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A Division of North American Aviation, Inc.

TECHNICAL DATA RECORD

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APPROVALS

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R D Ells

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TITLE Analysis of Test Data on Ablation of
SNAP 2/10A Fuel, Aluminum, and Stainless Steel
in an Arc-Heated Wind Tunnel

S/A NO. 11313

SECURITY CLASSIFICATION

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SUBACCOUNT TITLE

Fuel Reentry Burnup
Experiments

MASTER

STATEMENT OF PROBLEM

Perform an analysis of the results from the arc-jet tests conducted in October and November, 1963. Correlate these results with computations based on current methods of solution to explain the observed behavior during the tests.

ABSTRACT:

A series of arc-jet tests was performed for the purpose of investigating the behavior of SNAP 2/10A fuel in a simulated reentry environment. The data from the tests (motion pictures and transient temperature distributions) were analyzed and compared with computations which used an energy balance to describe the heating of the fuel to its melting temperature. The dissociation of hydrogen was assumed to occur as an isothermal, endothermic phase change. This concept neglects the kinetics of diffusion. (A computational model incorporating these kinetics was being developed concurrently with the test.) A temperature of 2000°F was assumed for the dissociation phase change and an alternate temperature of 1800°F for comparative purposes. The analytical results were, in general, found to agree very well with actual test data. It was therefore concluded that this concept of hydrogen dissociation occurring as an isothermal phase change was a valid approximation to describe the phenomena of hydrogen loss from the fuel in the configuration and with the heating rates used in these tests.

ACKNOWLEDGEMENT

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INTRODUCTION

The material presented herein is a summary of the test results and analytical computations for the arc-jet test series. The purpose of the tests was to provide experimental data for the study of reentry burnup of SNAP 2/10A fuel rods (previously reported in Reference 1). The scope of this report is the presentation of the test results and the analytical comparisons only as they refer to the test conditions. The application of these results to the conditions of reentry has been presented in Reference 2.

The test program comprised five series of tests. Each series was designed for specific objectives as follows:

1. TEST SERIES "0"

The specimens of this group were stainless steel (type 304) and aluminum (type 1100). The objectives of this series were to calibrate the jet conditions and to verify the adaptation of an analytical model to the data received from the actual testing. These materials were used because of their thermal simplicity, as compared with the reactor fuel.

2. TEST SERIES "1"

The material used for the specimens of this and succeeding groups was SNAP 2/10A reactor fuel, which is composed of zirconium-hydride alloyed with uranium (ZrH_x-U). The uranium content was 10 percent by weight, before hydriding. Natural uranium was used, and no fission products were present. The test runs of series "1" were performed in a helium jet for the purpose of providing data without the complications of surface reactions (oxidation).

3. TEST SERIES "2"

The objective of this series was to investigate the pre-ablation oxide formation on fuel specimens in an air jet stream.

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4. TEST SERIES "3"

Fuel specimens were clad with Hastelloy-N (Nickel alloy) to investigate the effects of cladding on fuel burnup. The gas jet for this test series was an oxygen and nitrogen mixture, simulating atmospheric air.

5. TEST SERIES "4"

This test series consisted of subjecting fuel specimens to heating in air for the purpose of providing combined phenomena data, i.e., from surface oxidation to complete fuel burnup.

Recorded data from the tests consisted mainly of surface and internal temperature distributions. The test data of series "0", "3", and "4" are considered in this report. All runs of series "0" were used in the thermal analysis but runs of series "3" and "4" were chosen on the basis of: (1) jet condition simulation to reentry heating, and (2) success and duration of the test run. It is beyond the scope of the analysis presented herein to consider the details of oxide formation in test series "2". However, temperature data were recorded and are used for comparison with analytical computations.

TEST DESCRIPTION

A. Facility

The arc-jet tests were performed in the Hyper-Thermal Electric Arc-Wind Tunnel. North American Aviation, Los Angeles Division. A detailed description of the facility and its operation can be obtained from Reference 3. Briefly, the facility is a continuously-running wind tunnel which produces Mach 3 gas flow at very high temperatures.

B. Specimen Configurations and Instrumentation

The configurations of the specimens tested in the jet were of two types. Both of these configurations were designed to provide specific information regarding fuel burnup.

Configuration I: This configuration is shown in Figure 1 and was used only in testing the fuel material. The actual fuel rods of the

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		MODEL NO.

UNCLAD SPECIMENS

SCALE: 1:1

FIGURE 1

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SNAP 2/10A reactor core are 12.45 inches in length and 1.212 inches in diameter. The Hastelloy-N (Nickel alloy) cladding of the fuel rods increases the diameter to a total of 1.25 inches.

Configuration I was used in test runs of series "1" through "4". The test specimens were 1.25 inches in diameter (all fuel material) and 2 inches in length for series "1", "2", and "4". Those specimens of series "3" were clad and conformed to the dimensions of the actual fuel rods except for length (Figure 2). The specimens of Configuration I were oriented for cross-axial flow in the jet stream and were rotated at between 1 to 4 revolutions per second (IA) or held stationary (IB). Configuration IA was designed to simulate the most probable reentry conditions, that is, axis normal to the jet velocity vector. Figure 3 shows a specimen in position for testing.

To provide support of the specimen in the jet stream, a tungsten rod of 3/16 inch diameter was inserted through the center of the specimen and held with a tungsten rod (as shown in Figures 1 and 2). The tube just above the test specimen in Figure 3 is Zirconia for insulation of the tungsten rod.

Instrumentation for test runs of Configuration I consisted mainly of an optical pyrometer (Thermodot TD-9H) aimed at the center of the specimen through an observation port of the test chamber. This provided measurement of the specimen temperature at its surface.

Configuration II: Figure 4 shows Configurations IIA and IIB both of which were oriented for axial flow in the jet stream. Configuration IIA was a flat-faced cylinder 1.25 inches in diameter and 3 inches in length. Configuration IIB was of the same overall dimensions as IIA but differed by having a hemispherically-tipped leading edge. Both configurations were mounted to a sting by means of a graphite adapter. A lavite cup inside the graphite provided insulation to minimize heat losses. The specimens were held in the graphite adapter by graphite setscrews. Figure 5 illustrates configuration IIB mounted and in a test position.

Instrumentation for Configuration II consisted of internally mounted thermocouples as well as pyrometer measurements. Location of the thermocouples is shown in Figure 4.

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CLAD SPECIMENS

SCALE: 1:1

FIGURE 2

Figure 3. Configuration I Installed on Rotator and in Test Position

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		MODEL NO.

CONFIGURATION IIA

CONFIGURATION IIB

TC 1,2,3 - THERMOCOUPLES
 SCALE: 1:1

FIGURE 4

Figure 5. Configuration IIB Mounted on Sting and in Test Position

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In addition to external and internal temperature measurements, each test run was recorded on color film by a 24-frame per second event camera. Some of the tests were also recorded by a Fastax camera which was operated at approximately 1000-1500 frames per second.

TEST CONDITIONS

An essential requirement of the test runs was the determination of the heating to the specimens. From the jet conditions recorded for each test run, a reference heat flux, which is the stagnation heat transfer rate to a one foot radius hemisphere, was computed using the equation:

$$\dot{q}_{REF} = \left(\dot{q}_s \sqrt{\frac{r}{P_T}} \right) \sqrt{\frac{P_T}{P_s}} \quad \text{BTU-}\sqrt{\text{FT}}/\text{FT}^2\text{-SEC} \quad \dots(1)$$

The parameter, $(\dot{q}_s \sqrt{r/P_T})$ Btu- $\sqrt{\text{in.}}/\text{atm}/\text{ft}^2\text{-sec}$ is obtained as a function of the stagnation enthalpy, (H_s) from the theory of Fay and Riddell (Reference 4). The stagnation enthalpy, (H_s) is calculated from known jet conditions (refer to Reference 3) and the pressure, (P_T) is measured directly by a pitot probe inserted into the jet stream. Table I presents the conditions of the test runs to be considered in this report.

Following completion of test runs 4.1 through 4.12, it was found that the operating conditions of the jet, as recorded during each run from 4.1 to 4.10, were in error or were questionable. Reasons for this discrepancy is fully described in the test report (Reference 3). The results of a few of these runs, however, were utilized in the analysis because of their similarity to the results of other test runs having the same jet conditions.

Heat flux measuring devices, calorimeters, were designed and fabricated for direct measurement of heat flux to the specimens. Three calorimeters were used: (1) a hemispherically-tipped unit in axial flow; (2) a flat-faced cylindrical unit in axial flow, and (3) a cross-axial assembly of the dimensions of Configuration I. The details of the design and test operation of these calorimeters are fully described by

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TABLE I TEST CONDITIONS

Run No.	Configu- ration	REFERENCE	Stagnation	Stagnation
		Heat Flux: q_{Ref} Btu- $\sqrt{ft}/ft^2$ -sec	Pressure P_{T_2} Atm	Enthalpy: H_s Btu/lb
<hr/>				
*Test Series "0"				
0.1	IIA	109.0	0.147	6837
0.2	IIA	111.8	0.149	6994
0.3	IIA	117.0		7400
0.4	IIA	71.6	0.130	4987
0.5	IIA	72.8	0.130	5014
0.6	IIA	41.1	0.055	4411
0.7	IIA	37.6	0.059	3906
0.8	IIA	34.7	0.052	3892
<hr/>				
Test Series "2"				
2.5	IIB	73.1	0.133	5016
2.6	IIB	71.3	0.130	5002
2.7	IIB	70.8	0.128	5000
2.8	IIB	71.0	0.130	4995
<hr/>				
Test Series "3"				
3.5	IB	94.5	0.142	6124
3.8	IB	71.3	0.129	4968
3.9	IB	93.8	0.139	6176
3.12	IB	73.5	0.130	5024
<hr/>				
Test Series "4"				
4.6	IB	67.0	0.150	4360
4.7	IB	65.0	0.127	4360
4.13	IB	91.0	0.146	5939
4.14	IB	83.7	0.125	5908
4.16	IB	68.7	0.124	4953
4.17	IIA	92.7	0.140	6107
4.18	IIB	93.8	0.141	6156
4.19	IIA	93.6	0.140	6151
4.20	IIB	93.1	0.141	6095
4.21	IIA	95.1	0.140	6095
4.22	IIA	120.2	0.157	7378

*Test run 0.1 through 0.6 were stainless steel 304; 0.7 and 0.8 were aluminum 1100.

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Reference 5. In addition, the arc-jet facility is equipped with a calorimeter probe of 0.25 inch hemispherical nose which is an absolute water-cooled unit. Measurements were also made with this probe. Table II presents a comparison of the reference heat flux, (q_{Ref}), as calculated from the jet conditions; as measured utilizing the designed calorimeter and as measured with the absolute water-cooled calorimeter probe of the test facility. As indicated, good agreement was found between the calculations and measurements. The results of all the calorimeter tests and their use in data analysis is presented in the following section of this report.

DATA ANALYSIS

A. Temperature and Film Data

Temperature versus time data from the thermocouple and pyrometer output was recorded during each test run on strip chart recorders. These recordings were reduced by the Los Angeles Division to temperature-time plots. In order to reduce the pyrometer output to useful data, it was necessary to correct the original data from an effective "black-body" temperature to a true surface temperature. A correction involving the radiation absorbed and reflected by the test chamber window was also made. Appendix (A) presents the details of the corrections made to the pyrometer data.

Each test run, from the time of specimen insertion into the jet until withdrawal of the sting, was filmed with a 24-frame per second, color motion picture event camera. The film was reviewed in detail with a frame-counting projector and events were recorded for the entire test run. Table 3 presents the events, as taken from the film analysis, for the test runs considered in this report. Following complete review of all the film, some significant test runs were selected for still photographing through the use of a Vanguard motion picture analyzer. The Vanguard analyzer enables each frame of motion picture film to be projected onto a screen, from which still photographs were taken with a Polaroid camera. Figures 6 through 16 show the film coverage of primary events for several test runs.

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TABLE II

COMPARISON OF REFERENCE HEAT FLUX MEASUREMENTSREFERENCE HEATING PARAMETER - CENTERLINE OF JET
(Btu- $\sqrt{\text{ft}}/\text{ft}^2\text{-sec}$)

Test	$q_s \sqrt{r}$ Theoretical Equation (1)	$q_s \sqrt{r}$ Test Calorimeter	$q_s \sqrt{r}$ Water-Cooled Calorimeter Probe
1	35	24-35*	23-31*
2	74 & 75**	75 & 78*	76
3	98 & 98**	99 & 103**	99
4	123	127	124

*Measurements from 2 different test runs.

**Between the jet centerline and 1 inch from centerline since the jet was not completely expanded for this test.

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TABLE III

FILM EVENT COVERAGE

		TIME (sec)	
		(t=0 @ insertion into jet)	
RUN NO.		EVENT	
Test Series "0"	0.1	1. Begin ablation	14.96
	0.2	1. Begin ablation	12.54
	0.4	1. Begin ablation	36.6
	0.5	1. Begin ablation	38.58
	0.7	1. Begin ablation	69.13
	0.8	1. Begin ablation	65.75
Test Series "3"	3.1	1. Cladding - Begin ablation	1.625
		2. Cladding - Completely dispersed	2.333
		3. Cracks appear in fuel	~ 17.04
		4. Tungsten rod failure	38.67
	3.2	1. Cladding - Begin ablation	2.083
		2. Cladding - Completely dispersed	7.042
		3. Cracks appear in fuel	~ 22.6
		4. Tungsten rod failure	41.88
	3.3	1. Cladding - Begin ablation	.0417
		2. Cladding - Completely dispersed	25.04
		3. Tungsten rod failure	29.83

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TABLE III (continued)

RUN NO.	EVENT	TIME (sec)
		(t=0 @ insertion into jet)
3.4	1. Cladding - Dispersed (explosive dispersal - 1 film frame)	140.3 to 140.34
	2. Specimen withdrawn (no ablation)	184.54
3.5	1. Cladding - Begin ablation	3.042
	2. Cladding - Bottom cap dispersed	3.208
	3. Cladding - Completely dispersed	8.75
	4. Fuel - Cracks appear	~ 4.08
	5. Fuel - Begin ablation	69.04
	6. Fuel - Approximately half ablated	79.0
3.6	1. Cladding - Begin ablation	.417
	2. Cladding - Completely dispersed	26.208
	3. Fuel - Cracks appear	~ 29.75
	4. Fuel - Begin ablation	37.792
	5. Tungsten rod failure	42.042
3.7	1. Cladding - Begin ablation	2.458
	2. Cladding - Dispersed (end caps first)	41.46
	3. Tungsten rod failure	49.75
3.8	1. Cladding - Begin ablation	4.083
	2. Cladding - Bottom cap dispersed	8.125
	3. Cladding - Completely dispersed	47.67
	4. Fuel - Cracks appear	~ 95.417

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TABLE III (continued)

RUN NO.	EVENT	TIME (sec) (t=0 @ insertion into jet)
3.8	5. Fuel - Begin ablation	128.458
	6. Fuel - Completely dispersed	144.167
3.9	1. Cladding - Begin ablation	1.542
	2. Cladding - Bottom cap dispersed	5.208
	3. Cladding - Completely dispersed	14.625
	4. Fuel - Cracks appear	~ 44.33
	5. Fuel - Begin ablation	73.042
	6. Fuel - Completely dispersed	99.75
3.12	1. Cladding - Begin ablation	6.958
	2. Cladding - Bottom cap dispersed	8.375
	3. Cladding - Completely dispersed	49.75
	4. Fuel - Begin ablation	107.458
	5. Fuel - Completely dispersed	132.14
Test Series "4" 4.1	1. Cracks appear	~ 32.042
	2. Begin ablation	82.542
	3. Approximately half ablated	88.208
	4. Tungsten rod failure	88.708
4.2	1. Cracks appear	~ 29.125
	2. Begin ablation	87.80
	3. Completely dispersed	97.60

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TABLE III (continued)

RUN NO.	EVENT	TIME (sec) (t=0 @ insertion into jet)
4.3	1. Begin ablation	89.708
	2. Tungsten rod failure	98.875
4.4	1. Cracks appear	~40.875
	2. Begin ablation	76.667
	3. Approximately half ablated	98.708
	4. Tungsten rod failure	105.625
4.5	1. Cracks appear	~75.458
	2. Begin ablation	140.917
	3. Tungsten rod failure	149.292
4.6	1. Cracks appear	~61.875
	2. Begin ablation	114.292
	3. Tungsten rod failure	134.33
4.7	1. Cracks appear	~48.292
	2. Begin ablation	115.583
	3. Approximately half ablated	132.29
	4. Tungsten rod failure	140.625
4.8	1. Crack appears	~5.125
	2. Central split (cross- axially)	95.75
	3. Top half split (axially)	97.125
	4. Piecemeal disintegration (top half)	98.958

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TABLE III (continued)

RUN NO.	EVENT	TIME (sec)
		(t=0 @ insertion into jet)
4.9	1. Crack appears	~ 23.167
	2. Begin ablation (bottom half)	59.708
	3. Lower third ablated	77.08
	4. Begin top half ablation	82.083
	5. Completely dispersed	88.80
4.10	1. Crack appears	~ 28.917
	2. Begin ablation	77.92
	3. Tungsten rod failure	87.542
4.13	1. Crack appears	~ 2.542
	2. Begin ablation	65.667
	3. Approximately half piece-meal disintegration	71.64
	4. Resume ablation	82.83
	5. Completely dispersed (piecemeal)	91.33
4.14	1. Cracks appear	~ 29.167
	2. Central split (cross-axially)	57.417
	3. Begin ablation	79.625
	4. Piecemeal dispersion (top-half)	82.458
	5. Completely dispersed (piecemeal)	93.667
4.15	1. Crack appears	~ 2.958
	2. Central split and lower half axial split	39.583

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TABLE III (continued)

RUN NO.	EVENT	TIME (sec) (t=0 @ insertion into jet)
4.15	3. Lower half dispersed (piecemeal)	41.0
	4. Specimen withdrawn	51.292
4.16	1. Cracks appear	~ 37.67
	2. Begin ablation	117.458
	3. Completely dispersed (piecemeal)	136.417
4.18	1. Begin ablation (tip)	46.0
	2. Heavy ablation	65.4
	3. Approximately half ablated	72.1
4.19	1. Crack appears (cross- axial)	~ 48.5
	2. Begin ablation	53.208
	3. Heavy ablation	162.458
	4. Stop ablation	168.625
	5. Specimen withdrawn	378.29
4.20	1. Begin ablation	39.67
4.21	1. Begin ablation	76.458
	2. Heavy ablation	163.208
4.22	1. Crack appears (cross-axial)	~ 21.417
	2. Begin ablation	70.125

$t = 0$

$t = 36.6$

$t = 44.5$

$t = 50$

$t = 58$

$t = 70$

$t = 75$

$t = 100$

Figure 6. ARC-JET TEST RUN No. 0.4

$t = 0$

$t = 50$

$t = 75$

$t = 124.3$

$t = 140.3$

$t = 140.34$

$t = 184.2$

Figure 7. ARC-JET TEST RUN No. 3.4

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$t = 0$

$t = 2$

$t = 4$

$t = 8$

$t = 12$

$t = 16$

$t = 40$

$t = 62.2$

$t = 70$

Figure 8. ARC-JET TEST RUN No. 3.9

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$t = 80$

$t = 85$

$t = 95.2$

$t = 99.5$

Figure 9. ARC-JET TEST RUN No. 3.9
(continued)

t = 0

t = 4

t = 8

t = 12

t = 15

t = 20

t = 30

t = 40

t = 49.4

Figure 10. ARC-JET TEST RUN No. 3.12

$t = 66.2$

$t = 85.0$

$t = 100.0$

$t = 115.0$

$t = 120.4$

$t = 130.1$

$t = 132.1$

$t = 132.14$

Figure 11. ARC-JET TEST RUN No. 3.12
(continued)

$t = 0$

$t = 40$

$t = 50$

$t = 74.2$

$t = 87.8$

$t = 91.8$

$t = 94.3$

$t = 97.4$

$t = 97.6$

Figure 12. ARC-JET TEST RUN No. 4.2

$t=0$

$t=20$

$t=33.9$

$t=60$

$t=65$

$t=82$

$t=85$

$t=88.6$

$t=88.8$

Figure 13. ARC-JET TEST RUN No. 4.9

$t = 0$

$t = 25.8$

$t = 35.9$

$t = 52.3$

$t = 65.7$

$t = 71.6$

$t = 71.64$

$t = 91.1$

$t = 91.3$

Figure 14. ARC-JET TEST RUN No. 4.13

$t = 0$

$t = 30$

$t = 61.8$

$t = 90$

$t = 120$

$t = 126.1$

$t = 136.3$

$t = 137$

Figure 15. ARC-JET TEST RUN No. 4.16

$t = 0$

$t = 20$

$t = 46$

$t = 56.4$

$t = 65.4$

$t = 66.6$

$t = 72.1$

Figure 16. ARC-JET TEST RUN No. 4.18

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B. Heating

In equation (1), the reference heat flux, q_{Ref} , is the heat rate at the stagnation point of a cold (300°K) hemisphere of one foot radius. To correct this stagnation heat rate to the heat rate on the configurations of the test series, a proportion factor, β , must be applied. The factor, β , is the ratio of the heat rate to a given surface to the heat rate at the stagnation point of a unit radius hemisphere. Dividing q_{Ref} by the square root of the radius, R_o , of the body under consideration further corrects the stagnation heat rate from a unit radius hemisphere to the radius of that body. Finally;

$$q = q_c / q_{sH} (1/\sqrt{R_o}) q_{Ref}$$

or

...(2)

$$q = \beta / \sqrt{R_o} q_{Ref}$$

where (q_c) is the heat rate to a particular configuration and (q_{sH}) is the stagnation heat rate to a hemisphere.

The configurations of specimens used in the arc-jet series were: (1) flat-faced cylinder in axial flow (Configuration IIA); (2) hemispherically-tipped cylinder in axial flow (Configuration IIB); and (3) a cylinder in cross-axial flow (Configuration I).

1. Flat-Faced Cylinder in Axial Flow

Vinokur (Reference 6) presents data on the ratio (q_{FF}/q_{sFF}) versus the ratio (x/a), where (x) is the distance from the centerline of a flat-faced cylinder measured parallel to the face, and (a) is the radius of the cylinder. The term (q_{FF}) is the local heat rate to a point (x) on the face and (q_{sFF}) is the heat rate at the stagnation point ($x=a$). The curves in Figure 17 are for various ratios of the free-stream density to the density behind the normal part of the shock wave. The jet stream of the Los Angeles Division wind tunnel was at a free-stream Mach number of 3 and therefore, the density ratio was approximately 0.25. The average ratio ($\bar{q}_{FF}/q_{sFF}$) was determined from Figure 17 by integration. This value is approximately 1.1. The factor β was then obtained from

FIGURE 17

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the relationship:

$$\beta = (\bar{q}_{sFF}/\bar{q}_{sH}) (\bar{q}_{FF}/\bar{q}_{sFF}) = \bar{q}_{FF}/\bar{q}_{sH} \quad \dots(3)$$

where $(\bar{q}_{sFF}/\bar{q}_{sH})$ is the ratio of the heating rate at the stagnation point of a flat-faced cylinder to the heating rate at the stagnation point of a hemispherically-tipped cylinder of the same radius. The values obtained for this ratio at a free-stream Mach number of 3, lie in the range of 0.50 to 0.65. The investigations made by Vinokur (Reference 7) yield a value of 0.50 for $(\bar{q}_{sFF}/\bar{q}_{sH})$; those of Boisson and Curtiss (Reference 8) yield a value of 0.65 and Stoney and Markley (Reference 9) give 0.55 ± 0.05 for this ratio. Using a value of 0.6, β for a flat-faced cylinder becomes:

$$\beta_{FF} = 0.6 \times 1.1 = 0.66$$

This value is in agreement with the value reported by Reference 10. The radius of the test specimens was 0.625 inch, therefore, equation (2) becomes:

$$\bar{q}_{FF} = [(0.66)/\sqrt{0.625/12}] \bar{q}_{sH} \sqrt{r} = 2.89 \bar{q}_{Ref} \quad \dots(4)$$

where $(\bar{q}_{Ref})$ is the reference heat rate.

Table IV presents the results from the calorimeter tests. The values given for sensor readings are not corrected for body radius, however. Graphical representation of the results is shown in Figure 18. The experimental ratio $(\bar{q}/\bar{q}_{sH})$ at the stagnation point, $(x/r=0)$, of the axial assembly, in Figure 18 is approximately 0.65 which agrees well with other reported values. Sensors 4 and 5 of the axial assembly were located, at the surface of the cylinder, 1 inch and 2 inches respectively, back from the front face. Readings from sensor 4 indicated a lateral heat rate, $(\bar{q}_{Lat})$, to the cylinder of approximately 10 percent of the heating at the front face and approximately 20 percent of $(\bar{q}_{FF})$ from sensor 5. This was found to be important in the analytical comparisons with the actual test data.

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TABLE IV

CALORIMETER TEST RESULTS

CALORIMETER ASSEMBLY	TEST NO.	NOMINAL $q_s \sqrt{r}$ (EQ. 1) $\text{Btu} - \sqrt{\text{ft}}/\text{ft}^2\text{-sec}$	SENSOR READING $\text{Btu}/\text{ft}^2\text{-sec}$				
			1	2	3	4	5
Axial Assembly	1	40	59	48	81		
	2	70	218	186	214	21	56
	3	100	284	298	256	26	82
	4	125	360	365	371	30	97
Cross-Axial Assembly	1	40	109	61			
	2	70	239	135	64		
	3	100	353	198	78		
	4	125	456	260	76		

AXIAL ASSEMBLY
SENSORS

CROSS-AXIAL ASSEMBLY
SENSORS

719-P

Figure 18. Graphical Representation of Calorimeter Test Results

2. Hemispherically-Tipped Cylinder in Axial Flow

The ratio of the average heat rate ($\bar{q}_H$) to the stagnation heat rate ($q_{s(H)}$) for a hemispherically-tipped cylinder in a flow of Mach number (M_∞) 3, is 0.465 (Reference 11). This ratio is the factor (β_H) and equation (2) becomes:

$$\bar{q}_H = (0.465 / \sqrt{.625/12}) q_{Ref} = 2.04 q_{Ref} \quad \dots(5)$$

The results from the calorimeter tests (see Table 2) indicated an increase of approximately 4 to 6 percent in reference heating as calculated from jet conditions. Therefore, equation (5) was corrected to:

$$\bar{q}_H = 2.04 (1.06) q_{Ref} = 2.16 q_{Ref} \quad \dots(6)$$

Figure 19 illustrates the heat input to Configuration II.

FIGURE 19

3. Cylinder in Cross-Axial Flow

The stagnation line heat rate to a cylinder with its axis normal to the flow stream is related to the stagnation heat rate of a hemisphere, ($q_{s(H)}$) by the factor ($q_{s(CYL)}/q_{s(H)} = 1/\sqrt{2}$). For a rotating cylinder, the average heat rate, ($\bar{q}_{CYL}$) to the stagnation rate, ($q_{s(CYL)}$), has the value of approximately 0.320 (Reference 12). However, the calorimeter test results (see Figure 18) indicated a value for the ratio, ($\bar{q}_{CYL}/q_{s(CYL)}$), of from 0.35 to 0.40. Using an average value of 0.375, equation (2) for a cylinder in cross-axial flow becomes:

$$\bar{q}_{CYL} = (0.375 / \sqrt{2R_o}) q_{Ref} = 1.16 q_{Ref} \quad \dots(7)$$

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Equation (7) assumes the cylinder to be infinitely long. However, it was found from the calorimeter results for the cross-axial assembly, that due to the finite length of the specimen, the heat flux at the stagnation point is increased approximately 10 percent to 14 percent. Correcting equation (7) for a 10 percent increase, yields:

$$\bar{q}_{\text{CYL}} = 1.16 (1.1) q_{\text{Ref}} = 1.278 q_{\text{Ref}} \quad \dots(8)$$

In previous studies, the value used for the ratio $\bar{q}_{\text{CYL}}/q_s(\text{CYL})$ was 0.36 and it should be noted that the product of this value and an increase of 14 percent in the heating yield approximately the same multiplying factor as that in equation (8).

The average total heat input, $(\bar{Q})$, to all test specimens was calculated with the equation:

$$\bar{Q} = A_s \bar{q}_c \left(\frac{H_s - H_w}{H_s - H_{300^\circ\text{K}}} \right) \quad \dots(9)$$

where:

A_s = Surface area (ft^2)

$\bar{q}_c$ = Average heat flux as discussed, per unit area per unit time, to a particular specimen configuration ($\text{Btu}/\text{ft}^2\text{-sec}$)

H_s = Enthalpy level of the jet gas at the stagnation point (Btu/lb)

H_w = Enthalpy level of the gas at wall temperature (Btu/lb)

$H_{300^\circ\text{K}}$ = Enthalpy level of the gas at 300°K (Btu/lb)

If $(H_{300^\circ\text{K}})$ is considered negligible compared to (H_s) , equation (9) becomes:

$$\bar{Q} = A_s \bar{q}_c \left(H_s - H_w / H_s \right) \quad \dots(10)$$

Table 5 presents a tabulation of the arc-jet test run conditions and the converted heating values for all test runs under consideration.

C. METHOD OF ANALYSIS

An early investigation was made for Configuration I tests,

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TABLE V

HEATING RATES

RUN NO.	q_{Ref} ($q_s \sqrt{r}$) (Btu- $\sqrt{ft}/ft^2$ -sec)	$\bar{q}_{FF}$	$\bar{q}_H$	$\bar{q}_{CYL}$
		(Btu/ ft^2 -sec)		
0.1, 0.2	110*	318		
0.3	117	338		
0.4, 0.5	72*	208		
0.6	41	118.5		
0.7, 0.8	36*	104		
2.5-2.8	72*		147	
3.5, 3.9	95*			121.2
3.8, 3.12	72*			92
4.6, 4.7 and 4.16	70*			89.4
4.13, 4.14	90*			115
4.17, 4.19 and 4.21	94*	272		
4.22	120	347		
4.18, 4.20	94*		192	

*Nominal

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utilizing the analog computer. This was done to enable a large number of parameter variations (heat rate, emissivity, etc.) to be made in the computations of temperature transients with a minimum of computing time. Details of the model used and data input to the analog computer are given in Appendix (C). A digital model, identical to the analog model, was prepared for solution with the TAP-3 (Thermal Analyzer Program) code with the same input parameters. The calculations were compared and found to be in agreement. However, due to the simplicity of the model, the temperature transients were not comparable to the actual test data. Therefore, a more detailed digital model network was made for solution by the TAP-3 code. A description of the networks for test Configurations I and II and calculations for input to the code are presented in Appendix (B).

In order to theoretically verify the digital computations, the temperature of the specimen surface of Configuration IIA (flat-faced cylinder) for test runs 0.1 through 0.5 was calculated using the method of Carslaw and Jaeger (Reference 13). The details of this analysis and the calculations are given in Appendix D. Also, the value of the heat flux, $(\bar{q})$, as calculated from the jet conditions by equation (4), for test runs 0.1 and 0.4 was computed from the known time (film data) for the flat-faced surface of the specimen to reach melting temperature. The details of these calculations are also presented in Appendix D. The calorimeter tests, however, proved to be a more suitable means of verifying the heat flux received by the test specimens.

In the analysis of test series 3 and 4 for the fuel material, the dissociation of hydrogen was taken into account in two ways. For the first method, a step change in the capacitance (C) of the fuel over a temperature interval was incorporated. This was done initially to include dissociation of hydrogen in the analog computations. The capacitance is defined by:

$$C = \frac{H}{\Delta T} \rho V \text{ Btu/}^\circ\text{F} \quad \dots(11)$$

where (H) is the heat of dissociation, (ρ) the density and (V) is the volume of material. The heat of hydrogen dissociation was taken from

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Reference 14 and calculated for the fuel as follows:

$$H = \frac{N_H \Delta H}{2 \eta \rho} \quad \dots(12)$$

where:

$$\Delta H = 40.5 \text{ kcal/gm mol } H_2$$

$$N_H = 6.35 \times 10^{22} \text{ } H_2 \text{ atoms/cm}^3$$

$$\rho = 6.0 \text{ gm/cm}^3$$

$$\eta = 6.023 \times 10^{23} \text{ (Avogadro's number)}$$

Using these values in equation (12) and converting the units:

$$H = 640 \text{ Btu/lb.}$$

Assuming dissociation of the hydrogen occurs over an interval of 200°F (indicated by thermocouple test data), the value of (C) becomes:

$$C = 640/200 (\rho V) = 3.2 (\rho V) \text{ Btu/}^\circ\text{F} \quad \dots(13)$$

The capacitance (C) at other temperatures was calculated using specific heat (C_p) as a function of temperature. The specific heat of the fuel was determined as presented in Appendix E. The dissociation was assumed to originate at temperatures of 1600°F, 1800°F, and 2000°F. Figure E-4 (Appendix E) is a graph of C versus temperature and the two curves represent the clad and unclad fuel specimens of test series 3 and 4. These specimens differed only in radii.

The second method of incorporating the dissociation of hydrogen from the fuel was to represent the process as an isothermal phase change occurring at constant temperatures of either 1800°F or 2000°F. In the computations with the TAP-3 code each node of the network absorbs the heat of dissociation. The temperature is monitored for each node and held constant at the dissociation temperature until sufficient heat is absorbed to remove the hydrogen. The transient for the node then continues. A dissociation temperature of 2000°F was selected on the basis that the effective time for hydrogen to diffuse rapidly changes from a long time to a short period of time at this temperature. A more detailed discussion of hydrogen dissociation as an isothermal phase change is presented by Reference 15. Finally, ablation of the material was not

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considered in the calculations due to the observed shape changes of the material which in turn changes the heat flux to the specimen. The thermal properties of all materials used in this analysis are presented in Appendix E.

Several computer runs were made for test series 0, 2, 3, and 4. The test runs in each series were grouped according to heat input and a nominal heating value was assumed in the digital computations. For several single runs, precise heating values were used. (See Table V).

RESULTS AND DISCUSSION

A. TEST SERIES "O"

The results of all the computations for test series "O" were compared to the actual test data. In Figure 20, the temperature at the flat-faced surface of the specimen of test run 0.1 and 0.2 is compared, using the method described by Appendix D and the TAP-3 code, up to the melting temperature. The two curves of computer transients correspond to different values of specimen lateral heating, (q_{LAT}), as explained in the preceding section. The time, (t_m), for the surface to reach the melting point, as determined from the film data, is also indicated. The theoretical computations of both methods were in good agreement with the actual data. Figures 21 through 23 show the internal thermocouple temperatures and the corresponding calculations. Although the actual data temperature transients are longer in time than is shown, the calculated temperatures were terminated at approximately the time of surface melting. The reason for this was due to the change in the configuration of the specimen as ablation proceeded rearward, which in turn changes the heat flux. Figure 6 illustrates the recession of the leading edge during ablation for test run 0.4.

The temperature data for test run 0.3 is shown with the calculated transients in Figures 24 through 27. The actual data was considered invalid since, due to improper fastening, the specimen moved partially out of and slightly forward from the holder base. However, the data was compared with calculations and found to be in reasonable agreement. The time, (t_m) could not be determined since movement of the specimen prevented the film recording of the initiation of melting.

(There is no Page 43 in original document.)

INTERNAL TEMPERATURE TRANSIENT
TEST SERIES "O" - STAINLESS STEEL 304
TEST RUNS O.1 AND O.2

TEST CONDITIONS

CONFIGURATION IIA

DATA LOCATION: THERMOCOUPLE NO. 1

T_{ref} : 0.1 104.0, 0.2 111.8

FIGURE 21

6-9-64 JA

INTERNAL TEMPERATURE TRANSIENT
TEST SERIES "O" - STAINLESS STEEL 304
TEST RUNS 0.1 AND 0.2

TEST CONDITIONS

CONFIGURATION II A

DATA LOCATION: THERMOCOUPLE NO. 2

T_{ref} : 0.1 109.0, 0.2 111.8

(NOTE: NO DATA - RUN NO. 0.2)

FIGURE 22

6-9-68 JA

INTERNAL TEMPERATURE TRANSIENT
TEST SERIES "O" - STAINLESS STEEL 304
TEST RUNS O.1 AND O.2

TEST CONDITIONS

CONFIGURATION 77A

DATA LOCATION: THERMOCOUPLE NO. 3

T_{ref} O.1 - 109.0, O.2 - 111.5

FIGURE 23

6-8-64 LA

SURFACE TEMPERATURE TRANSIENT
TEST SERIES "O" - STAINLESS STEEL 304
TEST RUN O.3

TEST CONDITIONS

CONFIGURATION: ITA
DATA LOCATION: FRONT FACE
 $T_{REF} = 117.0$

FIGURE 24

6-10-64 JA

INTERNAL TEMPERATURE TRANSIENT
TEST SERIES "O" - STAINLESS STEEL 304
TEST RUN O.3

TEST CONDITIONS

CONFIGURATION IIA

DATA LOCATION: THERMOCOUPLE NO. 1

T_{REF}: 117.0

FIGURE 25

6-10-64 JA

INTERNAL TEMPERATURE TRANSIENT
TEST SERIES 'O' - STAINLESS STEEL 304
TEST RUN G.3

TEST CONDITIONS

CONFIGURATION ITA

DATA LOCATION: THERMOCOUPLE NO. 2

$T_{ref} : 117.0$

FIGURE 26

6-10-64 JA

INTERNAL TEMPERATURE TRANSIENT
TEST SERIES "O" - STAINLESS STEEL 304
TEST RUN 0.3

TEST CONDITIONS

CONFIGURATION 11A

DATA LOCATION: THERMOCOUPLE NO. 3

$T_{\infty} = 117.0$

LEGEND

○ TEST DATA

— CALCULATED: $T_{int} = 0.05 \bar{T}_a$

— CALCULATED: $T_{int} = 0.10 \bar{T}_a$

TEMPERATURE, DEGREES F

600

500

400

300

200

100

0

10

20

TIME, SEC

FIGURE 27

6-10-64 JK

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The sensitivity of the internal temperatures to lateral heating on the specimen is seen most clearly in Figures 28 through 31 for test runs 0.4 and 0.5. The lateral heating, (q_{LAT}), which was calculated as a percentage of the heat flux to the leading edge (q_{FF} or q_H) is shown with values of 0, 5, and 10 per cent. In Figure 28, the calculated time to reach melting temperature (t_m) at the front surface agreed best for a lateral heating of 5 per cent. The assumption of no lateral heating resulted in a large deviation from the actual thermocouple transient. A lateral heating of 5 per cent agreed more closely with the actual temperatures than a value of 10 per cent for test runs 0.1 through 0.5. However, the lateral heating was found to vary with heat input as shown by Figures 32 through 35 for test run 0.6. This run was made with low heating ($q_{Ref}=41$) and the specimen reached equilibrium temperatures with no melting. A lateral heating of only one per cent agreed well with the test data. Variations of thermal properties with temperature were taken into account (Appendix E) and for long exposures to heat, the emissivity proved to be a significant factor. Figure 32 illustrates the effect of emissivity at high temperatures for long exposures.

The last two runs of series 0 (0.7 and 0.8) were made with aluminum specimens. Figures 36 through 40 show the temperatures from the runs and the analytical comparisons. Calculated temperatures for lateral heating of 1 and 5 percent of the face heating are plotted for the surface up to the melting temperature. The time at which this occurs, for 5 per cent (q_{LAT}), is in good agreement with the film data (see Figure 36). The calculated internal temperatures are plotted in Figures 37 through 39 and in general, agree with the test data. Figure 40 presents the actual temperature transients for thermocouple number one of runs 0.7 and 0.8 in their entirety. The sudden step change in temperature at approximately 1190°F corresponds with the melting temperature of aluminum which is within 30°F of the value reported.

B. TEST SERIES "2"

The results of internal temperature transient computations are shown with the actual data for test runs 2.5, 2.6, 2.7, and 2.8 in Figures 41 through 44. These were the only runs of this series that were analyzed for the purpose of this study since the major objective of

SURFACE TEMPERATURE TRANSIENT
TEST SERIES "O" - STAINLESS STEEL 304
TEST RUNS 0.4 AND 0.5

TEST CONDITIONS

CONFIGURATION ITA

DATA LOCATION: FRONT FACE

T_{ref} : 0.4 71.6, 0.5 72.8

FIGURE 28

6-4-64 JM

INTERNAL TEMPERATURE TRANSIENT
TEST SERIES "O" STAINLESS STEEL 304
TEST RUNS 0.4 AND 0.5

FIGURE 29

6-9-69 JA

INTERNAL TEMPERATURE TRANSIENT
TEST SERIES "C" - STAINLESS STEEL 304
TEST RUNS 0.4 AND 0.5

TEST CONDITIONS

CONFIGURATION: N/A

DATA LOCATION: THERMOCOUPLE NO. 2

T_{ref} : 0.4 - 71.6, 0.5 - 72.8

LEGEND

○ TEST DATA - RUN NO. 0.4

□ TEST DATA - RUN NO. 0.5

— CALCULATED: $T_{ref} = 0.05 \dot{T}_{ref}$

— CALCULATED: $T_{ref} = 0.10 \dot{T}_{ref}$

— CALCULATED: $T_{ref} = 0$

FIGURE 30

6-9-69 JA

INTERNAL TEMPERATURE TRANSIENT
TEST SERIES "O" - STAINLESS STEEL 304
TEST RUNS 0.4 AND 0.5

TEST CONDITIONS

CONFIGURATION 11A

DATA LOCATION: THERMOCOUPLE NO. 3

q_{ref} : 0.4 - 11.6, 0.5 - 12.8

LEGEND

○ TEST DATA - RUN NO. 0.4

□ TEST DATA - RUN NO. 0.5

CALCULATED: $\dot{q}_{ref} = 0.05 \dot{q}_{ref}$

CALCULATED: $\dot{q}_{ref} = 0.10 \dot{q}_{ref}$

--- CALCULATED: $\dot{q}_{ref} = 0$

FIGURE 31

6-4-64 JA

INTERNAL TEMPERATURE TRANSIENT
TEST SERIES 'O' - STAINLESS STEEL 304
TEST RUN 0.6

TEST CONDITIONS

CONFIGURATION T/A

DATA LOCATION - THERMOCOUPLE NO. 1

$g_{ext} = 41.1$

TEMPERATURE, DEGREES F

1400

1400

1200

1000

800

600

400

200

LEGEND

○ TEST DATA - TC 1

— CALCULATED: $g_{ext} = 0$

— CALCULATED: $g_{ext} = 0.01 g_{ext}$

100
TIME, SEC

200

FIGURE 33

6-9-64 JA

INTERNAL TEMPERATURE TRANSIENT
TEST SERIES "O" - STAINLESS STEEL 304
TEST RUN O.6

TEST CONDITIONS

CONFIGURATION II-A

DATA LOCATION: THERMOCOUPLE NO. 7

TIME: 41.1

FIGURE 34

6-4-64 JA

INTERNAL TEMPERATURE TRANSIENT
TEST SERIES "O" - STAINLESS STEEL 304
TEST RUN 0.6

TEST CONDITIONS

CONFIGURATION TTA

DATA LOCATION: THERMOCOUPLE NO. 3

T_{ref} : 411

FIGURE 3.5

6-8-64 JA

SURFACE TEMPERATURE TRANSIENT
TEST SERIES 'O' - ALUMINUM 1100
TEST RUNS 0.7 AND 0.8

TEST CONDITIONS

CONFIGURATION: T/A

DATA LOCATION: FRONT FACE

T_{ref} : 0.7 - 37.6, 0.8 - 34.7

FIGURE 36

6-12-64 JA

INTERNAL TEMPERATURE TRANSIENT
TEST SERIES "O" - ALUMINUM 1100
TEST RUNS 0.7 AND 0.8

TEST CONDITIONS

CONFIGURATION ITA

DATA LOCATION: THERMOCOUPLE NO. 1

T_{ref} : 0.7 - 37.6, 0.8 - 34.7

FIGURE 37

6-12-69 JA

INTERNAL TEMPERATURE TRANSIENT
TEST SERIES "O" - ALUMINUM 1100
TEST RUNS 0.7 AND 0.8

TEST CONDITIONS

CONFIGURATION: TIA

DATA LOCATION: THERMOCOUPLE NO. 7

T_{ref} : 0.7 - 32.6, 0.8 - 32.7

FIGURE 38

6-12-64 JM

INTERNAL TEMPERATURE TRANSIENT
TEST SERIES "O" - ALUMINUM 1100
TEST RUNS 0.7 AND 0.8

TEST CONDITIONS

CONFIGURATION IIA

DATA LOCATION: THERMOCOUPLE NO. 3

T_{ref} : 0.7 - 37.6, 0.8 - 39.7

FIGURE 39

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the series was the investigation of oxide formation. The method assumed for hydrogen dissociation in the calculations was with the step change in capacitance at a temperature of 1600°F. A temperature (T_D) of 1600°F was used since the test data from thermocouples 1, 2, and 3 showed a plateau at approximately this temperature. Two values of lateral heating were compared, as indicated in the figures, and reasonable agreement was achieved for the portion of the transient considered with a lateral heating value of 20 per cent ($0.20 \bar{q}_H$). The greatest deviation of the calculations from test data was observed for thermocouple number 4 in Figure 44. The higher test data was attributed to the heat input to the graphite holder which was neglected in the calculations.

C. TEST SERIES "3"

Test series 3 comprised Configuration I clad specimens. The results are presented in Figures 45 through 48. Actual temperatures below 1800°F were not obtained due to the limits of a pyrometer used with glass at lower temperatures. For the calculations of the surface temperature for these test runs, the cladding was neglected since the film data (see Figure 8) indicated that it was ablated away in a short period of time at relatively high heat rates. However, including the cladding made very little difference in the transient after dissociation at 2000°F, as shown in Figure 48 for test run 3.8. At a low heat flux ($q_{Ref}=40$) the cladding can be dispersed explosively as indicated by the film data for test run 3.4 (see Figure 7).

The dissociation of hydrogen was assumed as an isothermal phase change occurring at 1800°F and at 2000°F. Figure 46 presents both these calculations for test runs 3.5 and 3.9. Comparison of calculated and actual data for runs 3.5 and 3.9 indicated initial agreement but the actual transient rises rapidly just prior to ablation. The calculated surface temperature for test run 3.8 was in excellent agreement with the pyrometer data, as indicated in Figure 47. However, run 3.12 data rises rapidly near the melting temperature as was the case for runs 3.5 and 3.9.

The film event coverage was correlated with the pyrometer data and was found to be in good agreement. Figures 8 and 9 show the film coverage of run 3.9. The events of run 3.12 are shown by Figures 10 and 11. Other runs of series 3 were not considered in the analysis due to

INTERNAL TEMPERATURE TRANSIENT
TEST SERIES "Z" - FUEL
TEST RUNS 2.5-2.8

TEST CONDITIONS

CONFIGURATION NR

DATA LOCATION: THERMOCOUPLE No. 1

T_{int} 2.5 - 73.1, 2.6 - 71.3

2.7 - 70.8, 2.8 - 71.0

FIGURE 41

6-23-64 JM

INTERNAL TEMPERATURE TRANSIENT

TEST SERIES "2" - FUEL

TEST RUNS 2.5-2.8

TEST CONDITIONS

CONFIGURATION T/B

DATA LOCATION: THERMOCOUPLE No. 2

 T_{ref} : 2.5 - 73.1 2.6 - 71.3

2.7 - 70.8 2.8 - 71.0

FIGURE 42

G-23-64 JA

INTERNAL TEMPERATURE TRANSIENT
TEST SERIES "2" - FUEL
TEST RUNS 2.5 - 2.8

TEST CONDITIONS

CONFIGURATION 11B

DATA LOCATION: THERMOCOUPLE NO. 3

T_{ref} : 2.5 - 73.1 2.6 - 71.3

2.7 - 70.8 2.8 - 71.0

FIGURE 43

6-23-64 JA

INTERNAL TEMPERATURE TRANSIENT
TEST SERIES "2" - FUEL
TEST RUN 2.5

TEST CONDITIONS

CONFIGURATION II B

DATA LOCATION THERMOCOUPLE NO 4

$\tau_{ME} = 2.5 - 13.1$

LEGEND

○ TEST DATA RUN NO 2.5

— CALCULATED: $\tau_{ME} = 0.20 \tau_{ME}$

— CALCULATED: $\tau_{ME} = 0.15 \tau_{ME}$

TEMPERATURE, DEGREES F

2000

1000

0

20

40

60

80

100

TIME, SEC

FIGURE 44

6-23-64 JA

SURFACE TEMPERATURE TRANSIENT
TEST SERIES "3" FUEL
TEST RUNS 3.5 AND 3.9

TEST CONDITIONS

CONFIGURATION TB-CLAD

Fuel: 3.5 - 99.5 3.9 - 93.8

FIGURE 15

T-12-62 JA

SURFACE TEMPERATURE TRANSIENT
TEST SERIES "3" - FUEL
TEST RUNS 3.5 AND 3.9

TEST CONDITIONS

CONFIGURATION IR - CLAD

T_{in} : 3.5 - 94.5 3.9 - 93.8

FIGURE 46

7-14-64 JA

SURFACE TEMPERATURE TRANSIENT
TEST SERIES 13 - FUEL
TEST RUNS 3.8 AND 3.12

TEST CONDITIONS

CONFIGURATION 1B - CLAD

Run 3.8 - 71.3 3.12 - 13.5

FIGURE 47

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FIGURE 48

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test and/or data failures.

D. TEST SERIES "4"

The test specimens of series 4 were of Configuration I (unclad) and Configurations IIA and IIB. Specifically, test runs 4.1 through 4.16 were of Configuration I; runs 4.17, 4.19, 4.21, and 4.22 were Configuration IIA, and runs 4.18 and 4.20 were Configuration IIB. Figures 49 through 54 present the results of test runs 4.6, 4.7, 4.13, 4.14, and 4.16 and the analytical comparisons. The data from test runs 4.1 through 4.5 and 4.8 through 4.12 were not considered due to the uncertainty of the test conditions. Even though the conditions of runs 4.6 and 4.7 were questionable, the data was comparable to run 4.16 which was approximately under the same heat rate. This comparison is shown in Figure 49.

Figure 50 is a comparison of the two methods of assuming the dissociation of hydrogen in the calculations, as explained in the report section describing the method of analysis, plotted with the test data of run 4.16. It was found that the two methods made very little difference in the end results. Calculations based on hydrogen dissociation temperatures (T_D) of 1800°F and 2000°F (isothermal phase change) are shown in Figure 51 also with the test data of run 4.16. As can be seen in the figure, the calculated curve for a T_D of 1800°F reaches a peak temperature of 3400°F sooner than that for a T_D of 2000°F. This is due to the fact that radiation losses are greater for a specimen dissociating hydrogen at higher temperatures. A comparison of the method of assuming a capacitance step change at temperatures of 1800°F and 2000°F is made with test run 4.16 in Figure 52. The calculated final temperatures are approximately the same as in Figure 51 for isothermal phase change dissociation. The computations of both methods were in good agreement with the test data with the exception of the latter portion of the transient during which the actual temperature rises more rapidly to the melting point.

Figure 53 presents the results of test runs 4.13 and 4.14 with a calculated temperature transient which assumed an isothermal phase change at 2000°F. Figure 54 compares calculations of T_D equal to 1800°F and T_D equal to 2000°F with the test data of run 4.14. The calculations

SURFACE TEMPERATURE TRANSIENT
TEST SERIES "4" - FUEL
TEST RUNS 4.6, 4.7 AND 4.16

TEST CONDITIONS

CONFIGURATION 1B

Test 4.6-67, 4.7-65, 4.16-68.1

FIGURE 49

1-14-64 JA

FIGURE 50

7-10-64 JA

SURFACE TEMPERATURE TRANSIENT
TEST SERIES "4" - FUEL
TEST RUN 4.16

TEST CONDITIONS
CONFIGURATION TA
 T_{ref} : 4.16 - 68.7

FIGURE 51

1-14-64 JA

SURFACE TEMPERATURE TRANSIENT
TEST SERIES "4" - FUEL
TEST RUN 4.16

TEST CONDITIONS

CONFIGURATION TB

Free: 4.16-68.7

FIGURE 52

T. A. 60 JA

SURFACE TEMPERATURE TRANSIENT
TEST SERIES "4" - FULL
TEST RUNS 4.13 AND 4.14

TEST CONDITIONS

CONFIGURATION TB

Temp: 4.13 - 91.0 4.14 - 83.7

FIGURE 53

7-18-64 JA

FIGURE 54

7-14-64 JA

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were in good agreement with the test data except during approximately the last 25 seconds of the transient. The actual test data increased sharply to 3400°F as was the case for runs 4.6, 4.7, and 4.16.

The internal temperature data for Configuration IIA of test runs 4.17, 4.19, and 4.21 is shown in Figures 55 through 60 with corresponding calculated transients. The computations were based on lateral heat rates (q_{LAT}) of 10 and 15 per cent of the average front face heating ($\bar{q}_{FF}$) and isothermal phase change dissociation of hydrogen at 2000°F and at 1800°F. The test data from thermocouple number one for the three runs (4.17, 4.19, and 4.21) is shown in Figure 55 with calculated data for a T_D of 2000°F. The calculated transients agreed well with the test data up to approximately 1800°F, the point at which the test data levels off. Figure 56 shows the calculations for a T_D of 1800°F which appear to agree more closely with the test data of runs 4.17 and 4.19. It should be pointed out again here that the calculations were terminated when the surface reached the melting temperature and therefore the internal transients were incomplete. The influence of lateral heating on the specimen in the calculated results can be seen in these and following figures. Similar results are shown in Figures 57 and 58 for the location of thermocouple number two. In this case, the actual data was observed to plateau at 1600°F. Calculated comparisons with the test data for thermocouples 3 and 4 are shown in Figures 59 and 60. In Figure 59, the test data for runs 4.17 and 4.21 levels off at 1500°F and in Figure 60, the data of run 4.21 levels off at 1400°F. Thus, this plateau in temperature occurred at lower temperatures moving back from the front face to each thermocouple location. The calculations agreed with the test data more closely during the initial transients and with lateral heating of 15 per cent. The deviation of the calculated temperature from the test data for thermocouple number 4, located at the rear face of the specimen, was due to the heating of the graphite holder which was neglected in the calculations.

The results and analytical computations for test run 4.22 (Configuration IIA) are presented in Figures 61 through 65. The test data for thermocouple number one is compared in Figure 61 with calculated transients for a dissociation temperature of 2000°F and lateral heating of 10 and 15 per cent as was used for runs 4.17, 4.19, and 4.21 of the same configuration. Figure 62 is also data from thermocouple number one

FIGURE 55

FIGURE 56

INTERNAL TEMPERATURE TRANSIENT
TEST SERIES 4 - FULL
TEST RUNS 4.17, 4.19 AND 4.21

TEST CONDITIONS
 CONFIGURATION 71A
 DATA LOCATION:
 THERMOCOUPLE NO. 2
 $T_{ref} = 4.17 - 92.7$
 $4.19 - 93.6$
 $4.21 - 95.1$

FIGURE 57

7-19-68 JA

INTERNAL TEMPERATURE TRANSIENT
TEST SERIES "4" - FUEL
TEST RUNS 4.17 AND 4.19

TEST CONDITIONS
 CONFIGURATION 11A
 DATA LOCATION:
 THERMOCOUPLE NO. 2
 $\dot{q}_{acc}$ 4.17 - 92.7
 4.19 - 93.6

FIGURE 58

7-18-64 JA

INTERNAL TEMPERATURE TRANSIENT
TEST SERIES "4" - FUEL
TEST RUNS 4.17, 4.19 AND 4.21

TEST CONDITIONS

CONFIGURATION 11A

DATA LOCATION

THERMOCOUPLE NO. 3

Time 4.17 - 92.7

4.19 - 93.6

4.21 - 95.1

TEMPERATURE DEGREES F

3000

2000

1000

100

200

TIME, SEC

LEGEND

O - TEST DATA - RUN NO 4.17

+ - TEST DATA - RUN NO 4.19

△ - TEST DATA - RUN NO 4.21

— CALCULATED: $\dot{q}_{\text{net}} = 0.15 \dot{q}_{\text{ref}}$ — CALCULATED: $\dot{q}_{\text{net}} = 0.10 \dot{q}_{\text{ref}}$ (T_b = 2000 °F)

FIGURE 59

7-14-64 JA

INTERNAL TEMPERATURE TRANSIENT
TEST SERIES "4" - FLUE
TEST RUNS 4.17, 4.19 AND 4.21

TEST CONDITIONS

CONFIGURATION 11A

DATA LOCATION: THERMOCOUPLE NO. 4

(RUN NO 4.17 - NO DATA)

T_{int} : 4.17 - 92.7

4.19 - 93.6

4.21 - 93.1

TEMPERATURE, DEGREES F

3000

2000

1000

LEGEND

□ TEST DATA - RUN NO 4.19

△ TEST DATA - RUN NO 4.21

— CALCULATED: $\dot{Q}_{int} = 0.15 \dot{Q}_{ext}$

--- CALCULATED: $\dot{Q}_{int} = 0.10 \dot{Q}_{ext}$

($T_h = 2000^\circ F$)

100
 TIME, SEC

200

FIGURE 60

7-14-64 JA

INTERNAL TEMPERATURE TRANSIENT
TEST SERIES "4" - FUEL
TEST RUN 4.22

TEST CONDITIONS
 CONFIGURATION TIA
 DATA LOCATION:
 THERMOCOUPLE NO. 1
 $T_{REF} = 120.2$

FIGURE 41

7-14-64 JA

INTERNAL TEMPERATURE TRANSIENT
TEST SERIES "4" - FUEL
TEST RUN 4.22

TEST CONDITIONS

CONFIGURATION 11A

DATA LOCATION:

THERMOCOUPLE NO. 1

$T_{ref} = 120.2$

FIGURE 62

7-14-64 JA

INTERNAL TEMPERATURE TRANSIENT
TEST SERIES "4" - FUEL
TEST RUN 4.22

TEST CONDITIONS

CONFIGURATION IIA

DATA LOCATION :

THERMOCOUPLE NO. 2

$T_{ref} = 120.7$

TEMPERATURE, DEGREES F

3000

2000

1000

0

0

20

40

60

80

100

TIME, SEC

LEGEND

○ TEST DATA - RUN NO. 4.22

— CALCULATED: $\dot{q}_{in} = 0.15 \dot{q}_{ref}$

--- CALCULATED: $\dot{q}_{in} = 0.10 \dot{q}_{ref}$

($T_b = 2000^\circ F$)

FIGURE 63

7-14-64 JA

INTERNAL TEMPERATURE TRANSIENT
TEST SERIES "4" - FUEL
TEST RUN 4.22

TEST CONDITIONS

CONFIGURATION T/A

DATA LOCATION

THERMOCOUPLE NO. 3

T_{ref} : 120.2

FIGURE 6A

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INTERNAL TEMPERATURE TRANSIENT

TEST SERIES "4" - FUEL

TEST RUN 4.22

TEST CONDITIONS

CONFIGURATION 11A

DATA LOCATION:

THERMOCOUPLE NO. 4

 $T_{ref} = 120.2$ LEGEND

—○— TEST DATA - RUN NO. 4.22

CALCULATED: $T_{ref} = 0.15 T_{ref}$ CALCULATED: $T_{ref} = 0.10 T_{ref}$ $(T_b = 2000^\circ F)$

TEMPERATURE, DEGREES F

2000

1000

0

20

40

60

80

100

TIME, SEC

FIGURE G5

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but is compared with a calculated temperature transient for which T_D is equal to 1800°F . This was found to be in better agreement since the actual transient levels off at approximately 1800°F . The remaining thermocouple data (TC #2, 3, and 4) is shown in Figures 63, 64, and 65 with the calculated transients. As was the case for runs 4.17, 4.19, and 4.21, these thermocouples show a plateau at a lower temperature than that from thermocouple number one; approximately 1600°F . The greatest deviation of the computations from test data can again be seen for thermocouple number four. Also, the actual data curves for run 4.22 were dissimilar in shape to those of runs 4.17, 4.19, and 4.21. However, the agreement of calculated and test data was still quite good, for a lateral heating of 15 per cent, up to the termination of the computed data.

The internal temperature distributions for Configuration IIB of test runs 4.18 and 4.20 are compared with calculated transients in Figures 66 through 69. As in the calculations for the runs of test series 2, hydrogen dissociation was assumed to occur with a step change in capacitance at a temperature of 1800°F . Lateral heating (q_{LAT}) of 15 and 20 per cent of the frontal heat rate ($\bar{q}_H$) was also used in the computations. Figure 66 compares the calculated results with the test data for thermocouple number one and very good agreement is seen for a lateral heating of 20 per cent. The test data from thermocouples 2 and 3 show a plateau at 1600°F which was observed from runs 4.17, 4.19, 4.21, and 4.22. The calculated transient ($q_{\text{LAT}} = 0.20 q_H$) deviates from the test data only above this temperature since the dissociation temperature was assumed to be 1800°F . The calculated temperatures for thermocouple number 4 (Figure 69) are in reasonable agreement with the test data of run 4.20 but are quite low compared to that of run 4.18.

SUMMARY OF RESULTS AND CONCLUSIONS

One of the objectives of test series O was to verify the validity of a computational model. The model for Configuration II was made one-dimensional (Appendix B) since radial variations in temperature were assumed quite small. From the results of the analysis of the stainless steel and aluminum test runs, for which agreement between the calculated

FIGURE 66

FIGURE 67

INTERNAL TEMPERATURE TRANSIENT
TEST SERIES "4" - FUEL
TEST RUNS 4.18 AND 4.20

TEST CONDITIONS

CONFIGURATION 11B

DATA LOCATION:

THERMOCOUPLE NO. 3

T_{ref} : 4.18 - 93.8

4.20 - 93.1

FIGURE 68

1-14-64 JA

INTERNAL TEMPERATURE TRANSIENT
TEST SERIES "4" - FUEL
TEST RUNS 4.18 AND 4.20

TEST CONDITIONS

CONFIGURATION 11B

DATA LOCATION:

THERMOCOUPLE NO. 4

T_{ref} 4.18 - 93.8

4.20 - 93.1

TEMPERATURE, DEGREES F

3000

2000

1000

LEGEND

○ TEST DATA - RUN NO. 4.18

□ TEST DATA - RUN NO. 4.20

CALCULATED: $\tau_{int} = 0.20 \tau_c$

CALCULATED: $\tau_{int} = 0.15 \tau_c$

($T_b = 1800^\circ F$)

FIGURE 69

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and actual temperatures was achieved, it was concluded that the one-dimensional model could be used to describe the temperature transients of the fuel. Since the major objective of the arc-jet tests was to determine the behavior of SNAP reactor fuel in a simulated reentry environment, the discussion of test series "O" will not be further labored.

The basic assumptions employed in the analytical model for Configuration I (cross-axial flow) were: 1) neglect of axial conduction; 2) heating to the entire specimen, ($\bar{q}_{CYL}$), was assumed an average due to spinning, around the central circumference. It was also assumed that hydrogen is dissociated and lost as an endothermic constant temperature reaction. No consideration of oxidation was included in the analysis. For Configuration IIB, a one-dimensional model was also used and since the temperature differences in the hemispherically-tipped portion of the specimen are small, the body behaves as if it were flat-faced and receiving an average heat ($\bar{q}_H$) integrated over the hemispherical nose. All computations of temperature distributions were based on these assumptions and in general, good agreement was achieved with actual test data.

The process of ablation, or the melting and dispersal of the fuel material was not included in the model due to its complexity. Since the correlation up to melting was found to be the important factor, the added complications were unwarranted. Figures 11 through 15 show that for Configuration I, the specimens dispersed in piecemeal disintegration. However, a more smooth recession of the leading edge of Configuration II specimens was observed (Figure 16).

From the results of test series 3 (Configuration I - clad) it was observed that an apparent pressure buildup took place between the cladding and fuel at low heating. This caused an explosive dispersal of the cladding (Figure 7) as observed from the motion picture records. For higher heat rates, the cladding melted and was dispersed in short periods of time (Figures 8 and 10). The analytical solutions of the surface temperature of several test runs of this series which neglected the cladding, agreed well with the test data. When the cladding was considered, the difference was negligible as shown in Figure 48. Also, the test data from a clad specimen was compared to that of an unclad

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specimen tested under approximately the same conditions and were found to closely agree as Figure 70 shows.

The computations made for test series 4 were found to be in good agreement with the test data for Configuration I test runs. The two assumed methods by which the dissociation of hydrogen was simulated in the calculations which are part of a total energy balance and neglects the process of diffusion, made only a small difference in the time required to reach the melting temperature (Figure 50). Dissociation temperatures (T_D) of 1800°F and 2000°F were used and resulted in a difference of approximately 6 per cent in the total time to reach 3400°F as shown in Figure 51. This was due to the radiation losses which are less for lower dissociation temperatures.

In general, the actual test data exhibited a sudden rise in temperature during the latter portion of the surface temperature transients of series 3 and 4, Configuration I test runs. This was attributed to the shape change of the specimen during initial ablation and to increased oxidation, both of which can increase the heat flux. A study, presented in Reference 16, analyzing the effects of oxidation on the burnup of SNAP reactor fuel, has indicated that an increase in heating of from 4 to 60 per cent can result from oxidation depending upon the phenomena controlling its rate of formation.

The pyrometer was trained at the center of each specimen and melting usually first occurred at either extremity as shown by the film data (Figures 8 through 15). The melting temperature of the fuel is given as 3365°F but because of the way in which meltdown was observed to occur and the possible small inaccuracy of the pyrometer data and its conversion, a temperature of 3400°F was used as the approximate point of melting. As shown by the film event coverage (Table 3), the time at which a temperature of 3400°F was reached by the specimen, from pyrometer data, agreed with the event time at which approximately one-half of the specimen was dispersed, or that point at which melting was occurring. These event times for the test runs of Configuration I that were considered are tabulated in Table VI and the times corresponding to those just described, ($t_{\frac{1}{2}}$ and t_{m_2}), were seen to be in very close agreement. Also presented in Table VI is the time, (t_{m_1}) as taken from

SURFACE TEMPERATURE TRANSIENT
FUEL
TEST RUNS 3.8 AND 4.16

TEST CONDITIONS

CONFIGURATION TB

Free: 3.8 - 71.3 4.16 - 68.7

FIGURE 70

7-14-66 JA

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TABLE VI

EVENT TIME CORRELATIONS

RUN NO.	t_{m1}^* FILM DATA	t_D^{**} COMPUTED	$t_{1/2}^{***}$ FILM DATA	t_{m2}^{****} PYROMETER
3.5	69.04	50.0	79.0	74.2
3.8	128.46	—	~ 130.0	133.5
3.9	73.04	80.0	85.0	80.0
3.12	107.50	110.0	119.1	119.0
4.6	114.30	110.0	—	123.0
4.7	115.60	98.0	132.3	134.5
4.13	65.67	60.0	71.64	72.0
4.14	79.63	~ 60.0	82.5	83.0
4.16	117.46	98.0	~ 126.0	129.0

- * Ablation start at top of specimen
- ** Time at which calculated transient deviates from test data
- *** Time to ablate approximately 1/2 of specimen
- **** Time at which pyrometer read melting temperature (~3400°F)

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the film data, for melting to begin and the time, (t_D), at which the calculated temperature transients strongly deviate from the test data during the latter portion of the transient. In several cases these times agreed which, as previously discussed, is the point of increased heat flux to the specimen due to shape change and thus partially causing the observed sudden rise in actual temperature.

The analysis of Configuration IIA and IIB test runs of series 2 and 4 exhibited good agreement between the thermocouple data and the calculated transients. The thermocouple data, in all cases, produced temperature transients that plateaued at varying temperatures depending upon the depth of the thermocouple in the specimen. This temperature range was from approximately 1500°F for thermocouple number 3, to 1800°F at the location of thermocouple number 1. This seemed to be in conflict with the assumed constant dissociation temperatures throughout the specimen of 1800°F and 2000°F. However, this effect was attributed to diffusion of hydrogen to the thermocouple holes which decrease the effective diffusion length and therefore, the dissociation temperature appears to be in the above range.

Observation of the film data revealed the formation of cracks in the fuel specimens. In Figures 8, 9, and 12 through 15, the cracks can be seen by the strong temperature gradients at specific locations on the specimens. In some cases, specifically runs 3.5, 4.6, 4.8, 4.13, and 4.15, the cracks appeared quite early in the test which were visible on the film but could not be observed in still photographs. The times of crack appearance, based on initial detection are given in Table 3. The piecemeal dispersal of the fuel took place at these cracks. The cross-axial specimens (Configuration I) were drilled through the center to allow a tungsten rod holder to be mounted. It is believed that this hole may have caused undue stresses in the specimen and therefore, creating the large cracks during testing which led to the dispersal of the fuel in pieces. However, the cracking of zirconium-hydride has been observed in previous experimental work in which the specimens tested were solid (Reference 17). The formation of cracks was also observed during the axial (Configuration II) test runs.

From the results of this arc-jet test series and the agreement between the actual and calculated data, it is concluded that the method

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of assuming hydrogen dissociation and loss from the fuel as an endo-thermic constant temperature reaction is a valid approximation in these cases.

In connection with the observation of cracks in the cross-axial test runs, it is recommended that further experimentation be conducted with solid fuel specimens to verify and study the phenomena of cracking and piecemeal dispersal. If this is found to occur consistently, the melting and dispersal of these pieces should be investigated.

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APPENDIX A

TEMPERATURE CORRECTION FOR PYROMETER OUTPUT

To reduce the pyrometer output to useful data, it was necessary to apply appropriate corrections. The first correction involves the radiation absorbed and reflected by the test chamber window. The correction is given in Reference 3 as:

$$T_A = 1.122 (T_u - 22)^\circ\text{F for a clean window} \quad \dots(\text{A-1})$$

$$T_A = 1.122 (T_u + 45)^\circ\text{F for a dirty window}$$

where T_A is the temperature as measured through air, and T_u is the temperature measured through the window. Also, it was necessary to correct the temperature converted pyrometer reading to an effective "black-body" temperature (emissivity: $E = 1.0$). This was done using the equation (Reference 3):

$$T_B = \frac{T_A}{1 - 8.869 \times 10^{-5} \lambda T_A \log_{10} E_{\text{set}}} \quad ^\circ\text{R} \quad \dots(\text{A-2})$$

where: T_B = equivalent black-body temperature, $^\circ\text{R}$

T_A = temperature indicated by the pyrometer with the emissivity control set at " E_{set} " and corrected for window effect by Equation (A-1)

λ = median wavelength of the passband of the optical pyrometer (0.8 microns for thermidot TD-9H pyrometer)

The final correction converts T_B to a true surface temperature. Using Wien's equation (Reference 18) and knowing the "gray-body" emissivity (ϵ_{GB}) of the specimen, the final corrected surface temperature is obtained. Therefore, from the equation:

$$E = \epsilon c_1 \lambda^{-5} e^{-c_2/\lambda T_B} \quad \dots(\text{A-3})$$

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where: E = total emissive power

ϵ = Emissivity

C_1 = constant (1.1870×10^8 Btu μ^4 /hr-ft - $\mu = 10^{-4}$ cm)

λ = wavelength, micron

C_2 = constant ($25,896 \mu^\circ R$)

the conversion from T_B ($\epsilon = 1.0$) to the final corrected temperature (T_{corr}) was made by:

$$E_B(\epsilon = 1.0) = E_{\text{corr}}(\epsilon = \epsilon_{\text{GB}})$$

or

$$C_1 \lambda^{-5} e^{-C_2/\lambda T_B} = \epsilon_{\text{GB}} C_1 \lambda^{-5} e^{-C_2/\lambda T_{\text{corr}}}$$

Further reduction yields:

$$e^{-C_2/\lambda T_B} = \epsilon_{\text{GB}} e^{-C_2/\lambda T_{\text{corr}}}$$

Taking the natural logarithm of the above equation and rearranging:

$$T_{\text{corr}} = T_B - \frac{\lambda T_{\text{corr}} T_B}{C_2} \ln \epsilon_{\text{GB}} \quad \dots (A-4)$$

Figure A-1 is a graph of the corrected temperature versus read temperature for several values of "gray-body" emissivity.

PYROMETER TEMPERATURE CORRECTION FOR EMISSIVITY AND WINDOW ABSORPTION

FIGURE A-1

7-17-64 JA

APPENDIX B

THERMAL NETWORKS - THERMAL ANALYZER PROGRAM

For computations of the temperature transients of the test runs, a digital program (TAP-3) was used. The network for Configuration IIA is shown in Figure B-1 which was used for test series "O" (stainless steel and aluminum) and series "4" (fuel). The one-dimensional network consisted of 23 nodes through the specimen, each having a capacitance, C , calculated by:

$$C = C_p \rho V \text{ Btu/}^\circ\text{F} \quad \dots(\text{B-1})$$

where C_p is the specific heat of the material, ρ is the density and V the node volume. Each node is connected by an admittance, Y , which was calculated using:

$$Y = KA/l \text{ Btu/hr-}^\circ\text{F} \quad \dots(\text{B-2})$$

where K is the material thermal conductivity, A , the area, and l , the length between nodes. Heat input to the network is described by Equation (10) which was desired in a form for input to TAP-3. The equation for heat; unidirectional flow, is:

$$Q = Y \Delta T = Y(T_{HS} - T_w) \quad \dots(\text{B-3})$$

where: Y = thermal admittance
 T_{HS} = heat source temperature
 T_w = wall temperature

Since the stagnation enthalpy, H_s is proportional to $C_p T_s$, and the enthalpy at the wall, H_w is proportional to $C_p T_w$, Equation (10) can be written:

$$\bar{Q} = A_s \bar{q}_c / H_s (CT_s - CT_w) = A_s \bar{q}_c C / H_s (T_s - T_w) \quad \dots(\text{B-4})$$

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where: C = mean specific heat, $\bar{C}_p$ (for air at the wall temperature;
 $\bar{C}_p = \Delta H / \Delta T = 0.27 \text{ Btu/lb-}^\circ\text{F}$)

A_s = surface area

Equation (B-4) can now be used and for data input:

$$T_s = T_{Hs} = H_s / C \quad (\text{B-5})$$

and

$$Y = A_s \bar{q}_c C / H_s. \quad (\text{B-6})$$

The heat flux $\bar{q}_c$ is defined by Equation (2). Finally, combining Equations (B-4) through (B-6) yields:

$$\bar{Q} = A \bar{q}_c \frac{\bar{C}_p}{H_s} \left(\frac{H_s}{\bar{C}_p} - T_w \right). \quad (\text{B-7})$$

In Figure B-1, the heat source nodes, 24 and 25 are connected by admittances to nodes 1 (front surface heating, $\bar{q}_{FF}$) and nodes 2 through 19 (lateral heating q_{LAT}). Nodes 20 through 23 are inside the specimen holder and were considered perfectly insulated. In addition to the heat source nodes, nodes 1 through 19 are connected by radiation admittances to node 26, a radiation heat sink node. Radiation admittances are calculated by the code from the equation:

$$Q_{RAD} = Y(T_i - T_j) = A \mathcal{F} \sigma (T_i^4 - T_j^4). \quad (\text{B-8})$$

Solving for Y:

$$Y_{RAD} = A \mathcal{F} \sigma (T_i + T_j) (T_i^2 + T_j^2) \quad (\text{B-9})$$

where T_i and T_j are the temperatures of nodes i and j connected by Y_{RAD} . The input data is $A \mathcal{F}$, the "equivalent conductance," where A is the surface area and $\mathcal{F}$ is the gray-body shape factor which is a function of body shape and the material emissivity, ϵ . The Stefan-Boltzmann constant σ , is incorporated in the code. Table B-1 is a tabulation of the cal-

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culations for the network of Test Configuration IIA. The thermocouple axial locations are indicated in Figure B-1 which correspond to network nodes 10, 14, and 18.

Figure B-2 represents the network for Test Configuration IIB (hemispherically-tipped). The nodes of this network were made somewhat larger than those of Figure B-1 and for simplicity, the tip was represented by a single node. Network calculations are tabulated in Table B-2.

The thermal network for Configuration I is shown in Figure B-3. One-dimensional radial conduction only was considered and the conduction admittances were calculated from:

$$Y = \frac{2\pi K}{\ln r_i/r_j} \quad (B-10)$$

where r_i and r_j are the radii of nodes i and j . All other network parameters were calculated according to Equations (B-1), (B-5), (B-6), and (B-9). Table B-3 is a tabulation of the calculations for this network.

FIGURE B-1

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 CHECKED BY:
 DATE: 8-3-64

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 CONFIGURATION IIA
 THERMAL NETWORK

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FIGURE B-2

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SCALE: 10:1

FIGURE B-3

APPENDIX C

ANALOG COMPUTER SOLUTION OF FUEL TEMPERATURE TRANSIENTS FOR CONFIGURATION I

The analog model consisted of 3 nodes (Figure C-1) and the equations for input to the circuit were:

$$1. \quad \dot{T}_1 = \frac{1}{C_1} [Q_{\text{heat}} - Q_{\text{radiation}} - Q_{\text{conduction (1-2)}}]$$

$$\text{where: } \dot{T}_1 = \frac{dT}{dt}$$

$$C_1 = c_p \rho V_1$$

$$Q_{\text{heat}} = A_s \bar{q}_{\text{CYL}} (H_s - H_w) / H_s$$

$$Q_{\text{radiation}} = (A_s \epsilon \sigma) T_{1R}^4 (T_1; ^\circ R)$$

$$Q_{\text{cond. (1-2)}} = Y_{1-2} (T_1 - T_2)$$

$$2. \quad \dot{T}_2 = \frac{1}{C_2} [Q_{\text{cond. (1-2)}} - Q_{\text{cond. (2-3)}}]$$

$$\text{where: } C_2 = c_p \rho V_2$$

$$Q_{\text{cond. (2-3)}} = Y_{2-3} (T_2 - T_3)$$

$$3. \quad \dot{T}_3 = \frac{1}{C_3} [Q_{\text{cond. (2-3)}}]$$

$$\text{where: } C_3 = c_p \rho V_3.$$

The above equations were arranged in the following form:

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$$\begin{aligned}
 \text{a. } k_1 C_1 \dot{T}_1 &= A - A\beta T_1 - BT_{1R}^4 - D(T_1 - T_2) \\
 &= A - (A\beta + D)T_1 - BT_{1R}^4 + DT_2
 \end{aligned} \tag{C-1}$$

$$\begin{aligned}
 \text{b. } k_2 C_2 \dot{T}_2 &= D(T_1 - T_2) - E(T_2 - T_3) \\
 &= DT_1 - (D + E)T_2 + ET_3
 \end{aligned} \tag{C-2}$$

$$\text{c. } k_3 C_3 \dot{T}_3 = E(T_2 - T_3) \tag{C-3}$$

where: $k = w/W_{\text{total}}$ (weight of node to total weight)

$$A = A_s \bar{q}_{\text{CYL}} \quad (\text{see Equations 8 and 10})$$

$$\beta = \bar{C}_p / H_s \quad (\text{see Equation B-7})$$

$$B = A_s \epsilon \sigma$$

$$D = Y_{1-2} \quad (\text{see Equation B-10})$$

$$E = Y_{2-3}$$

$$C = C_p \rho V \quad (\text{see Figure E-4})$$

The analog computer schematic is shown in Figure C-2 and the instrument (POT) settings for the coefficients in Equations (C-1) through (C-3) are given in Tables C-1 and C-2. The parameters that were varied in the analog computations and some typical values are tabulated in Table C-3. The results of some of the analog solutions are compared to the results of an identical digital model in Figures C-3 and C-4. In Figure C-3, the reference heating was 70 and the two solutions differ only by a small amount due to the initial temperature, T_D . The heat rate used for the calculations given in Figure C-4 was 90 and for both heat rate conditions, a dissociation temperature (T_D) of 1600°F was

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assumed. Several other analog computer runs were made with a T_D of 2000°F and Figure C-5 shows the results for the same conditions as for those in Figure C-3. It should be noted that the temperature transients rise in steps following the phase change. This was due to the three node network which caused an over simplification of the computations even though they were accurate. It was for this reason that a more detailed digital model (13 nodes) was used in the final analysis.

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SCALE: 10:1

FIGURE C-1

Figure C-2. Analog Computer Schematic Diagram for 3 Node Network

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FIGURE C-3

FIGURE C-4

FIGURE C-5

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PROBLEM AEROSPACE
BY R.K. SEFERIAN

ANALOG COMPUTER LABORATORY
PAGE 231-R POT SHEET

10 MAR 1964 DATE
D COMPUTER

P-SERIES		POT NO.	Q-SERIES	
DESCRIPTION	SET		SET	DESCRIPTION
		00		
		01		
		02		
		03		
		04		
		05		
$\Delta C / \Delta T / T_2 - T_3$	4754	06	2756	$\Delta C / \Delta T / T_2 - T_1$
		07		
		08	RUN SCH	$\Delta \frac{1}{SC_0} / T_2 - T_1$
		09		
		10	0920	460°/5000
		11		
		12		
		13	RUN SCH	10 ¹³ B _I / 8
		14	RUN SCH	
I.C. T ₁ /5000	0016	15	RUN SCH	10(A+B+D)
AOC/500	RUN SCH	16	8450	2K ₁
10 D	6840	17	RUN SCH	10/5CM
$\Delta \frac{1}{SC_0} / T_2 - T_3$	RUN SCH	18		
		19		
		20		
		21	0800	$\Delta T_2 / 5000$
		22	3600	$T_2 / 5000$
		23		
		24		

P-SERIES		POT NO.	Q-SERIES	
DESCRIPTION	SET		SET	DESCRIPTION
		25		
		26	0800	$\Delta T_1 / 5000$
		27	3200	$T_1 / 5000$
		28		
		29		
		30		
$\Delta C / \Delta T / T_2 - T_3$	4754	31	2756	$\Delta C / \Delta T / T_2 - T_1$
		32		
		33	RUN SCH	$\Delta \frac{1}{SC_0} / T_2 - T_1$
		34		
		35		
$\Delta C / \Delta T / T_2 - T_3$	4754	36	2756	$\Delta C / \Delta T / T_2 - T_1$
		37		
		38	RUN SCH	$\Delta \frac{1}{SC_0} / T_2 - T_1$
		39		
I.C. T ₃ /5000	0016	40	2608	10 E
		41	3874	2 K ₃
10 E	2608	42	RUN SCH	10/5CM
$\Delta \frac{1}{SC_0} / T_2 - T_3$	RUN SCH	43		
		44		
I.C. T ₂ /5000	0016	45	9448	10(D+E)
10 E	2608	46	7680	2 K ₂
10 D	6840	47	RUN SCH	10/5CM
$\Delta \frac{1}{SC_0} / T_2 - T_3$	RUN SCH	48		
		49		

TABLE C-1

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PROBLEM AEROSPACE

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ANALOG COMPUTER LABORATORY

POT SCHEDULE SHEET

3/10/64

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2

COMPUTER

[illegible][illegible]

APPENDIX D

CALCULATED SURFACE AND INTERNAL TEMPERATURE
TRANSIENTS AND HEAT FLUX FROM THE TIME REQUIRED
TO MELT THE SPECIMEN SURFACE

TEST SERIES "O" - STAINLESS STEEL

A. Calculated Surface and Internal Temperature Transients

To investigate the surface temperature as a function of time for the stainless steel test series prior to the use of a digital computational solution, the equation for linear flow of heat in a solid bounded by two parallel planes given by Carslaw and Jaeger, was used (Reference 13). The equation was derived for a slab with prescribed heat flux at its surface. However, the results also apply to a rod of length l (see Figure D-1) with the same end conditions as for the slab and with no heat loss from its surface, i.e., Q_{RAD} is zero.

For the region $0 < x < l$, zero initial temperature, constant heat flux Q into the rod at $x = l$ and no heat flow over $x = 0$:

$$T_{(x,t)} = \frac{Q t}{\rho C l} + \frac{Q l}{K} \left\{ \frac{3x^2 - l^2}{6l^2} - \frac{2}{\pi} \sum_{n=1}^{\infty} \frac{(-1)^n}{n^2} e^{-\alpha t n^2 \pi^2 / l^2} \cos \frac{n \pi x}{l} \right\} \quad \dots (D-1)$$

where ρ is the density, C_p is the specific heat and K , the thermal conductivity of the material. The first term of Equation (D-1) is a linear increase in temperature with time t , but the second term depends on position and time. This latter term is plotted in Figure D-2 in the form:

$$\left[\frac{KT}{Ql} - \frac{\alpha t}{l^2} \right] = \phi \quad (D-2)$$

where ϕ is read from the graph for a computed value of $\alpha t/l^2$ and position x/l . Solving Equation (D-2) for the temperature T , yields:

$$T = \frac{Ql}{K} \left[\frac{\alpha t}{l^2} + \phi \right]. \quad (D-3)$$

Since $\alpha = K/\rho C_p$:

$$\begin{aligned} T &= \frac{Ql}{K} \left(\frac{Kt}{\rho C_p l^2} \right) + \frac{Ql}{K} \phi \\ &= \frac{Qt}{\rho C_p l} + \frac{Ql}{K} \phi \end{aligned} \quad (D-4)$$

which is Equation (D-1). Equation (D-4) was solved for the stainless steel test conditions of run 0.1, 0.2, 0.4, and 0.5 at an x/l of 1.0 and 2/3, which correspond to the front face of the cylinder and the location of thermocouple number one. The calculations are tabulated in Tables D-1 and D-2. Thermal properties used in the calculations are presented in Appendix E.

B. Heat Flux Calculation From the Time Required to Melt the Specimen Surface

In order to theoretically verify the heat flux $\bar{q}_{FF}$ as given for test runs 0.1 and 0.4, the equation for constant heating up to the melting temperature was utilized. For an infinitely long rod with insulated sides, suddenly exposed to a source of heat at its face which continues

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to deliver a constant amount of heat per unit time to the free surface, the boundary conditions are:

$$1. \quad \theta = 0 @ t = 0; \quad \theta = T_s - T_0$$

T_s = surface temperature

T_0 = initial temperature

$$2. \quad \frac{q}{K} = - \frac{\partial \theta}{\partial x} = C \text{ (constant) } @ x = 0$$

$$3. \quad \theta = 0 @ x = \infty$$

Letting ($v = C + \frac{\partial \theta}{\partial x}$) and differentiating the Fourier equation, yields:

$$\frac{\partial}{\partial x} \left(\frac{\partial \theta}{\partial t} \right) = \alpha \frac{\partial^2 v}{\partial x^2} = \frac{\partial v}{\partial t} \quad (D-5)$$

Solution of Equation (D-5) with the above boundary conditions gives:

$$q = K \left(\frac{T_m - T_0}{2} \right) \sqrt{\frac{\pi}{\alpha \tau}} \quad (D-6)$$

where: T_m = melting temperature at the surface

$$\alpha = K / \rho c_p$$

$$\tau = t_m = \text{time for surface to reach } T_m$$

(For a detailed description of the solution of Equation D-5, see Reference 19, pp 256-258.)

Using average thermal properties of stainless steel 304 and the time (t_m) from film data of the test runs, Equation (D-6) was solved.

SAMPLE CALCULATIONS

Test Run No. 0.1 ($t_m = 15$ seconds)

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For stainless steel 304: $\bar{K} = 13 \text{ Btu/hr-ft-}^\circ\text{F}$, $\bar{\alpha} = .19 \text{ ft}^2/\text{hr}$,
 $T_m = 2600^\circ\text{F}$. With $T_0 = 80^\circ\text{F}$, $T_m - T_0 = 2520^\circ\text{F}$, and therefore:

$$q = 13 \frac{\text{BTU}}{\text{HR-FT-}^\circ\text{F}} \frac{(2520^\circ\text{F})}{2} \sqrt{\frac{\pi}{.19 \text{ FT}^2/\text{HR} (15 \text{ SEC})} \frac{3600 \text{ SEC}}{\text{HR}}} \left(\frac{1 \text{ HR}}{3600 \text{ SEC}} \right)$$

$$= 273 \sqrt{\frac{\pi}{.19 (15)}} = 285 \text{ BTU/FT}^2\text{-SEC}$$

and

$$q_{\text{REF}} = 285 \left(\frac{\sqrt{R_0}}{.66} \right) = 431 (.22822)$$

$$q_{\text{REF}} = 98.6 \text{ BTU-}\sqrt{\text{FT}}/\text{FT}^2\text{-SEC}$$

$$(q_{\text{REF}} \text{ FOR RUN 0.1 — TABLE I IS } 109.0)$$

Run No. 0.2 ($t_m = 12.5 \text{ sec}$)

$$q = 273 \sqrt{\frac{\pi}{.19 (12.5)}}$$

$$q = 314 \text{ Btu/ft}^2\text{-sec}$$

and

$$q_{\text{Ref}} = 314 \left(\frac{.22822}{.66} \right) = 314 (.346)$$

$$q_{\text{Ref}} = 108.7 \text{ Btu-ft}^{1/2}/\text{ft}^2\text{-sec}$$

$$(q_{\text{Ref}} - \text{Table I is } 111.8)$$

Run No. 0.4 ($t_m = 36.6 \text{ sec}$)

$$q = 273 \sqrt{\frac{\pi}{.19 (36.6)}}$$

$$q = 183.5 \text{ Btu/ft}^2\text{-sec}$$

$$q_{\text{Ref}} = 183.5 (.346)$$

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$$q_{\text{Ref}} = 63.5 \text{ Btu-ft}^{\frac{1}{2}}/\text{ft}^2\text{-sec}$$

(q_{Ref} - Table I is 71.6)

TEMPERATURE DISTRIBUTION IN A ROD WITH A
CONSTANT HEAT FLUX AT ITS SURFACE - ($x = L$)

FIGURE D-2

APPENDIX E

THERMAL PROPERTIES

(Note: Superscripts designate references)

A. Stainless Steel (Type 304)

Thermal Conductivity:	Figure E-1
Specific Heat:	Figure E-1
Density:	Figure E-1
Emissivity:	0.2 - 0.6
Melting Temperature: ²⁴	2600°F

B. Aluminum (Type 1100)

(Commercially Pure)

Thermal Conductivity: ²²	130 Btu/hr-ft-°F
Specific Heat:	Figure E-2
Density: ²²	169.4 lb/ft ³
Emissivity: ²⁴	0.05
Melting Temperature: ²²	1218°F

C. Fuel

($\sum_r H_x$ - 10 wt % U)

Thermal Conductivity:	15 Btu/hr-ft-°F
Specific Heat:	

The specific heat of the fuel was calculated from the empirical relationship (Reference 20):

$$C_p = a + (bx10^{-3})T + (c \times 10^{-6})T^2 + \frac{d+10^5}{T^2} \text{ cal/mole-°K} \quad (\text{E-1})$$

For Zirconium

$$C_{pZr} = 6.83 + (1.12 \times 10^{-3})T - 0.87 \times 10^5 / T^2 \quad (\text{E-2})$$

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and for hydrogen:

$$C_{p_H} = 6.62 + (0.81 \times 10^{-3})T \quad (E-3)$$

and uranium:

$$C_{p_U} = 3.25 + (8.15 \times 10^{-3})T + (0.80 \times 10^{-5})T^2 \quad (E-4)$$

Combining the specific heats of zirconium and hydrogen gives the relationship:

$$C_{p(ZrH_x)} = \left[(C_p)_{Zr} + x/2 (C_p)_{H_2} \right] / 91.22 + 1.008 \times \text{cal/gm-}^\circ\text{K} \quad (E-5)$$

where: x = Ratio of hydrogen atoms to zirconium atoms (H/Zr)

The composition of SNAP 10A/2 fuel is as follows:

Zr - 88.38 wt %
 U - 9.82 wt % (after hydriding)
 H - 1.80 wt %
 H/Zr - 1.87

Therefore, the specific heat of the fuel was expressed in the form:

$$C_{p(\text{fuel})} = 0.9018 C_{p(ZrH_{1.87})} + 0.0982 C_{p(U)} \quad (E-6)$$

Finally, combining Equations (E-2) through (E-6) and converting to $^\circ\text{C}$:

$$C_{p(\text{fuel})} = 0.1334 + 2.153 \times 10^{-5} T_{(^\circ\text{C})} - \frac{0.8095 \times 10^3}{(T_{(^\circ\text{C})} + 273)^2} \frac{\text{cal}}{\text{gm-}^\circ\text{C}} \quad (E-7)$$

The values calculated for C_p of the fuel are plotted in Figure E-3 with hydrogen loss (isothermal phase change) at 2000°F. Assuming all hydrogen is lost after 2000°F is reached, the value of C_p for Zr - 10 wt % U is constant to the melting point.

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Density: 374 lb/ft³
Emissivity: 0.4
Melting Temperature: 3365°F

D. Tungsten²²

Thermal Conductivity Figure E-5
Specific Heat: Figure E-5
Density: 1210 lb/ft³
Melting Temperature: 6110°F

THERMAL PROPERTIES STAINLESS STEEL - TYPE 304

FIGURE E-1

SPECIFIC HEAT
COMMERCIAL PURE ALUMINUM

FIGURE E-2

CALCULATED SPECIFIC HEAT
ZIRCONIUM HYDRIDE URANIUM

FIGURE E-3

FIGURE E-4

FIGURE C-5

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NOMENCLATURE

a	=	Radius of flat-faced cylinder, ft
A_s	=	Surface area, ft^2
C	=	Capacitance, $\text{Btu}/^\circ\text{F}$
C_p	=	Specific heat, $\text{Btu}/\text{lb}-^\circ\text{F}$
H_s	=	Stagnation air enthalpy, Btu/lb
H_w	=	Air enthalpy at wall temperature, Btu/lb
$H_{300^\circ\text{K}}$	=	Air enthalpy at 300°K , Btu/lb
H	=	Heat of hydrogen dissociation, $\text{Btu}/\text{lb}_{\text{fuel}}$
ΔH	=	Heat of hydrogen dissociation, $\text{KCAL}/\text{gm Mol } \text{H}_2$
M_∞	=	Free-stream mach number
N_H	=	Hydrogen concentration, H_2 Atoms/ cm^3
P_{T_2}	=	Pitot pressure (stagnation), Atm
$\bar{Q}$	=	Average total heat, Btu/sec
q	=	Local heat flux to a point on a body, $\text{Btu}/\text{ft}^2\text{-sec}$
$\bar{q}_c$	=	Average heat flux to a specimen configuration, $\text{Btu}/\text{ft}^2\text{-sec}$
$\bar{q}_{\text{CYL}}$	=	Average heat flux to a cylinder around the central periphery, $\text{Btu}/\text{ft}^2\text{-sec}$
$\bar{q}_{\text{FF}}$	=	Average heat flux to a flat-faced cylinder, $\text{Btu}/\text{ft}^2\text{-sec}$
$\bar{q}_H$	=	Average heat flux to a hemispherical-nosed cylinder, $\text{Btu}/\text{ft}^2\text{-sec}$
q_{LAT}	=	Lateral heat flux to a cylinder, $\text{Btu}/\text{ft}^2\text{-sec}$
q_{Ref}	=	Reference heat flux ($q_s \sqrt{r}$), $\text{Btu}-\sqrt{\text{ft}}/\text{ft}^2\text{-sec}$
q_s	=	Heat flux at the stagnation point, $\text{Btu}/\text{ft}^2\text{-sec}$
R_o	=	Outer cylinder radius, ft
r	=	Cylinder radius, ft
T_D	=	Dissociation temperature, $^\circ\text{F}$
t_m	=	Time for surface to reach melting point, sec
V	=	Volume, ft^3
x	=	Distance from center axis of flat-faced cylinder, parallel to the face, toward the outer radius, ft

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NOMENCLATURE

β = Ratio of heat flux to a given surface configuration to the flux at the stagnation point of a unit radius hemisphere
(q_c/q_{s_H})

ρ = Density, lb/ft³

N_A = Avagadro's number

SUBSCRIPTS

c = Configuration
CYL = Cylinder
D = Dissociation
FF = Flat-faced
H = Hemispherical-nosed
LAT = Lateral
m = Melting point
Ref = Reference
s = Stagnation

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