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Experimental Heat Transfer Distribution on the SNAP 10A Reactor

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PROGRAM

SUBACCOUNT TITLE

Reactor Reentry Disintegration Analysis

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STATEMENT OF PROBLEM

Correlate heat transfer data obtained at the Rhodes and Bloxsom 60 inch wind tunnel facility.

ABSTRACT

Heating distributions have been obtained for the SNAP 10A reactor by means of a thermal paint technique in the Rhodes and Bloxsom 60 in. hypersonic wind tunnel. Data and correlations are presented only for those reactor components where the ratio of the local heat transfer to that on the stagnation point of the calibration sphere was found to be independent of tunnel conditions. It is shown that these heating distributions can be applied directly to reentry conditions provided the thermally painted and the bare reactor surfaces are both catalytic to atom recombination.

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INTRODUCTION

In order to predict the disintegration of SNAP units during reentry to the earth's atmosphere, the heat transfer rates to the various components of the reactor must be known. Because of the complicated geometry of the SNAP reactor an experimental program was required to establish the heat transfer rates.

The Rhodes and Bloxson experimental facility where these heat transfer rates were determined is described in detail in Reference 1. There it was emphasized that caution must be exercised in applying the experimental data to actual flight conditions because the simulated environment in the test facility is not the same as that in free flight. For example, if the ratio of the heat transfer on any given surface of the reactor to the heat transfer at the stagnation point of the calibration sphere (F_q) is found to be dependent on the flow parameters in the tunnel, then a knowledge of the exact values of the free stream velocity, density, total enthalpy, and the effect of free stream dissociation on F_q must be known so that the data can be extrapolated to the corresponding free flight condition. While work is in progress to this end, the present report presents information about those heating rates which were found to be independent of tunnel conditions and therefore may be applied directly to calculate reactor disintegration in free flight.

DATA REDUCTION

The heating ratios (F_q) were calculated by dividing the local color number (C_L) by the reference color number on a 12 inch radius sphere (C_S). The tunnel reported conditions (R) and the corrected conditions (C) for which these heating factors were obtained are listed in Table 1. Data existed for angles of attack (α) of 0°, 30°, 60°, and 90°. The letters "A" and "B" following the angle of attack refer to flow direction perpendicular to the plane of the NaK outlet pipes and parallel to the plane of the NaK outlet pipes, respectively. The model for Runs 1-1, -2, -3, and -4 consisted of

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a full scale complete reactor without the shield and converter assemblies. The model for Runs I-5A, -5B, -5C, -6A, -6B, and -6C was quarter scale and included the shield and a portion of the converter assembly. The model for Runs II-1 ($\alpha = 0^\circ, 30^\circ, \text{ and } 90^\circ$) was quarter scale, included the shield and a portion of the converter assembly, but was without the pump, fins, and transverse NaK pipe. (The downcomer NaK pipes were cut off level with the top head.) The model for Runs II-2 ($\alpha = 0^\circ \text{ and } 30^\circ$) was identical except the pump (only) was attached to the top head.

TABLE 1

MODEL SCALE	RUN NUMBER	H_s/RT_o		U_∞ , ft/sec		ρ_∞ , gm/cc		Z_∞	
		R	C	R	C	R	C	R	C
FULL	I-1	384	374.8	17,000	20,300	3.46×10^{-8}	2.64×10^{-8}	1.6	1.4
FULL	I-2	384	374.8	17,000	20,000	9.4×10^{-9}	9.13×10^{-9}	1.6	1.42
FULL	I-3	384	387.4	17,000	21,600	2.6×10^{-7}	5.72×10^{-8}	1.6	1.56
QUARTER	I-5A, -5B,-5C -6A,-6B -6C II-1,-2	S A M E A S R U N I - 1							

H_s = stagnation enthalpy, U_∞ = free stream velocity, ρ_∞ = free stream density, Z_∞ = free stream dissociation

RESULTS

NaK Pipe

Figures 1-5 show the variations of F_q around the circumference of the NaK pipe for five positions (Figure 21) along the pipe. For all positions F_q decreases in the same manner from the stagnation line. Down approximately to 45° , F_q decreases as $\cos \theta$ where θ is the angular position from the stagnation line. Below 45° the data falls above the

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cosine curve (Figure 3). It will be noted that the values of F_q in all cases are independent of tunnel conditions.

Thermal Switch

The heat transfer distribution around the circumference of the thermal switch is shown in Figures 6-7. (Figure 20 shows the three circumferential locations considered.) The heating rates are independent of tunnel condition and decrease linearly from the stagnation point in accordance with the following equations:

$$F_q = 3.9 - 4.5 x \quad 0 < x < .8$$

At the ends of the cylindrical switch:

$$F_q = 6.5 - .715 x \quad 0 < x < .9$$

NaK Fill Pipe

The heat transfer rates on the flattened portion of the center NaK fill pipe (see Figure 20 for exact location) decrease very slowly from the edge and are independent of tunnel conditions as is shown in Figure 8.

Fins

The heat transfer rates at the center of the blunt leading edge are plotted in Figure 9 vs the distance from the tip of the fin. (See Figure 19 for fin designation.) As can be expected the heating rates from the tip decrease with the increase in fin thickness. This decrease can be expressed by

$$F_q = t^{-0.64} \quad 0 < t < 3 \text{ in.}$$

where t is the thickness of the fin.

For distances from the tip which are larger than three inches the fin is in the region where it interacts with the shock and the wake

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of the thermal switch and as it can be seen from Figure 10 it is a function of tunnel conditions.

Vessel Lip

The heat transfer distribution on the vessel lip is shown in Figure 11. Because of symmetry, the values of F_q for only one-half of the vessel lip are presented. With the exception of the regions close to 90° and 70°, the heating rates show dependence on tunnel conditions. The maximum heating rates occur at 90°.

Vessel Wall

Vessel wall heating ratios were available for only one tunnel condition. Nevertheless, due to the relatively clean geometry, a number of circumferential heating ratio distributions at a wall location six inches from the vessel lip for various angles of attack and top heat configurations are included. The data as summarized in Table 2 is shown in Figures 12, 13, and 14.

TABLE 2

FIGURE NO.	RUN NO.	ANGLE OF ATTACK	TOP HEAD CONFIGURATION
12	I-5C	30°B	With all components
	II-2	30°B	With pump only
	II-1	30°B	Clean top head
13	I-6A	90°B	With all components
	II-1	90°B	Clean top head
14	I-5B	30°A	With all components
	I-6C	60°A	With all components
	I-6B	90°A	With all components

Magnetic Collar

Heat transfer rates across the magnetic collar (see Figure 22 for data location) are plotted in Figure 15. The results indicate heating ratios to be generally independent of tunnel conditions. There is some deviation of data for Run 1-3 at distances greater than 0.5 inches from the edge of the collar as can be seen in the figure.

Fuel Rods

The heat transfer distribution on 0.40 scale fuel rods for angle of attack of 0, 30, and 60 degrees is shown in Figure 16-18. The following conclusions may be drawn from these figures:

- (1) The heat transfer factor F_q is independent of tunnel condition.
- (2) F_q varies as $\cos \theta$ around the circumference of the fuel rod at zero angle of attack.
- (3) The edges of the fuel rod experience the highest heating rates. The circumferential distributions of F_q at the edges falls above the cosine curve.
- (4) The stagnation line heat transfer decreases with the angle of attack. According to theoretical predictions this decrease should be proportional to $\cos^{1.1} \alpha$, where α is the angle of attack. The experimental data, however, falls above this theoretical prediction.

DISCUSSION

According to the thin similar boundary layer theory, the ratio of the local to the stagnation heat transfer (F_q) is insensitive to flight velocity and altitude and depends only on body geometry. Furthermore, it was found experimentally by Vidal (Reference 2) and Hickman (Reference 3) that F_q as predicted by the boundary layer theory is also applicable to the low Reynolds number flow, or to the so-called "transition flow regime."

Similar to the expected results in free flight, the experimental data presented above indicated that F_q is independent of tunnel velocity and altitude. However, since the surface characteristics of the model due to the use of the paint technique may not be the same as the bare reactor, and also the chemistry of the free stream in the tunnel is not the same as that in free flight, the direct applications of the experimental values of F_q to free flight can be justified only if the catalytic efficiency of the paint is the same as that of the bare reactor component. A brief discussion explaining this point is given below.

Calculations made by means of the Cornell code indicate that for all tunnel conditions the entire shock layer of the calibration sphere is frozen at the dissociation level of the free stream air. For these flow conditions, the stagnation heat transfer rate to the calibration sphere can be expressed as a fraction of the equilibrium boundary layer heating.

$$(1) \quad q_s = \gamma'(\phi, \alpha_s) q_{s,eq}$$

where, q_s is the stagnation heat transfer, $q_{s,eq}$ is the stagnation heat transfer rate as predicted by the equilibrium boundary layer theory, ϕ is the effective catalytic efficiency (Reference 4) and α_s is the degree of dissociation at the edge of the boundary layer. In general, it can be expected that the local heating on any arbitrary surface of the reactor will not depend on the catalytic efficiency of the surface. This is because the boundary layer returns to equilibrium at some distance away from the stagnation point due to the rapid cooling of the gas and subsequent increase in the ratio of diffusion time to atom recombination time in the boundary layer. Thus, if q_L denotes the local heating rate and $q_{L,eq}$ is the heating rate as predicted from the equilibrium boundary layer theory, the heating rate on any surface of the reactor provided it is sufficiently removed from the stagnation point is

$$(2) \quad q_L = q_{L,eq}$$

Since by definition $F_q = q_L/q_s$, combination of equations 1 and 2 yields

$$(3) \quad F_q = \frac{q_L}{q_s} = \frac{q_{L,eq}}{\Psi(\phi, \alpha_s) q_{s,eq}}$$

From the equilibrium boundary layer theory the ratio $q_{L,eq}/q_{s,eq}$ is a function of geometry only, say $f(r)$, so that F_q may be expressed by

$$(4) \quad F_q = \frac{f(r)}{\Psi(\phi, \alpha_s)}$$

Examination of the above equation leads to the conclusion that in order for the experimental values $F_{q,tunnel}$ to be the same as those in free flight, the following conditions must be fulfilled.

$$(5) \quad \Psi(\phi, \alpha_s)_{tunnel} = \Psi(\phi, \alpha_s)_{flight}$$

Since the degree of dissociation at the edge of the boundary layer at the stagnation point of the calibration sphere (α_s) is not the same in the tunnel and in free flight it is clear from equations (4) and (5) that even if the value of ϕ for the paint is the same as for the bare reactor the experimental value of F_q will differ from those of free flight. If, however, $\phi = 1$ (fully catalytic surface) for both the paint and the bare reactor then the degree of dissociation at the stagnation point has no effect on the heat transfer and the experimental values of F_q will be the same as those in free flight.

SUMMARY

Heating distributions have been obtained for the SNAP 10A reactor by means of a thermal paint technique in the Rhodes and Eloxsom 60 in. hypersonic wind tunnel. Data and correlations are presented only for those reactor components where the ratio of the local heat transfer to that on the stagnation point of the calibration sphere was found to be independent of tunnel conditions. It is shown that these heating

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distributions can be applied directly to reentry conditions provided the thermally painted and the bare reactor surfaces are both catalytic to atom recombination.

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3. Hickman, R. S. and Giedt, W. H., "Heat Transfer to a Hemisphere Cylinder at Low Reynolds Number," AIAA J, Vol. 1, No. 3, pp 665-672, March 1963
4. Hopenfeld, J., "Methods for Calculating Heat Transfer Rates Along a SNAP 10A Reentry Trajectory," NAA-SR-TDR-10698

FIGURE 1 - NAK PIPE HEATING RATIOS - (STATION A)

FIGURE 2 - NAK PIPE HEATING RATIOS - (STATION B)

FIGURE 3 - NAK PIPE HEATING RATIOS - (STATION C)

FIGURE 4 - NAK PIPE HEATING RATIOS - (STATION D)

FIGURE 5 - NAK PIPE HEATING RATIOS - (STATION E)

FIGURE 7 - THERMAL SWITCH HEATING RATIOS (STA.C)

FIGURE 6-THERMAL SWITCH HEATING RATIOS (STA.A,B)

(CLOCAL HEATING)/(STAG. HEATING ON 1 FT R SPHERE) F(Q)

FIGURE 9
 FIN HEATING RATIOS
 LEADING EDGE

1-25-65 RT

FIGURE 10
FIN LEADING EDGE (FINS I-IV)
HEATING RATIOS

1-25-65 RT

FIGURE II
VESSEL LIP HEATING RATIOS

FIGURE 12
VESSEL WALL HEATING RATIO
6 INCHES FROM VESSEL LIP
 $\alpha = 30^\circ B$

FIGURE 13
VESSEL WALL HEATING RATIOS
6 INCHES FROM VESSEL LIP
 $\alpha = 90^\circ B$

FIGURE 14
VESSEL WALL HEATING RATIOS
6 INCHES FROM VESSEL LIP
 $\alpha = 30^\circ A, 60^\circ A, 90^\circ A$

HEATING RATIO, $F_w = \frac{q_w}{q_{cs}}$

O RUN I-5B $\alpha = 30^\circ$
A RUN I-6C $\alpha = 60^\circ$
H RUN I-6B $\alpha = 90^\circ$

4.0

3.2

2.4

1.6

0.8

0.4

20

30

40

50

60

70

80

90

ANGLE (DEG)

MEASURED FROM PLANE OF NAK PIPE

12-25-64-27

FIGURE 15 - MAGNETIC COLLAR HEATING RATIOS

FIGURE 16

FUEL ROD HEATING RATIOS
CENTER OF FUEL ROD
ON STAGNATION LINE

FIGURE 17

FUEL ROD HEATING RATIOS
CENTER OF FUEL ROD
0° ANGLE OF ATTACK

1-29-65 90

FIGURE 1B

FUEL ROD HEATING RATIOS
EDGE OF FUEL ROD
0° ANGLE OF ATTACK

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CHECKED BY:		NAA-SR-TDR-10967
DATE: 1-25-65	FIGURE 19, REACTOR TOP VIEW	REPORT NO.
		MODEL NO.

FIN DESIGNATION

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DATE: 1-26-65	FIGURE 20, FOLDOUT DRAWING	MODEL NO.

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FIGURE 21, EIGHTH DRAWING

MODEL NO.

TRANSVERSE NAK PIPE

STATION

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DATE: <i>1-29-65</i>	FIGURE 22, FOLDOUT DRAWING	MODEL NO.

MAGNETIC COLLAR