complete mounting of the vessel, the dome head, RADE A and RADE B head configurations, were mounted to the vessel in that order for testing. The outlet coolant lines for the model heads (outlet and inlet lines for the dome head) were installed through the center of the vessel and arm. They were then connected, with flexible coolant lines drawn down the rear side of leg, to the manifold. Figure 19 shows the coolant line installation scheme for the calorimeter model at the manifold. Each of the model heads as mounted in test position is shown in Figures 22, 23 and 24.

The installation of the RADE ablation models was much less complex since no coolant lines were involved. Mounting of each model to the arm was similar to the mounting of the calorimeter model with the thermocouple leads and plugs drawn through the arm and leg and connected to proper receptacles on the receptacle plate in the chamber wall. The models mounted at 30° angle of attack and in test position are shown in Figures 25 and 26.

D. SUPPORTING INSTRUMENTATION

1. Data Recording Equipment

In order to adequately obtain the amount of data required from the RADE test, a data-recording equipment package was assembled by AI personnel. This recording system contained an input capacity of 48 channels which were multiplexed into 12 channels, amplified by a factor of ten (10) and then recorded on 12 channels of an FM tape recorder. The system is schematically outlined in Figure 27 and a brief description follows.

a. Input Signals

Forty-eight input signals could be recorded on the data system. No signal conditioning was performed on the incoming signals; however, a low-pass filter was available at the input to the amplifier.

b. Temperature Reference Junction Box

All thermocouples on the RADE models were chromel-alumel; therefore, a chromel-alumel junction box was used. The specified temperature of the box was $150 \pm 0.1^{\circ}\text{F}$.

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Figure 22. Dome Head Calorimeter Model Mounted
in Test Position at 0° Angle of Attack

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Figure 23. RADE A Head Calorimeter Model Mounted
in Test Position at 30° Angle of Attack

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Figure 24. RADE B Head Calorimeter Model Mounted in Test Position at 30° Angle of Attack

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Figure 25. RADE A Ablation Model Mounted in Test Position at 30° Angle of Attack

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Figure 26. RADE B Ablation Model Mounted in Test Position at 30° Angle of Attack

c. Multiplexer

A 48-channel relay multiplexer converted the input signals into 12 lines of data with 4 serialized data channels per line. Three of these channels contained data and the fourth was used for calibration and a timing signal.

The multiplexer was driven by a square wave generator. The output of the generator, as well as a frequency divider network, was recorded on the tape recorder and used for demultiplexing. The sampling rate of each channel was 10 samples per sec, and the oscillator frequency was 20 cycles per sec.

The demultiplexer used the same logic circuits as the multiplexer and its drive signals were taken from two channels of the tape recorder. The output to the x-y recorder was a series of steps at a real time frequency of 10 steps per sec.

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Figure 27. Schematic Diagram of Data Recording Equipment

d. Amplifiers

The amplifiers used with the data system had a specified accuracy of 1%, and a common mode rejection of 120 db at 60 cps. The amplifiers also contained selectable low-pass filters of 10 kc, 312 cps and 10 cps. The 312 cps filter was used during the RADE tests.

e. Analog Tape Recorder

The analog tape recorder used with the recording system was a CEC PR3300. The tape speed was 15 in. /sec for recording and was adjusted to a lower speed for playback. A precision frequency power source was used to keep line frequency and voltage fluctuations from affecting the accuracy of the tape recorder.

Since the normal tape recorder speed was 15 in. /sec, each tape could last 45 min for continuous recording.

d. Data Output

The x-y recorder was used to plot data output in mv versus time. The recorder was operated during each test to record one channel as a monitor and all channels were plotted following the completion of the RADE test.

The data recording equipment was assembled in a 4-ft by 3-ft by 2-ft portable instrument rack. Final assembly was made at the test facility. The power was supplied to the rack from a 1.2-kva isolation transformer with 24,000 volts isolation between primary and secondary. The isolation transformer was used to prevent possible arcing which could result in damage to the equipment and endanger the safety of personnel in the facility.

Data output leads, which were braided and sheathed with teflon tubing, were connected to insulated receptacles on the receptacle plate located on the exterior wall of the test chamber. These leads were then connected to the data recording system.

2. Photography Equipment

Two 16mm movie cameras were used during each RADE ablation test run to obtain normal speed (24 frames-per-sec) event coverage of model disintegration. A third 16mm camera (Milliken) was utilized for high-speed motion picture coverage and was operated at 128 frames-per-sec. The load capacity of the two

24 fps cameras was 400 ft of film which represents approximately 12 min of continuous film coverage. The Milliken camera was equipped with a 1200-ft film magazine in order to record the same amount of time coverage as the event cameras. The positions of these cameras outside the test chamber are shown in Figure 28.

Documentary coverage of the installation and test procedures was taken prior to the actual testing. Still photography was obtained, throughout the test cycle, of the facility, test setup, and the models before and immediately following each test run.

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Figure 28. Schematic Diagram of Motion Picture Camera Placement
(Frontal view of test chamber looking downstream)

IV. TEST PROCEDURES AND DATA ACQUISITION

A. TEST CONDITION CALIBRATION

Although operating curves were not available for the Ames test facility, it was determined that the necessary conditions for the environment simulation required for the RADE test (see Section II) could be obtained at this facility. The primary parameters needed to describe the state of the gas exiting the nozzle for the purpose of the reentry simulation are the stagnation enthalpy, H_s , and stagnation pressure, P_s , with uniform hypersonic flow ($M \geq 5$). The specified values of these parameters were 8000 to 8500 Btu/lb_m for H_s and 0.02 to 0.05 atm for P_s . The corresponding reference heat flux ($q_s \sqrt{R}$) for these conditions is approximately 60 Btu- $\sqrt{\text{ft}}/\text{ft}^2\text{-sec}$.

An initial test calibration run was made resulting in conditions very close to those specified. The procedure for calibrating to these conditions consisted of bringing the flow stream to a steady state (constant power input and gas flow rate) and inserting a pitot probe and slug-type hemispherical calorimeter into the center of the flow stream at 1 in. downstream of the nozzle exit plane. The location of these measuring devices in the "out" position can be seen in Figure 21. From the calorimeter measured heat flux (Btu/ft²-sec) and the pitot probe measurement, the stagnation enthalpy was determined using Equation (1), rearranged to yield:

$$H_s = \left(q_s \sqrt{R_n} / 0.0417 \sqrt{P_s} \right) + H_{300^\circ\text{K}} \quad \dots (10)$$

where

$$H_{300^\circ\text{K}} = 130 \text{ Btu/lb}_m.$$

The reference heat flux ($q_s \sqrt{R_n} = q_{\text{ref}}$) may be interpreted as the heat flux to a 1-ft radius hemisphere at the stagnation point for equilibrium boundary layer flow.

The determination of the stagnation enthalpy (equilibrium boundary layer flow) as described above cannot be considered entirely accurate for this case since the recombination rate parameter indicates essentially a frozen boundary layer for these conditions ($C_1 \ll 1$). Therefore, the effect of catalycity on the measured

heat flux would be expected to be significant,⁽⁸⁾ and the use of this heat flux would alter the true value of the stagnation enthalpy. The calorimeter used in making the heat flux measurements was copper which is known to have a relatively high catalytic efficiency⁽¹²⁾ and thus it was assumed that the stagnation enthalpy value was not a significant deviation from the desired condition.

A modification in voltage and current was made for the second calibration run, resulting in conditions that were entirely satisfactory for actual testing. Table 1 lists the primary parameters for each calibration run and all subsequent test runs. In order to verify the effect of catalycity at this test condition, the hemispherical calorimeter was spray-coated with teflon which is a material having a low catalytic efficiency. The measured heat flux with the teflon coating was reduced by approximately 32%; a strong decrease in heat flux. Calibration Runs 6 and 7 still had teflon intact on the calorimeter and for Run 8, it was cleaned off entirely.

The above calibration was made to establish the approximate test condition parameters; however, since the models would be inserted into the stream at approximately 8-in. downstream of the nozzle exit, a stream survey was conducted in both longitudinal and lateral directions. The instruments used for the survey consisted of a pitot probe and an Asymptotic calorimeter (Hy-Cal Model No. C-1301) which were mounted to a hydraulically operated rail fixed to mounts on the floor of the test chamber. Figure 29 shows the position of the instruments in the test chamber (see also Figure 22). The lateral survey was made to determine the test "core" of the stream or the diameter of the central area of the jet stream for which the primary parameters are at a constant maximum. The results of the flow stream survey are presented in Figures 30 and 31. It should be noted that the measured heat flux from the longitudinal survey at 8-in. downstream does not agree with the lateral centerline measurement at the same distance downstream. This was believed to be due to the calorimeter not being at the centerline of the jet for the longitudinal survey. The difference, at maximum, is approximately 10% and is not considered significant. The lateral survey showed that the "effective" test core diameter was approximately 8 to 12 in. The deviation of heat flux from the maximum centerline measurement to the measurement at 4 in. to the right and left of center was approximately 12% for Runs 9 and 10. At 6 in. from the centerline the decrease in

TABLE 1
SUMMARY OF TEST CONDITION DATA

Run No.	P _s (atm)	q _{ref} [*] ($\frac{\text{Btu}}{\text{ft}^2 \cdot \text{sec}}$)	H _s [†] ($\frac{\text{Btu}}{\text{lb}_m}$)	Total Run Time (sec)	Remarks
1	0.0492	68.7	7530	132.9	Initial calibration run
2	0.0377	63.9	7970	135.6	Calibration run for final conditions
3	0.0375	62.2	7760	106.2	Repeatability check
4	----	----	----	----	No run — power failure
5	0.0379	40.2	5030	58.4	Teflon coating on hemispherical calorimeter
6	0.0369	47.6	6030	68.5	Repeatability check
7	0.0373	50.6	6350	183.2	Inserted RADE A wooden model @ 0°—Teflon still intact on hemispherical calorimeter
8	0.0373	59.3	7430	362.6	Steady-state stream survey—teflon removed from hemispherical calorimeter
9	0.0373	58.5	7310	367.9	Stream survey-dome head calorimeter inserted @ 0°
10	0.0379	58.5	7300	253.9	Stream survey-RADE A head calorimeter inserted @ 0°
11	0.0379	58.5	7300	85.3	Repeat run on RADE A head @ 0° — no survey
12	0.0379	60.8	7590	153.3	RADE B head calorimeter inserted @ 0° — no survey
13	0.0378	61.0	7620	162.0	Stream survey — repeat run on RADE B head @ 0°
14	0.0363	58.0	7250	600.1	RADE A ablation model run @ $\alpha = 0^\circ$ (model exposed ~ 8 min)
15	0.0373	60.7	7580	840.0	RADE B ablation model run @ $\alpha = 0^\circ$ (model exposed ~ 10 min)
16	0.0373	62.4	7790	240.3	Inserted RADE A wooden model @ $\alpha = 30^\circ$
17	0.0381	60.8	7590	86.5	RADE B head calorimeter inserted @ $\alpha = 30^\circ$
18	0.0377	64.4	8030	69.4	Repeat run on RADE B head calorimeter @ $\alpha = 30^\circ$
19	0.0371	57.8	7160	71.4	RADE A head calorimeter inserted @ $\alpha = 30^\circ$
20	0.0377	65.3	8130	80.6	Repeat run on RADE A head calorimeter @ $\alpha = 30^\circ$
21	0.0373	62.8	7840	900.7	RADE B ablation model run @ $\alpha = 30^\circ$ (model exposed ~ 14 min)
22	0.0395	66.8	8130	937.4	RADE A ablation model run @ $\alpha = 30^\circ$ (model exposed ~ 14 min)

*q_{ref} from hemispherical slug-type calorimeter @ 1 in. downstream of nozzle exit: Equation (12)

†H_s calculated from q_{ref}: Equation (10)

Figure 29. Schematic Diagram of Instrument Orientation for Lateral and Longitudinal Flow Stream Surveys

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Figure 30. Stagnation Pressure and Heat Flux Measurements from Longitudinal Flow Stream Survey

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Figure 31. Stagnation Pressure and Heat Flux Measurements from Lateral Flow Stream Survey
(Taken at 8 in. downstream from nozzle exit)

heat flux, for the same runs, was 25%, which is too great to be considered part of the "effective" test core; however, the decrease at the same points for Run 13 is only 11%. Therefore, an average of 10 in. was considered to be the "effective" test core diameter and was entirely sufficient for testing the RADE models.

In order to determine the stagnation enthalpy from the stream survey, it was first necessary to convert the measured heat flux $[q_{s(ff)}]$ to the reference value (q_{ref}) for a hemisphere. Since the Asymptotic calorimeter was a flat-faced (ff) cylinder, the following relationship was used:

$$q_{ref} = q_{s_{hemi}} \sqrt{R_n} = \frac{q_{s(ff)} \sqrt{0.026}}{0.5} \frac{\text{Btu} \cdot \sqrt{\text{ft}}}{\text{ft}^2 \cdot \text{sec}} \quad \dots (11)$$

where 0.5 is the value of the ratio $(q_{s(ff)}/q_{s_{hemi}})$ as given in Reference 13 for Mach 5 flow. The stagnation enthalpy, {using the maximum measured heat flux $[q_{s(ff)}]$ of 200 Btu/ft²-sec which converts to a reference value of 71 Btu- $\sqrt{\text{ft}}$ /ft²-sec from Equation (11)} was determined from Equation (10) to be 8880 Btu/lb_m. This value, as previously discussed, is based on a measured heat flux in frozen flow where the influence of catalytic efficiency reduces the heat flux by an amount depending on the material exposed to the stream. The calorimeter used in the survey was composed of copper as a heat sink with a sensing disc area of constantan (nickel alloy). The metal, copper, is known to have a relatively high catalytic efficiency,⁽¹²⁾ but that of nickel is lower by an approximate factor of six. Since no data exist on the reduction of heat flux with this combination of materials at these flow conditions, the value of 8880 Btu/lb_m for stagnation enthalpy was accepted for testing. The reference heat flux, however, was approximately 18% higher than the specified 60 Btu- $\sqrt{\text{ft}}$ /ft²-sec.

The substantial difference in the slug-type calorimeter measurements and the survey Asymptotic calorimeter heat flux measurements at 1-in. downstream of the nozzle exit was attributed to the possible inaccuracy of the slug-type calorimeter due to the method used in determining heat flux from its readings.

The readings, or output signal, of the slug-type calorimeter was obtained as the slope of the temperature rise vs time curve obtained from oscillograph recordings. The reference heat flux ($q_s \sqrt{R_n}$) was then calculated using the equation:

$$q_{\text{ref}} = \frac{mC_p}{A} \sqrt{R_n} \frac{dT}{dt} \quad \dots (12)$$

where

m = weight of calorimeter slug,

C_p = specific heat of slug (copper),

A = active area of calorimeter slug,

dT/dt = slope of temperature vs time curve.

It is the value used for the specific heat in the above calculation that may cause deviation of the heat flux from its true value, whereas the Asymptotic calorimeter measures the heat flux directly.

Before making any actual test runs with the calorimeter model, wooden (oak) models of the RADE A and B configurations were inserted into the flow stream as checkout specimens for the purpose of (1) determining the possible existence of flow blockage and shock impingements, and (2) testing the model support system operation during a test run. Flow blockage, by creating a "hot core" in the jet stream, could severely damage the calorimeter model and shock impingements from the model could cause failure of the support system. A thermocouple was mounted in the tip of the center NaK overflow tube on two of the RADE A wooden models to provide a preliminary check of the data system operation under testing conditions. Figure 32 shows a RADE B wooden replica as mounted in the 0° angle of attack test position.

The wooden model tests were successful at both 0° and 30° angles of attack and gave no indication of flow blockage. The support system operated as anticipated and shock impingements were not severe enough to cause any damage to the system. The thermocouple in the RADE wooden models (center NaK tube) produced output for approximately 5 sec, thus providing an adequate checkout of the data acquisition system.

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Figure 32. RADE B Oak Model Mounted in
Test Position at 0° Angle of Attack

B. CALORIMETER AND ABLATION TESTS

The procedure for the calorimeter tests consisted of first installing the vessel on the support arm, followed by the installation of each head configuration to the vessel. With the calorimeter model fully installed and the electrical leads connected, a continuity check was made on the heat sensors. The coolant (water) was then turned on and the flow regulated to the proper pressure. The model was cycled into test position with the outside control switch several times to adjust the pneumatic actuator pressure and to check for possible leakage in the coolant system. A check of the heat sensor continuity was again made to insure their operation after actuation of the arm into and out of test position.

The facility preparations required prior to and following a data run are not described here in detail, however, the AI data system and model preparations were conducted in harmony with the established procedure at the facility. The test chamber was closed after model installation and checkout, evacuated, and the jet started. When steady-state flow conditions were reached, the hemispherical calorimeter and pitot probe unit was inserted into the stream. This was followed by a calorimeter and pitot survey of the stream (according to the run sequence in Table 1).

Once the desired flow conditions were established and the flow survey measurements completed, the photographic and data recording equipment were activated. Voice communication with the control room and test conductor was accomplished with intercom earphones. The model support system was then activated, swinging the model into the center of the flow stream. The x-y recorder of the data system was operated throughout each test run, monitoring one channel of data. The leading tip heat sensor on the dome head model was monitored (and recorded) as a primary reference heat flux measurement, and an immediate check with the flow survey measurements. The run time in the jet for the calorimeter models was restricted to approximately 10 sec to avoid possible over temperature (450°F maximum) failure of the sensors. Since the calorimeter response rate was about 250 msec, only a few seconds exposure to the flow stream was required to measure the desired data. A second run was made on all calorimeter model head configurations at both 0° and 30° angles of attack for a repeatability check, with the exception of the dome head which failed (severe coolant channel rupture) during the last seconds of the first run with this head.

Since the pressure to the pneumatic cylinder was minimized to avoid severe bouncing of the model at the stop position in the flow stream, the arm and leg assembly could not be withdrawn. However, the test conductor was able to effect an almost instantaneous shutoff of the arc without damage to the facility systems and this procedure was followed for termination of each run.

The test procedure for the ablation-disintegration runs was similar to the sequence described above for the calorimeter runs. With the RADE model installed and a systems check completed, the test chamber was closed and evacuated. The arc was then started and the stream brought to steady-state flow followed by the usual calorimeter and pitot measurements. The model was inserted into the stream after activation of the data recording equipment and the motion picture cameras. There was no preset run time for the ablation models; however, due to facility capabilities the maximum running time was set at 14 min. All test runs, calorimeter and ablation, were made at the 0° angle of attack orientation first, followed by a change to the 30° angle of attack system for all remaining runs. The entire test run sequence for the RADE models is presented in Table 2.

The output from the calorimeter model runs (heat sensors) and the chromel/alumel thermocouple output from each of the RADE model ablation runs was recorded on FM tape throughout each run. The signal from the limit switch located on the support system at the tripod apex was used to mark the tape as the model reached test position (time zero). Other data recorded during the ablation runs were color motion picture film coverage consisting of normal event (24 frames-per-sec) coverage and high-speed (128 frames-per-sec) coverage.

TABLE 2
SUMMARY OF RADE MODEL TEST RUNS

Run No. (Refer to Table 1)	Model	Angle of Attack (α)	Total Exposure Time (sec)
7	Wooden Model - RADE A	0°	~150.0
9	Calorimeter - Dome Head		15.0
10	RADE A Head		9.5
11	RADE A Head		8.7
12	RADE B Head		12.0
13	RADE B Head		13.5
14	Disintegration - RADE A		517.0
15	RADE B		610.0
16	Wooden Model - RADE A	30°	~200.0
17	Calorimeter - RADE B Head		10.5
18	RADE B Head		6.2
19	RADE A Head		6.6
20	RADE A Head		5.2
21	Disintegration - RADE B		822.0
22	RADE A		830.0

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V. TEST RESULTS AND ANALYSIS

A. CALORIMETER TESTS

The FM tape recorded data, following the completion of all testing, was corrected to provide more accurate results by eliminating extraneous noise. The data were then plotted from the tape on an x-y recorder. The resulting plots of millivolt output from the heat sensors versus time was reduced to measured heat flux (q_m) using the calibration curve for each sensor provided by the manufacturer. These data are presented in Table 3 for the entire series of calorimeter tests.

The initial calorimeter test, made with the dome head configuration, was used as a standard for establishing the reference heat flux (q_{ref}) to the subsequent ablation models. Converting the measured value from heat sensor A to the heat flux to a 1-ft radius hemisphere yields a reference value (q_{ref}) of 73 Btu- $\sqrt{ft}/ft^2$ -sec. This value is in good agreement with that measured by the flow survey calorimeter (71 Btu- $\sqrt{ft}/ft^2$ -sec). Using the dome head reference heat flux, the stagnation enthalpy was calculated from Equation (10) to yield 9080 Btu/lbm. A calculation of the recombination rate parameter (C_1) was made for this test condition, using the equation:

$$\frac{C_1}{R_n} = k_1 T_s^{-3.5} \frac{P_s^2}{R^2} \sqrt{\frac{\rho_s}{2 P_s}} \quad \dots (13)$$

which results from Equations (7) and (8) after assuming $P_\infty \ll P_s$. The term C_1/R_n is shown in Figure 4 as a function of stagnation pressure and enthalpy (Section II). The resulting C_1 value for the test conditions, $H_s = 9080$ Btu/lbm and $P_s = 0.038$ atm, was 2.12×10^{-5} . This determination of C_1 was made to verify the test condition flow regime as that of frozen flow ($C_1 \ll 1$) since a determining factor of the chemistry of boundary layer flow is the recombination rate parameter.

The effect of catalycity on the heat flux at conditions similar to those of the RADE test have been measured and are presented in Reference 8. These measurements show that the reduction of heat flux to a gold-plated calorimeter is

TABLE 3
RADE CALORIMETER MODEL TEST RESULTS

Angle of Attack α	Model Component	Heat Sensor (Refer to Figures 17, 18)	q_m (Btu/ft ² -sec)	q_m (Btu/ft ² -sec)
0° ↓	Dome Head ↓ Vessel ↓	A B C H I J K L M N	Run 9	
			167	
			124	
			52	
			6	
			8	
			11	
			--	
			--	
			2	
0° ↓	RADE A Head ↓ Vessel ↓	A B C D E F G H I J K L M N	Run 10	Run 11
			5.5	5.5
			75.0	85.0
			165.0	165.0
			3.0	4.0
			3.0	3.1
			14.0	14.0
			4.0	5.0
			2.5	2.5
			6.5	6.5
			7.5	7.5
			4.0	3.0
			8.0	7.0
			6.0	----
			2.5	2.5
0° ↓	RADE B Head ↓ Vessel ↓	A B C D E F G H I J K L M N	Run 12	Run 13
			179	194
			8	8
			59	65
			59	63
			103	85
			69	79
			16	9
			3.0	5.5
			4.0	4.0
			7.5	6.5
			4.5	3.5
			8.0	6.5
			6.5	5.5
			7.5	7.7
30° ↓	RADE B Head ↓ Vessel ↓	A B C D E F G H I J K L M N	Run 17	Run 18
			69	92
			75	74
			168	166
			22	24
			66	68
			97	97
			6	5
			24.0	25.5
			20.0	21.0
			14.0	15.0
			17.5	16.5
			42.0	41.5
			43.0	37.0
			49.0	48.0
30° ↓	RADE A Head ↓ Vessel ↓	A B C D E F G H I J K L M N	Run 19	Run 20
			227	227
			429	430
			102	99
			18	18
			77	73
			43	49
			5.5	4.0
			8.0	7.5
			16.0	16.0
			6.5	4.5
			17.5	12.0
			33.0	32.0
			15.0	15.0
			42.0	41.5

equal to that of a stainless steel coated calorimeter at those conditions. Therefore, it was concluded that the heat flux to the stainless steel ablation models would be equal to that measured by the gold-plated calorimeter model configurations for the RADE tests.

From the measured readings of the sensors located in the dome head, local-to-stagnation point heating ratios (q_l/q_s) were calculated. The resulting ratios are plotted in Figure 33 as a function of angle from the stagnation point. Also plotted in the figure is a theoretical curve for the ratio q_l/q_s obtained from the work of Lees.⁽¹⁴⁾ The excellent agreement of the measured ratio with that of theory substantiates the validity of the measured data at the stagnation point for use as a standard value of reference heat flux.

The heat sensors in all calorimeter test runs did, for the most part, function properly and repeated measurements were made with good accuracy from run to run as shown in Table 3. However, there were some readings lost and some questionable. Specifically, three sensors in the vessel (sensors K, L, and M) during the dome head run did not record due to an amplifier failure in the data system. For the same reason, sensor M again did not record during the RADE A calorimeter model run 2 at 0° angle of attack. In previous tests made with coated calorimeters to determine the effect of catalytic efficiency on heat flux,⁽⁸⁾ it was important that the calorimeters be kept clean of jet stream contamination from run to run in a hypersonic wind tunnel. Therefore, the models were cleaned with pure alcohol following each test run.

B. REACTOR ABLATION TESTS

1. Photography

Each ablation test run, from the time of model insertion into the jet stream until run termination, was filmed with two 24 frames/sec color motion picture cameras. Two cameras were used to enable a more complete observation of the model disintegration by recording both right port and top port views. The film was reviewed in detail with a frame-counting projector and the events of ablation and disintegration of the models were recorded. In addition to the normal event film, high-speed (128 frames/sec) color motion picture film was used to record three of the runs. A high-speed film record was not obtained during the RADE A test run at 0° angle of attack due to a malfunction of the camera. The high-speed

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Figure 33. Heat Transfer Distribution Around the Hemispherical Head Calorimeter

film was also reviewed in detail and the primary events recorded. A listing is given in Tables 4, 5, 6, and 7 of the significant events observed from the film for each ablation test. The event sequences listed in the tables are a compilation of the normal (24 fps) and high-speed (128 fps) film observations with the high-speed film given precedence due to the greater film speed accuracy of the Milliken camera.

Following the tables of events for the test runs are still photographs, made from the motion picture film, illustrating the ablation sequence. The photographic event sequence of the test runs is shown in Figures 34 through 37.

Each test model was photographed while still in test position following the termination of each test run. Two of these are shown in Figures 38 and 39 and illustrate the fact that these tests did not result in the predicted breach of the reactor vessel and subsequent release of the fuel elements. Figures 40 through 43 are post-test photographs of the models after their removal from the test chamber showing the components that were dispersed from the models. These components were recovered from the settling chamber downstream from the test section (Figure 5). From these figures (40 through 43) it can be seen that ablation of the vessel and core did not proceed beyond the upper grid plate at the 0° angle of attack position and only a portion of the vessel and core was ablated at the 30° angle-of-attack test position. A more detailed discussion of these results is presented in Section V-B-3 of this report.

2. Data Analysis

a. Analytical Model Description

A thermal analyzer program computer code (TAP-3) analog was developed to represent a 180° portion of each RADE experimental model configuration for both the head-on (0°) and 30° angle of attack test positions. The analog of the RADE A experimental model consists of the external NaK pipe network, magnets, thermoelectric pump, cooling fins, top head, upper grid plate, and reactor core assembly. The TAP analog of the RADE B experimental model includes the NaK outlet pipe, top head, upper grid plate, and reactor core assembly. These analogs were used in correlating the RADE ablation data with the analytical methods and procedures.

TABLE 4
MOTION PICTURE FILM EVENT DATA FOR
RADE A TEST RUN AT $\alpha = 0^\circ$

Event	Time* (sec)
1. Commence ablation of [†] upper thermal switches	1.38
2. Lower thermal switches and NaK transverse pipe — begin ablation [†]	1.58
3. Initial ablation of pump fins at [†] forward edges	2.25
4. Lower NaK overflow tube and 1/2 of transverse pipe — begin breach from center outlet pipe [†]	4.50
5. Lower NaK tube and downcomer pipe dispersed [†]	4.58
6. Commence ablation of center NaK fill tube	4.96
7. Top NaK transverse pipe begin breach from center outlet pipe [†]	5.50
8. Top NaK pipe assembly (including downcomer pipe) dispersed [†]	8.25
9. Center fill tube ablated back to transverse pipe intersection	27.33
10. Transverse pipe remainder dispersed	29.17
11. Pump fins fully ablated down to pump	29.58
12. Commence ablation of pump at [†] forward tip	33.42
13. Top of pump and pump fins fully ablated	40.58
14. One-half of magnet dispersed	65.17
15. Remaining one-half of magnet dispersed	70.79
16. Base of center outlet pipe dispersed	88.38
17. Vessel head fully ablated to upper grid plate	109.04
18. Run terminated — no vessel and core disintegration	517.0

*t = 0 at full insertion into jet stream

†Refers to orientation in the jet stream from right side port
(see Figure 11)

TABLE 5
MOTION PICTURE FILM EVENT DATA FOR
RADE B TEST RUN AT $\alpha = 0^\circ$

Event	Time* (sec)
1. Commence ablation of NaK pipe at [†] forward tip	6.12
2. Commence breach of NaK pipe at [†] forward tip	12.84
3. NaK pipe dispersed	17.55
4. Begin ablation of vessel head at outer periphery	21.78
5. Remaining NaK pipe at head junction fully ablated — begin vessel head breach	64.74
6. Vessel head dispersed	64.85
7. Continued slow ablation of upper grid plate to this time	257.0
8. Run termination — little change in vessel and core	610.0

*t = 0 at full insertion into jet stream

†Refers to orientation in the jet stream from side port (see Figure 12)

TABLE 6
MOTION PICTURE FILM EVENT DATA FOR
RADE B TEST RUN AT $\alpha = 30^\circ$

Event	Time* (sec)
1. Commence ablation of NaK pipe at [†] forward tip	7.39
2. Commence breach of NaK pipe at [†] forward tip	18.97
3. NaK pipe dispersed	21.71
4. Begin ablation of vessel head	24.29
5. Head ablated to fully expose upper grid plate	113.66
6. Head completely ablated	116.06
7. Run termination — no vessel and core disinte- gration	822.0

*t = 0 at full insertion into jet stream

†Refers to orientation in the jet stream from side port (see Figure 12)

TABLE 7
MOTION PICTURE FILM EVENT DATA FOR
RADE A TEST RUN AT $\alpha = 30^\circ$

Event	Time* (sec)
1. Commence pump fin ablation at [†] leading edges	1.04
2. Commence ablation of pump at [†] forward edge	2.13
3. Commence transverse NaK pipe ablation	2.70
4. Commence ablation of [†] top NaK overflow tube and thermal switches	4.01
5. Begin ablation of [†] bottom NaK overflow tube	4.50
6. Begin ablation of [†] center NaK fill tube	5.65
7. Breach of NaK transverse pipe from center outlet pipe	6.54
8. Top overflow tube dispersed [†]	8.41
9. Breach of [†] bottom NaK pipe from center pipe at cross-point	9.09
10. Center fill tube dispersed	9.77
11. Top NaK downcomer pipe dispersed [†]	10.79
12. Bottom overflow tube dispersed [†]	10.91
13. Portion of [†] bottom fin breached and dispersed	11.68
14. Bottom NaK downcomer pipe dispersed [†]	12.55
15. Lip on vessel head is ablating	19.21
16. Pump fins and top of pump fully ablated	26.88
17. Pump and magnet dispersed	34.26
18. Begin breach of center NaK outlet pipe — held to head by feet	35.12
19. Center NaK pipe dispersed	40.31
20. Continuous slow ablation of head to this time	80.92
21. Commence breach of vessel at [†] leading edge	173.79
22. Run termination	830.0

*t = 0 at full insertion into jet stream

†Refers to orientation in the jet stream from side port (see Figure 11)

t = 0 sec

t = 1.38

t = 3.29

t = 4.50

t = 5.50

t = 27.33

t = 29.17

t = 50.0

t = 65.17

t = 70.79

t = 88.38

t = 111.25

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Figure 34. Event Sequence for
RADE A Ablation Test Run at
0° Angle of Attack
(Film Speed: 24 fps)
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t = 17.09

t = 17.55

t = 22.23

t = 64.30

t = 64.81

t = 64.85

t = 100.0

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Figure 35. Event Sequence for
RADE B Ablation Test Run at
0° Angle of Attack
(Film speed: 128 fps)

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t = 0 sec

t = 7.39

t = 13.13

t = 18.97

t = 21.71

t = 24.29

t = 32.96

t = 200.0

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Figure 36. Event Sequence for
RADE B Ablation Test Run at
30° Angle of Attack
(Film speed: 24 fps)

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t = 4.50

t = 8.41

t = 9.77

t = 10.79

t = 11.68

t = 12.55

t = 21.45

t = 34.19

t = 34.26

t = 40.31

t = 59.39

t = 100.0

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Figure 37. Event Sequence for
RADE A Ablation Test Run at
30° Angle of Attack
(Film Speed: 128 fps)

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Figure 38. RADE A Model in Test Position
at 0° Angle of Attack Following
Termination of Test Run

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Figure 39. RADE A Model in Test Position
at 30° Angle of Attack Following
Termination of Test Run

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Figure 40. RADE A Model After Test Run
at 0° Angle of Attack

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Figure 41. RADE B Model After Test Run
at 0° Angle of Attack

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Figure 42. RADE A Model After Test Run at 30° Angle of Attack

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Figure 43. RADE B Model After Test Run at 30° Angle of Attack

(1) Description of the RADE A Analytical Model (Analog)

Due to size limitations of the TAP-3 computer code the complete external geometry of the RADE A experimental model could not be included in the analog. Those portions of the experimental model which contain thermocouples were simulated by the TAP-3 analog. The analog of the RADE A experimental model consists of one-half of the external NaK pipe network, the instrumented cooling fin, the complete center NaK fill tube, magnetic thermoelectric pump assembly, and a 180° portion of the top head, upper grid plate, and reactor core.

The RADE A analog is symmetrical with respect to the heat source with the exception that only one cooling fin could be simulated due to size limitations of the TAP-3 code. The shaded portion of Figure 44 shows the external geometry of the RADE A experimental model included in the TAP-3 analog.

Detailed illustrations of the RADE A, TAP-3 analytical model network (analog) are given in Figures 45 through 50. Figure 45 shows both a top view and a front view of that portion of the NaK pipe system simulated by the analytical model. The horizontal cross pipe to which the thermoelectric switches are attached was divided into four circumferential segments and seven cross-axial segments. The center NaK fill tube and the outer NaK overflow tube are each represented by a single segment. All of the nodes in the external NaK pipe system are interconnected by heat conduction and radiation paths. The heat conduction paths in Figures 45 through 50 are represented by zigzag lines, and the dashed lines represent the radiation resistances. All external nodes radiate to an ambient temperature of 80°F.

Figure 46 shows a side view of the magnet and thermoelectric pump portion of the RADE A experimental model showing the major aspects of the analytical network. This section of the reactor model was divided into five cross-axial segments. One of these segments, section DD, is illustrated in Figure 46. Section DD is that segment of the analytical model which contains the network representing the two halves of the RADE A magnets. This portion of the analytical model is connected above to the NaK cross-pipe and below to the top head by conduction heat transfer paths.

Figure 47 shows a side view and a top view of the cooling fin portion of the RADE A analog. The cooling fin was divided into five axial segments and five

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Figure 44. Portions of the RADE A Experimental Model (Shaded areas) Represented by the TAP-3 Analytical Model

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Figure 45. RADE A External NaK Pipe Analytical Network

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CONDUCTION HEAT TRANSFER PATHS
ALL EXTERNAL NODES RADIATE TO ENVIRONMENT

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Figure 46. RADE A Magnet and Thermoelectric Pump Analytical Network

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Figure 47. RADE A Cooling Fin Analytical Network

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Figure 48. RADE A Top Head and Upper Grid Plate Analytical Network

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Figure 49. Axial Divisions of RADE A Analytical Model

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Figure 50. RADE A and RADE B Top Core Segment Analytical Network

transverse segments. Each segment is connected to adjacent segments by conduction paths. Both sides of the cooling fin radiate to an ambient temperature of 80°F. The cooling fin network is connected to the analytical network representing the thermoelectric pump by means of three transverse heat conduction paths. Figure 44 shows which of the experimental cooling fins are represented by the analytical model.

The 180° portion of the top head and upper grid plate that was included in the RADE A analog was divided into six circumferential, 30° pie-shaped segments. An axial cross-section of the top head and upper grid plate is shown in Figure 48. The total depth of the grid plate is represented by a single axial segment. Each 30° segment of the upper grid plate not only receives radiant heat from those nodes directly above, as shown by the dashed lines in Figure 48, but also from those nodes in each adjoining 30° segment of the top head. Each node in a given axial layer is connected by circumferential heat conduction paths. Each node in a given 30° pie-shaped segment is connected to the corresponding nodes in adjacent axial layers by radial heat conduction paths.

The 180° core portion of the RADE A TAP-3 model was divided into two axial segments as shown in Figure 49. The top axial segment represents 1/6 of the core depth. The bottom axial segment includes the rest of the core length. The analytical network representing the top axial layer is shown in Figure 50. The dashed lines in Figure 50 illustrate the various radiation paths between fuel rods, internal reflectors, and the vessel wall included in the top axial layer. The zigzag lines are the heat conduction paths in the internal reflectors and the RADE A vessel wall. The bottom axial layer of the RADE A core analytical model differs from the top layer in that no transverse heat transfer paths were included between the internal core components. Due to size limitations of the TAP-3 computer code, the bottom axial nodes serve only as heat sinks for corresponding nodes in the top axial layer. The vessel wall nodes in both axial layers radiate to the surrounding environment.

(2) Description of RADE B Analytical Model

The TAP-3 analog which was developed to represent the RADE B experimental model consists of the complete NaK outlet pipe and a 180° portion of the top head, upper grid plate, and reactor core. An axial cross section of the NaK

outlet pipe, top head, and upper grid plate portion of the RADE B analytical model is shown in Figure 51. The NaK pipe was divided into four segments, each representing 22.5° of the 90° section that was included in the TAP-3 model. Each segment of the NaK pipe was composed of eight nodes, one located every 45° around the circumference of the pipe. There is a similar series of eight nodes located at the interface between the NaK pipe and the top head. Section AA in Figure 51 shows a typical cross-axial cross section of the NaK pipe at the location of the nodes. The dashed lines in section AA represent the radiation heat exchange paths between nodes that were incorporated into the TAP model. Each node in a given NaK pipe segment was connected by a circumferential heat conduction path. Each segment was connected by longitudinal heat conduction paths.

The 180° portion of the top head and upper grid plate that was included in the TAP-3 analog was divided into six circumferential 30° pie-shaped segments. An axial cross section of the top head and upper grid plate portion of the analytical model is also shown in Figure 51. The heat conduction and radiation paths that were incorporated into each 30° segment of the analytical model are represented as before. Each 30° segment in the top surface of the upper grid plate not only receives radiant heat from those nodes directly above, as shown in Figure 51, but also from those nodes in each adjoining 30° segment of the top head. Each node in a given axial layer is connected by a circumferential heat conduction path.

The 180° core portion of the TAP-3 model was divided into two axial segments as shown in Figure 52. The top axial segment represents $1/6$ of the core depth. The bottom axial segment includes the rest of the core length. A typical cross section of the core is given in Figure 50. All of the nodes in each segment were connected to the corresponding nodes below by axial conduction resistances. The local heat input at each nodal location was a function of: (1) the geometry of the experimental model area represented by the given node, and (2) the angle of attack of simulated aerodynamic heating. Since all exterior nodes in a given reactor model receive heat input independently, local heating perturbations can be incorporated into the analytical calculations.

Heat input is distributed throughout the analytical models by means of the various radiation and conduction networks illustrated in Figures 44 through 52.

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Figure 51. TAP-3 Analog of RADE B NaK Pipe,
Top Head and Grid Plate

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Figure 52. Axial Division of RADE B Analytical Model

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Conduction heat transfer resistances are functions of the length between connected nodes, heat transfer area, and the thermal conductivity of the material involved. Radiation resistances are calculated by the TAP-3 computer code from the surface areas, emissivities, temperatures, and view factors of the two connected nodes. External nodes in both analytical models radiate to the ambient temperature within the test facility which was assumed to be held constant at 80°F.

Heat is stored by the various nodes according to their thermal capacity which is a function of volume and specific heat capacity of the material.

(3) Thermophysical Properties Used

The thermophysical properties used in the RADE A and B analytical models are as follows.

- 1) Thermal conductivity of SS-316, varied approximately linearly with temperature, from 8.0 Btu/ft-hr-°F at 0°F to 20.3 Btu/ft-hr-°F at 2790°F
- 2) Specific heat capacity of SS-316, varied approximately linearly with temperature, from 0.10 Btu/lb-°F at 0°F to 0.139 Btu/lb-°F at 2790°F
- 3) Density of SS-316: 475 lb/ft³
- 4) Emissivity of SS-316: for internal radiation 0.7 for external radiation to environment 0.89
- 5) Thermal conductivity of Monel internal reflectors: 8.6 Btu/ft-hr-°F
- 6) Specific heat capacity of Monel internal reflectors: 0.127 Btu/lb-°F
- 7) Density of Monel: 0.319 lb/in³
- 8) Emissivity of Monel: 0.43
- 9) Emissivity of Hastelloy-N cladding: 0.3
- 10) Thermal conductivity of fuel alloy: 15 Btu/ft-hr-°F
- 11) Specific heat capacity of fuel alloy: 0.1 Btu/lb-°F
- 12) Density of fuel alloy: 0.216 lb/in³
- 13) Thermal conductivity of aluminum RADE A cooling fin: 244.5 Btu/ft-hr-°F

- 14) Specific heat capacity of aluminum RADE A cooling fin: 0.277 Btu/lb-°F
- 15) Density of aluminum: 168.5 lb/ft³
- 16) Emissivity of aluminum: 0.89.

b. Heat Flux Input to Analytical Models

Using the calorimeter results given in Section V-A, geometric heating factors were calculated for various portions of the experimental models. These heating factors were then incorporated into the analogs representing the four experimental test configurations.

Five analytical calculations were made. The first two were made using the RADE A analog with simulated head-on (0°) and 30° angles of attack heating conditions. Two calculations were made using the RADE B analog with simulated head-on (0°) and 30° angles of attack heat input.

Upon examination of the pictorial data (Section V-B-1) it was found that two distinct phases occurred during the ablation sequence of each experimental model. During the initial 60 sec of each test case the external components of the various reactor models readily ablated and dispersed. At the end of this period only the reactor vessel, core assembly, and partially ablated top head portions of each of the test models remained. After approximately 60 sec the remaining portion of the top head of each model slowly ablated away exposing the upper grid plate to aerodynamic heating. Following complete dispersal of the top head during each experimental case, the reactor vessel and core components of each model appeared to establish and remain at a condition of thermal equilibrium. To conserve computer time, the first four analytical calculations were made to simulate only the first 60 sec of each experimental case.

A fifth analytical calculation was made to simulate the long-term "thermal equilibrium" portion of the RADE B, 0° angle of attack heating case. It was felt that due to the similarity of the core sections of the RADE A and RADE B models and the lack of experimentally determined heat input values to a RADE core section (geometry change due to ablation) one calculation would be sufficient to duplicate the second phase of all the experimental cases.

The local heating factors used in the various calculations were entered into the analogs as the ratio of q_{local} to q_{ref} . The heating factors which were

experimentally determined for the four test cases are illustrated in Figures 53 and 54. Each heat sensor location on the calorimeter models was assigned a letter designation which is given in Figure 18. The number beside the letter at each heat sensor location in Figures 53 and 54 is the geometric heating factor for that location. These local heating factors were obtained by dividing the average heat flux measured during the two calorimeter runs for each model head configuration (Table 3) by the value of q_{ref} to a 1-ft sphere.

Experimental wind tunnel data⁽²⁾ were used to determine local heating factors for points on the RADE A model where heat sensor measurements were not obtained experimentally. This data consist of an experimental determination of the local heating rates to a SNAP 10A reactor for head-on (0°) and 30° angle of attack heating. A cosine distribution was used to determine local heating factors on the RADE B reactor model where heat sensor measurements were not obtained.

To approximate the "thermal equilibrium" portion of the RADE B head-on heating case, the network representing the NaK outlet pipe and top head was removed from the analog. Aerodynamic heating was fed directly into the surface of the upper grid plate and external surface of the reactor vessel. The heat distribution used in this calculation was assumed to be the same as that to a flat-faced cylinder under head-on heating conditions, which is described by Klett.⁽¹⁵⁾

c. Ablation Test Results

Representative temperature versus time traces, obtained at various thermocouple locations during the four experimental runs, are given as the solid lines in Figures 55 through 76. The position of each thermocouple on the RADE A and RADE B experimental models is shown in Figures 11 and 12 respectively. Data traces were not obtained for the following thermocouples which failed to transmit a data signal to the data recording system: RADE A, 0° , Thermocouples 3, 4, 10, 11, 15, and 29; RADE A, 30° , Thermocouple 2.

d. Results of Analytical Calculations

The results of the analytical calculations of the simulation of the initial 60 sec of the four experimental runs are shown as dashed traces in Figures 55 through 76. Not all thermocouple positions could be superimposed identically in the analog networks as in the actual models due to size limitations of the analog

$$\text{NUMBERS} = \frac{\text{AVERAGE OF THE TWO DATA MEASUREMENTS}}{72.6 \frac{\text{Btu}}{\text{ft}^2\text{-sec}} (q_{\text{ref}} \text{ TO A ONE-FOOT SPHERE})}$$

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Figure 53. RADE A Calorimeter Test Results at 0° and 30° Angles of Attack

$$\text{NUMBERS} = \frac{\text{AVERAGE OF THE TWO DATA MEASUREMENTS}}{72.6 \frac{\text{Btu}}{\text{ft}^2 \cdot \text{sec}} (q_{\text{ref}} \text{ TO A ONE FOOT SPHERE})}$$

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Figure 54. RADE B Calorimeter Test Results at 0° and 30° Angles of Attack

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Figure 55. Comparison of
Calculated to Experimental
Temperature for T/C9
(Upper grid plate) -
RADE A at $\alpha = 0^\circ$

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Figure 56. Comparison of
Calculated to Experimental
Temperature for T/C 13
(Lip of top head) -
RADE A at $\alpha = 0^\circ$

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Figure 57. Comparison of
Calculated to Experimental
Temperature for T/C 16
(Surface of fin) -
RADE A at $\alpha = 0^\circ$

6-6-67 UNC

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Figure 58. Comparison of
Calculated to Experimental
Temperature for T/C 20
(Top NaK pipe assembly)
- RADE A at $\alpha = 0^\circ$

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Figure 59. Comparison of
Calculated to Experimental
Temperature for T/C 21
(Top NaK pipe assembly)
- RADE A at $\alpha = 0^\circ$

6-6-67 UNC

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Figure 60. Comparison of
Calculated to Experimental
Temperature for T/C 9
(Upper grid plate) -
RADE A at $\alpha = 30^\circ$

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Figure 61. Comparison of
Calculated to Experimental
Temperature for T/C 13
(Lip of top head) -
RADE A at $\alpha = 30^\circ$

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Figure 62. Comparison of
Calculated to Experimental
Temperature for T/C 16
(Surface of fin) -
RADE A at $\alpha = 30^\circ$

6-6-67 UNC

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Figure 63. Comparison of Calculated to Experimental Temperature for T/C 20 (Top NaK pipe assembly) -RADE A at $\alpha = 30^\circ$

6-6-67 UNC

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Figure 64. Comparison of Calculated to Experimental Temperature for T/C 21 (Top NaK pipe assembly) -RADE A at $\alpha = 30^\circ$

6-6-67 UNC

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Figure 65. Comparison of Calculated to Experimental Temperature for T/C 7 (Center of Rod No. 10) -RADE B at $\alpha = 0^\circ$

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Figure 66. Comparison of Calculated to Experimental Temperature for T/C 10 (Upper grid plate) -RADE B at $\alpha = 0^\circ$

6-6-67 UNC

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Figure 67. Comparison of Calculated to Experimental Temperature for T/C 12 (Top of Rod No. 10) -RADE B at $\alpha = 0^\circ$

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Figure 68. Comparison of Calculated to Experimental Temperature for T/C 19 (Vessel top head) -RADE B at $\alpha = 0^\circ$

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Figure 69. Comparison of Calculated to Experimental Temperature for T/C 20 (Vessel top head) -RADE B at $\alpha = 0^\circ$

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Figure 70. Comparison of Calculated to Experimental Temperature for T/C 22 (NaK pipe) -RADE B at $\alpha = 0^\circ$

6-6-67 UNC

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Figure 71. Comparison of
Calculated to Experimental
Temperature for T/C 25
(NaK pipe) - RADE B
at $\alpha = 0^\circ$

6-6-67 UNC

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Figure 72. Comparison of
Calculated to Experimental
Temperature for T/C 10
(Upper grid plate) -
RADE B at $\alpha = 30^\circ$

6-6-67 UNC

7700-25258

Figure 73. Comparison of
Calculated to Experimental
Temperature for T/C 19
(Vessel top head) -
RADE B at $\alpha = 30^\circ$

6-6-67 UNC

7700-25259

Figure 74. Comparison of
Calculated to Experimental
Temperature for T/C 20
(Vessel top head) -
RADE B at $\alpha = 30^\circ$

Figure 75. Comparison of
Calculated to Experimental
Temperature for T/C 22
(NaK pipe) - RADE B
at $\alpha = 30^\circ$

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Figure 76. Comparison of
Calculated to Experimental
Temperature for T/C 25
(NaK pipe) - RADE B
at $\alpha = 30^\circ$

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networks or the manner in which the experimental models were divided into segments for analysis.

The results of the analytical calculation made to simulate the long-term behavior of the RADE B, 0° angle of attack heating case are given as broken lines in Figures 65, 66, and 67, where they are compared to the corresponding thermocouple temperature versus time traces. The initial temperature for the five analytical calculations was set at 80°F.

e. Comparison of Analytical and Experimental Results

From Figures 55 through 76, it can be seen that the results obtained from the analogs compare reasonably well with those of the four experimental cases. The extent of correlation between the analytical and experimental results is much greater for the two RADE B ablation runs than for the two RADE A tests. This may be attributed to the simplicity of the external configuration of the RADE B reactor model.

The major discrepancy between the analytical and experimental results for both RADE B test cases exists at thermocouple location 14. This thermocouple is located at the top of the center fuel element directly below the NaK outlet pipe. No allowance was made in the RADE B analog for radiant heat transfer between the interior of the NaK outlet pipe and the reactor core components. As can be seen from the various traces, the best correlation for RADE B test cases was obtained at those thermocouple locations on the NaK outlet pipe prior to initiation of ablation. At these positions, the heat input was well defined and was not altered by the dispersal of other portions of the test model. By assuming that the heat distribution over the RADE B models followed a cosine law, it was possible to interpolate between the various calorimeter locations to obtain a complete local heat flux distribution for both the head-on and 30° angle of attack cases.

Due to the limited heat flux measurements in the thermoelectric pump and external NaK pipe portions of the RADE A models, it was difficult to develop a complete local heat flux distribution to simulate the two experimental cases. Experimental wind tunnel data⁽²⁾ were used to augment the calorimeter data from which the analytical heat distributions were obtained. The heat flux measurements pertaining to the top head and reactor vessel portions of the RADE A models were made without the cooling fins attached to the calorimeter models.

The heat distribution obtained from these measurements may differ from that during the two ablation tests when the cooling fins were attached to the reactor models. It is felt that the approximate nature of the heat distributions thus obtained prevented better correlation between analytical and experimental results for the two RADE A test runs.

The temperature-versus-time traces of the various external thermocouples on the two RADE test models become very erratic after short periods of time. This may be attributed to either the change in local heat input due to dispersal of reactor components or to molten metal hitting the thermocouple locations. The analytical calculations cannot duplicate the disintegration sequence during the four test runs, or the effect of changing heat flux distribution due to reactor component dispersal.

As in the two RADE B test cases, the best correlation for both RADE A cases was attained for thermocouples which were not influenced by the ablation and dispersal of other portions of the reactor model. The thermocouples which were located on the NaK cross-pipe and on the pump fin during the RADE A, 0°, and 30° angle of attack cases, correlated best with the experimental results.

The analytical calculation simulating the long-term thermal behavior of the RADE B, 0° angle of attack heating case was made using a theoretical heat distribution to a flat-faced cylinder under head-on heating conditions. As can be seen in Figure 41, the RADE B, 0°, reactor experimental model did not exactly approximate a flat-faced cylinder after the NaK outlet pipe and top head had melted and dispersed. The residual molten mass around the periphery of the upper grid plate would cause the heat input to the experimental model to deviate from that used in the analytical calculation. Another reason for the apparent poor correlation, particularly during the initial period, is that the calculation did not duplicate the ablation sequence of the RADE B, 0° case before dispersal of the NaK outlet pipe and top head. Therefore, the initial conditions used in the analog were different from those of the experimental model at the time at which the top had ablated and dispersed.

The results of the long-term analytical calculation did substantiate the following three important facts.

1) The analog can approximate the thermal behavior of the experimental model for long periods of time, if allowance is given for differences in initial conditions and heat input values used;

2) The experimental model did not establish a thermal equilibrium condition with the surrounding environment as might be assumed from some of the experimental data;

3) The experimental model did not lose an appreciable amount of heat to the model support arm during the ablation tests.

As can be seen by comparing the experimental and analytical traces for Thermocouples 7 and 12 (Figures 65 and 67), even though the thermocouples near the front of the respective models approach a constant value, those in the interior of the core experience a steady increase in temperature until termination of the experimental run. From this it is felt that the experimental models did not establish thermal equilibrium but that the large heat capacity of the reactor core components absorbed enough heat from the upper grid plates to prevent their ablation.

It is further felt that no significant amount of heat was lost to the experimental model support arm since the analytical calculations approximate the experimental case without incorporation of any such heat loss.

Post-test examination of the vessels (Section V-B-3) showed a blackened, porous surface on the upper grid plate and an oxidized vessel surface both of which would have a high emissivity. Therefore, an emissivity of approximately 0.9 was used in the analytical model. At high temperature, where the effect of emissivity becomes meaningful, the calculations did agree quite well with the experimental results, indicating an additional amount of heat lost from the upper grid plate and vessel wall due to radiation.

3. Post-Test Analysis

Since the RADE model vessels did not breach (ablate) sufficiently to affect the release of the fuel elements under the simulated reentry conditions of the Ames Test Facility, a post-test analysis was conducted on two of these vessels to determine the state of the vessels and their core contents. This analysis consisted of the disassembly and physical and metallurgical examination of the

RADE B model tested at 0° angle of attack and the RADE A model tested at 30° angle of attack.

The vessel wall of the RADE B model was cut, circumferentially, at approximately 3 in. below the upper grid plate. The stopring-nut assembly at the base of the model was then removed followed by the unobstructed removal of the lower grid plate. The vessel was then easily pulled away from the core at the cut. There was no apparent damage to the Monel reflectors which were removed without difficulty from the upper grid plate. Several fuel elements were also easily removed from the grid plate. The disassembled RADE B model is shown in Figure 77. Fifteen of the elements, shown in Figure 78, were welded solid to the upper grid plate and could not have been removed without machining. Figure 79 illustrates the extent of upper grid plate ablation and shows the top pins of the elements welded in position.

A summary of the physical removal and examination of the fuel elements from the RADE B model tested at 0° angle of attack is presented in Table 8. The location of the numbered elements in the core is shown in Figure 80 which corresponds to a head-on view as mounted in test position.

Fuel elements 29 and 1 were painted with temperature sensitive paints and, according to these paints, Element 29 reached 1900°F and Element 1, which is the center element, reached a temperature of between 1200 and 1300°F. The bottom grid plate, which was not visibly damaged, was painted with temperature-sensitive paints to change color at 900, 800, 700, and 500°F (see Figure 13). Only the 900°F paint remained.

Several wafer samples (5/16-in. thick) of zirconium-hydride were cut from selected fuel rods and chemically analyzed for hydrogen content. The original rods ($H/Zr = 1.75$) contained a hydrogen weight percent of 1.92. Also analyzed were metal chips from the upper grid plate. The results of the chemical analysis are summarized in Table 9. The three readings given in the table correspond to those from randomly selected pieces of each wafer which were broken down in order to be accommodated by the analyzer (weight-limited).

The cladding was removed from the remainder of fuel element 29, and both pieces are shown in Figure 81. The cracks observed in the zirconium-hydride material, clearly visible in Figure 81, is characteristic of the rapid dehydriding of this material when exposed to high temperatures.

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Figure 77. RADE B Model ($\alpha = 0^\circ$) Disassembled for Post-Test Examination

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Figure 78. Base of Fuel Elements Welded to the Upper Grid Plate
of the RADE B Model ($\alpha = 0^\circ$)

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Figure 79. Frontal View of Upper Grid Plate
from the RADE B Model ($\alpha = 0^\circ$)

TABLE 8
SUMMARY OF POST-TEST EXAMINATION OF
RADE B ($\alpha = 0^\circ$) FUEL ELEMENTS

Element No. (Refer to Figure 80)	Remarks
2	Welded to upper grid plate, difficult to remove. Cladding was expanded at top weld with rupture in the seam
7	Welded to upper grid plate, difficult to remove. Cladding expanded on one side measured 0.605 OD at bulge vs 0.563 OD of an undamaged element
8	Ablated back 1-1/8 in. from forward end of element
9	Welded to upper grid plate; difficult to remove. Cladding expanded (bulged) at top of element and slightly ruptured
11	Ablated back 1/8 in. from end. Cladding bulged at the weld joint; measured 0.620 OD vs original 0.563 OD
15	End of element ablated smooth; difficult to remove from grid plate
18	Ablated back 3/4 in. from forward end of element
19	Ablated back 5/8 in. from forward end of element
20	Welded to grid plate, difficult to remove. Cladding bulged at top of element; measured 0.617 OD vs original 0.563 OD
21	Same as for Element 20. Measured at bulge 0.600 OD
36	Ablated back 15/16 in. from forward end of rod; no damage to ZrH rod
37	Ablated back 3/4 in. from forward end of rod. Also welded to Element 19
1,3,4,5,6 10,16,17,22 23,24,32,33 34,35	Welded solid to upper grid plate; not removed (see Figure 78)
12,13,14,25 26,27,28,29 30,31	Removed from upper grid plate without difficulty; no damage

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Figure 80. Frontal View of Fuel Element Orientation in the Flow Stream for RADE A ($\alpha = 30^\circ$) and RADE B ($\alpha = 0^\circ$) Models

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TABLE 9
RESULTS OF CHEMICAL ANALYSIS CONDUCTED ON SAMPLES
FROM RADE B MODEL ($\alpha = 0^\circ$)

Sample No.	Description	Results of Analysis		
		wt% H 1	wt% H 2	wt% H 3
1	Chips from upper grid plate	0.018	0.016	0.020
2	Wafer from bottom of fuel rod 29	1.60	1.67	1.59
3	Wafer from center of fuel rod 29	1.84	1.83	1.81
4	Wafer from top of fuel rod 29	1.79	1.81	1.79
5	Wafer from center of fuel rod 7	1.84	1.82	1.83
7	Wafer from center of fuel rod 31	1.86	1.86	----
8	Wafer from center of fuel rod 20	1.87	1.88	----
9	Wafer from center of fuel rod 26	1.83	1.87	----
10	Wafer from center of fuel rod 8	1.83	1.92	1.86
11	Wafer from center of fuel rod 25	1.81	1.80	----
12	Wafer from center of fuel rod 2	1.83	1.85	----
13 ↓	Chips from upper grid plate ↓	X-ray fluorescent analysis shows Sample 13 to contain principally Fe, Cr, and Ni in the relative proportions associated with a 300 series of stainless steel along with some Zr, less Mo, and a little Ag. By x-ray diffraction the material is predominantly Fe_3O_4 .		

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Figure 81. Sectioned Fuel Rod (ZrH) and Cladding of Element No. 29
of the RADE B Model ($\alpha = 0^\circ$)

The vessel of the RADE A model tested at 30° angle of attack ablated to a greater extent than any of the other ablation models. This was possibly due to a somewhat higher heat flux as indicated by the flow condition data listed in Table 1 for Run 22. Figure 82 is a closeup view of the RADE A vessel with a frontal piece of what appears to be a heavy oxide layer removed to reveal a large void area where, obviously, the fuel rods had been substantially ablated.

The first step taken to disassemble the RADE A vessel was to physically remove as many fuel elements from the front of the vessel as possible. This required the piecewise breaking away of the vessel wall in the vicinity of the severely ablated area as shown in Figure 83. Figure 84 shows the vessel following the withdrawal of all loose fuel elements.

In order to examine the remainder of the core and elements, the vessel was axially sectioned. Following this sectioning, more of the fuel elements were removed. These elements were welded together in groups as shown in Figure 85. The material located between the remaining elements in the sectioned vessel and holding them securely welded together in Figure 86 is zirconium-hydride flowback from the recessive ablation of the rods. The closeup view of the exterior of the vessel section in Figure 87 clearly shows the extent of fuel rod ablation and flowback on the side of the vessel that was directly exposed to the flowstream. It should be pointed out that in many cases the zirconium-hydride appears to have been melted inside the cladding, as seen in the figures, even though the melting temperature of the cladding is approximately 1000°F less than that of ZrH. When dissected, these elements were found void of ZrH at their base which would indicate that a possible back pressure from hydrogen outgassing forced the rods forward and into direct contact with the flowstream which caused recessive ablation. The intentionally dented cladding at the base of the far right element in Figure 88 illustrates that it is void of ZrH at that point. Table 10 presents a summary and description of the fuel elements and Monel reflectors taken from the RADE A vessel and includes a listing of the percent of zirconium-hydride left in each rod.

As was done with some rods from the RADE B model, wafer samples were cut from selected rods of the RADE A model ($\alpha = 30^\circ$) and analyzed for hydrogen content. The large section of oxide taken from the vessel forward end (see Figure 82) and the flowback metal from between the fuel elements (Figure 86) were also analyzed. The results of the analysis are given in Table 11.

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Figure 82. RADE A Model ($\alpha = 30^\circ$) Showing Void Area
Beneath Oxide Layer

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Figure 83. Side View of RADE A Model with Sections
of the Forward Vessel Wall Removed

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Figure 84. Frontal View of RADE A Model Interior Following Removal of Approximately One-Half of the Fuel Elements

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Figure 85. Group of Welded Fuel Elements Removed
from the RADE A Model ($\alpha = 30^\circ$)

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Figure 86. Interior of Sectioned RADE A Model Following the Removal of Fuel Elements Shown in Figure 85. (Note the metal flowback between elements.)

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Figure 87. Closeup View of the RADE A Model Showing Extent
of Fuel Element Ablation

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Figure 88. Final Disassembly of the RADE A Model ($\alpha = 30^\circ$)

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TABLE 10
SUMMARY OF POST-TEST EXAMINATION OF RADE A
($\alpha = 30^\circ$) FUEL ELEMENTS AND REFLECTORS
(Sheet 1 of 2)

Element or Reflector (R) No. (Refer to Figure 80)	% ZrH Left in Element	Remarks
1	97	Ablated back 3/8 in. from forward end of element. T/C at center of element still intact. Temperature paint on element showed that element reached a temperature $>1300^\circ\text{F}$
2	95	Ablated 3/8 in. from forward end
3	95	Cladding ablated back 1/4 in. on one side
4	95	Cladding ablated back 3/4 in. on one side
5	90	Ablated back 1 in. from forward end
6	95	Cladding ablated away from ZrH rod 3/4 in. on one side. Temperature paint on element showed that element reached a temperature $>1300^\circ\text{F}$
7	85	Ablated back 1 in. from forward end. Element welded to Element 17
8	95	Cladding ablated back 3/8 in.
9	95	Cladding ablated back 3/4 in. from ZrH rod
10	100	Ablated back 1/8 in. Cladding bulged at top. T/C located at center of element still intact
11	95	Ablated back 3/8 in. from forward end
12	85	Ablated back 1/4 in. from forward end
13	75	Cladding ablated away 3/4 in. from ZrH rod on one side only
14	50	Cladding ablated away 1-1/4 in. from ZrH rod leaving a pinnacle of ZrH
15	95	Same as for Element 14
16	70	Same as for Element 14. Temperature paint showed that element reached a temperature $>1300^\circ\text{F}$
17	90	Ablated back 1 in. from forward end. Element welded to 7
18	35	Cladding ablated back 1-1/2 in., ZrH rod ablated back 3-7/8 in.
19	95	Cladding ablated back 3/8 in. on one side. Element welded to 37
20	100	Cladding bulged at top of element
21	95	Ablated back 1/8 in.
22	100	Ablated back 1/2 in.
23	100	Ablated back 1/4 in. Cladding bulged at top. T/C's at top and center of element still intact

TABLE 10
SUMMARY OF POST-TEST EXAMINATION OF RADE A
($\alpha = 30^\circ$) FUEL ELEMENTS AND REFLECTORS
(Sheet 2 of 2)

Element or Reflector (R) No. (Refer to Figure 80)	% ZrH Left in Element	Remarks
24	95	Ablated back 1/4 in.
25	90	Cladding ablated away 3/8 in. from ZrH rod leaving a pinnacle of ZrH at tip.
26	90	Same as for Element 25 except distance ablated which was 3/4 in.
27	75	Same as for Element 25 except distance ablated which was 1-1/2 in.
28	50	Same as for Element 27.
29	40	Same as for Element 25 except distance ablated was 1-5/8 in.
30	45	Same as for Element 25 except distance ablated was 2 in.
31	40	Cladding ablated away 2-3/4 in from ZrH rod leaving a pinnacle of ZrH at tip. Element is welded to Reflector R-1 which in turn is welded to vessel.
32	1	Cladding ablated back 4-3/4 in. on one side. ZrH has completely ablated away. Remainder of cladding welded to vessel. Temperature paint showed that element reached a temperature $>1300^\circ\text{F}$.
33	15	Cladding ablated back 4-1/8 in.
34	5	Cladding ablated back 4-1/8 in.
35	30	Cladding and ZrH rod ablated back 2-1/2 in.
36	80	Cladding ablated back 1-1/8 in. ZrH rod ablated back 1-3/8 in.
37	80	Cladding ablated back 3/8 in. on one side. Element welded to 19.
R-1	-	Ablated back 2-7/8 in. from forward end.
R-2	-	Ablated back 1-1/2 in. from forward end.
R-3	-	Intact, small piece of grid plate welded to tip.
R-4	-	Intact except one corner slightly ablated.
R-5	-	Ablated back 1-1/8 in.
R-6	-	Ablated back 1-3/4 in.

TABLE 11
RESULTS OF CHEMICAL ANALYSIS CONDUCTED ON SAMPLES
FROM RADE A MODEL ($\alpha = 30^\circ$)

Sample No.	Description	Results of Analysis		
		wt% H 1	wt% H 2	wt% H 3
14	Wafer cut from center of Rod 27	1.50	1.61	1.55
15	Wafer cut from center of Rod 4	1.89	1.88	----
16	Wafer cut from center of Rod 2	1.82	1.85	----
17	Wafer cut from center of Rod 16	0.97	0.99	----
18	Wafer cut from center of Rod 37	1.81	1.80	----
19	Wafer cut from center of Rod 1	1.86	1.83	----
20	Section of material from forward end of vessel	Sample 20 was found to be predominantly Zr by x-ray fluorescence and specifically identified as ZrO_2 by diffraction.		
21	Metal flowback from between fuel elements	Sample 21 is mostly Zr and Ni with some Cu and a small amount of Fe and Mo. By x-ray diffraction the material is ZrNi.		

VI. SUMMARY AND CONCLUSIONS

Experimental investigation of SNAP reactor thermal behavior due to reentry aerodynamic heating has been conducted. Half-scale models of the SNAP 10A and SNAP 8 nuclear reactor configurations were tested in the NASA Ames hypersonic wind tunnel under simulated atmospheric reentry conditions. Surface heat flux measurements were made with calorimeter models, employing Asymptotic calorimeter heat sensors, to determine local heating to the complex geometry of the SNAP reactors. The experimental RADE (reactor ablation-disintegration experiment) models were ablated back to the reactor core containing the fuel elements at both 0° and 30° angles of attack in the flow stream. The temperature response of the models to the aerodynamic heating of the jet stream was obtained throughout each test run from thermocouples strategically mounted in the models.

In summary, the RADE test series was highly successful in satisfying most of the primary test objectives. Aerodynamic heat flux measurements, obtained with the calorimeter model, provided experimental local heat rates to a SNAP reactor that, previously, were based on theory. These measurements were utilized as initial condition input to analogs of the models resulting in good correlation of the analytical calculations with the experimental temperature response of the models. Therefore, experimental support of the analytical capability to accurately predict the preablation temperature response of SNAP reactors reentering the earth's atmosphere has been achieved.

Throughout each ablation test, event motion picture film coverage (24 frames-per sec) and high-speed motion picture film coverage (128 frames-per-sec) was obtained which provided a detailed visual description of the sequence of events during reactor ablation-disintegration. These events clearly defined the meltdown and mode of disintegration of the reactor components forward of the vessel under simulated reentry conditions, and can be incorporated into future analytical studies to enable the production of a complete history of reentry disintegration.

It was predicted in analytical studies^(1,5) made prior to the RADE test that the vessel walls of a SNAP reactor would ablate during reentry by an amount sufficient to allow the release of the fuel elements to the reentry environment.

The extensive exposure of the RADE half-scale models to the continuous constant heat flux in the flow stream of the hyperthermal wind tunnel failed to demonstrate the mode of fuel element release and thus did not satisfy that test objective. A post-test analysis conducted on two of the models, was made to determine the physical and chemical state of the remaining intact vessel and core. This analysis showed that a large amount of welding occurred between the upper grid plate and the fuel element bundle. Also, in the 30° angle of attack case, molten metal flowback into the core caused several elements to be welded to each other. Examination of the interior of the reactor vessel base, lower end of the elements and bottom grid plate, showed that no significant heating was experienced by that portion of the model. The analytical correlation made with the actual temperature response of the models led to the conclusion that no appreciable amount of heat was lost to the water-cooled support arm, however, the large heat capacity of the core components absorbed a sufficient amount of heat from the upper grid plate to prevent its complete ablation.

The post-test examination of the RADE A model, tested at 30° angle of attack, showed that the upper portion of these fuel rods that were directly exposed to the flow stream had been ablated to a large extent. It is well-known⁽⁶⁾ that a great deal of heat is required to release the hydrogen from zirconium-hydride prior to its being ablated. Therefore, a tremendous amount of total heat input would be necessary to ablate the reactor vessel and the core of fuel elements as a single mass when stabilized, under actual reentry or hyperthermal wind tunnel conditions, at 0° and 30° angles of attack. This may not be the case, however, if a SNAP reactor reenters the earth's atmosphere in a coning, rolling, or random tumbling mode. It is recommended that future investigation of reactor reentry disintegration include the dynamics of SNAP reentry and that an experiment be conducted, similar to the one described in this report, incorporating flight dynamics. Such an experiment may well demonstrate that, under the conditions of flight motion, fuel element release from the reactor vessel can be affected.

In conclusion, the reactor model thermal behavior correlations that were obtained from the RADE test data have provided a valuable analytical tool for the Aerospace Nuclear Safety Program at Atomics International. These data will provide additional knowledge for more accurate analytical evaluations of the thermal behavior of SNAP reactor configurations during atmospheric reentry conditions.

VII. REFERENCES

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