MASTER

SNAP 8 CONFIGURATION REENTRY
HYPERSONIC HEATING RATES DERIVED
FROM A SHOCK TUNNEL TEST

AEC Research and Development Report

ATOMICS INTERNATIONAL

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By
D. K. NELSON

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ABSTRACT

Reentry aerodynamic heating distributions for the SNAP 8 configuration have been obtained based on hypersonic shock tunnel experiments. The heat-transfer correlations are given as a function of angle of attack from 0 to 70 degrees. The perturbative effect of piping on the flow field, and consequently the heat-transfer distributions, was also investigated at the 30- and 60-degree angle-of-attack positions.

Test objectives and the criteria upon which the experimental work was based are given along with a description of the Cornell 48-in. Hypersonic Shock Tunnel, test model, and heat-transfer instrumentation. The heat-transfer data has been normalized by the stagnation point value of a hemisphere with the reactor vessel radius. This heat-transfer rate ($29.05 \text{ Btu/ft}^2\text{-sec}$) was obtained experimentally in the shock tunnel and verified by theory. In addition to the data point values of the sensors in tabular form, schematics of the heat-transfer rates on the reactor-piping complex are given for cases where flow emanates from 0, 30, and 60 degrees from the SNAP 8 system centerline. Finally, aerodynamic heat-transfer rates are shown as functions of angle of attack for locations on the system piping, vessel head, and reactor vessel.

I. INTRODUCTION

Aerospace Nuclear Safety Program studies concerning the reentry of reactor systems depend upon the interrelated relationships of flight dynamics and aerodynamic heating. Definition of the aerodynamic heating distribution on a SNAP reactor configuration defies accurate theoretical definition due to the complex reactor system geometry. Accurate flow definition, with the corresponding heat transfer, is a particular problem due to the perturbations (primarily separations and reattachments) that develop in the piping, vessel head, and geometrically blunt radiation shield. In addition, these effects are a strong function of the spatial position of the system with reference to free stream flow. Aeroheating results are given for the SNAP 8 nominal reentry configuration where the reflectors have been ejected in orbit before reentry. The aeroheating distributions are presented for twelve system positions with respect to the hypersonic air flow in the range from 0 to 70° angle of attack.

II. TEST OBJECTIVES AND REQUIREMENTS

A. FACILITY DESCRIPTION

Since the objective of the test was to obtain aerodynamic heating rate distributions about the SNAP 8 reactor configuration in the attitude range expected for reentry in hypersonic continuum flow, facility selection was based on the following criteria: The flow properties must have the correct enthalpy level and unit Reynolds number to produce a flow field about the model with shock wave displacement, separation, reattachment, and heat-transfer distribution corresponding to actual hypersonic flight condition. In addition, the uniform core of the flow field must be large enough to accommodate a model of the scale selected. Based on these requirements, the Cornell Aeronautical Laboratory (CAL) 48-in. Hypersonic Shock Tunnel was selected for determining the aerodynamic heating distribution on the SNAP 8 configuration (see Figure 1).

The basic shock tunnel components are the shock tube, expansion nozzle, and model support and instrumentation systems. The shock tube is separated into regions of high (driver gas) and low (driven test air) pressure by a set of diaphragms; the pressure and temperature ratios dictate the flow conditions and must be set to give a tailored interface for the driver-to-driven gases. The downstream end of the shock tube is terminated by a convergent-divergent nozzle where the area ratio of the nozzle throat to shock tube cross-section is small. This has the effect of almost completely reflecting the primary shock wave upstream from the throat, leaving a region of almost stagnant, compressed, and heated air at the end of the low-pressure section of the shock tube. This processed air is then expanded through the nozzle to the desired hypersonic conditions.

B. MODEL DESCRIPTION

The aeroheating model design was based on criteria set to satisfy the test objectives. Therefore, the model configuration was selected to be representative of a reactor system at reentry into the upper atmosphere of the earth after a space mission. The aeroheating test model comprised of components representing the SNAP 8 reactor, radiation shield, and system piping is shown in Figure 2, with heat-transfer sensor locations identified. The model tunnel

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Figure 1. Basic Components of the Hypersonic Shock Tunnel Used in the Aeroheating Test

support system was designed so that the model could be oriented at any desired combination of angle-of-attack and roll from 0 through 90 and 360°, respectively. This freedom of positioning allowed the measurement of aerodynamic heat-transfer rates where flow perturbation, due to piping over the basic body configuration, ranged from negligible to maximum.

The aeroheating model shown in Figure 3, was a one-fifth scale of the actual system. It was small enough to be accepted by the CAL Shock Tunnel and large enough to house the 44 heat-transfer gages installed on the model. The placement of heat-transfer gages on the model was made with a concentration on the reactor vessel section. This resulted in a distribution of 8, 25, and 11 heat-transfer sensors on the piping, reactor vessel, and radiation shield, respectively. Heat-transfer gage locations are shown on Figure 2, and the physical dimensions are given in Table 1.

C. FLOW CONDITIONS

The flow conditions were based on criteria established to provide heat-transfer data in the reentry hypersonic continuum flow regime. To be more specific, the flow must correspond to the environment that would be experienced by a SNAP configuration (Figures 2 and 3) during the aerodynamic heating phases of continuum flow. These flight conditions are represented by high altitude and velocity well before the maximum heating point in the reentry trajectory is reached. With these criteria in mind, the test conditions were set at a unit Reynolds number of 35,000, corresponding to a simulated altitude of 250,000 ft for a one-fifth scale model and a free-stream Mach number of 18.4 for flow field similitude.

D. HEAT FLUX GAGE

The heat-transfer measurements were accomplished by use of the thin-film heat-transfer gages described in References 1 and 2. These devices were inserted, or integrally fabricated, into the model at specified locations. Typical sensor placement and orientation in the model can be seen in Figure 4, where the portion of the model representing the reactor vessel and piping is shown. During the test interval of just under 4 msec, each of the sensors measured the temporal variations in local surface temperatures. This limited test time

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Figure 3. Aeroheating Test Model Installed in Tunnel
(angle of attack = 30°)

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TABLE 1
HEAT-TRANSFER SENSOR LOCATIONS

Heat-Transfer Gage Identification	Gage Station on Model (1/5-Scale Model, Figure 2)	Reference Location (x/r); x = axial length, r = reactor vessel radius	Sensor Reference Angle; Clockwise from Top Front	Remarks
HT-1	-2.816	-2.988	0.0	Parallel to flow ↓
HT-2	-2.476	-2.627	180.0	
HT-3	-1.384	-1.468	180.0	
HT-4	-1.200	-1.273	180.0	
HT-5	0.400	0.424	0.0	Normal to flow ↓
HT-6	1.200	1.273	90.0	
HT-7	2.000	2.122	180.0	
HT-8	-1.000	-1.061	180.0	
HT-9	-0.900	-0.955	0.0	Parallel Normal ↓
HT-10	-0.900	-0.955	90.0	
HT-11	-0.800	-0.849	180.0	
HT-12	-0.350	-0.371	45.0	
HT-13	-0.350	-0.371	135.0	Parallel to flow ↓
HT-14	-0.075	-0.080	135.0	
HT-15	-0.075	-0.080	180.0	
HT-16	0.200	0.212	135.0	
HT-17	0.400	0.424	180.0	Parallel to flow ↓
HT-18	0.800	0.849	45.0	
HT-19	0.800	0.849	112.5	
HT-20	1.200	1.273	135.0	
HT-21	1.600	1.700	67.5	Normal to flow ↓
HT-22	1.600	1.700	157.5	
HT-23	2.000	2.122	0.0	
HT-24	2.000	2.122	90.0	
HT-25	2.000	2.122	180.0	Parallel to flow ↓
HT-26	2.400	2.546	120.0	
HT-27	2.800	2.971	22.5	
HT-28	2.800	2.971	150.0	
HT-29	3.200	3.395	135.0	Normal to flow ↓
HT-30	3.754	3.983	180.0	
HT-31	3.898	4.136	135.0	
HT-32	4.042	4.288	180.0	
HT-33	4.464	4.736	180.0	Parallel to flow ↓
HT-34	4.686	4.972	150.0	
HT-35	4.908	5.207	120.0	
HT-36	5.687	6.034	112.5	
HT-37	5.687	6.034	180.0	Normal to flow ↓
HT-38	6.803	7.218	135.0	
HT-39	7.919	8.402	157.5	
HT-40	9.035	9.586	112.5	
HT-41	9.035	9.586	180.0	Parallel to flow ↓
HT-42	10.151	10.770	90.0	
HT-43	11.310	12.000	180.0	
HT-44	4.430	4.700	0.0

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Figure 4. Thin-Film Thermometers on the
Aeroheating Model

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requires an extremely fast response and dictates the use of the thin-film heat-transfer gage. This instrument is represented by a one-dimensional finite thickness of platinum mounted on the dissimilar semi-infinite Pyrex material. The platinum acts as the temperature sensor, while the Pyrex body provides the required mechanical support for the sensor and the thermal heat sink.

In essence, the thin-film heat-transfer gage senses the transient surface temperature variations of a substrate material characterized as semi-infinite, homogeneous, and isotropic. This history of surface temperature change with time, combined with a knowledge of the gage thermal and electrical properties, provides the necessary information to calculate heat-transfer rates. The primary effect on the accuracy of the heat-transfer data depends on the accuracy to which the gage properties are known. Gage calibration represents the key to the high accuracy inherent in the measured values of surface temperatures by this type of sensor. The basic calibration of thin-film thermometers consists of determining the temperature coefficients of resistance for the platinum film and the thermal properties of the Pyrex mounting material. The technique developed by Skinner^{(3)*} was used to determine the value of the thermal quantity $(\rho c k)^{1/2}$ for the substrate material, while eliminating the calibration inaccuracies of sensor dimension uncertainties. The basis for this technique is that when an instrument is electrically calibrated in a thermally conducting fluid, the heat transfer will divide between the fluid and the mounting material. Therefore, the gage sensor (platinum thin-film) dimensions can be removed from the problem, provided that identical calibration is made in a fluid with known thermal properties (distilled water) and in air, where sensibly all heat is absorbed by the Pyrex mounting material.

Local aerodynamic heating rates at each gage position on the model (Figure 2) were calculated by the methods described in Reference 1 for a semi-infinite, homogeneous, and isotropic slab of known thermal properties with specified surface temperature-time relationships.

*Superscript numbers in parentheses refer to References at back of this report.

III. TEST DATA AND CORRELATIONS

A. HEMISPHERICAL HEAD CALIBRATION RUN

Heat-transfer data were acquired at a 0° angle-of-attack position with a hemispherical head on the reactor vessel in place of the dome head and piping. The hemispherical head was equipped with heat-transfer sensors at body angles of $0, 30, 45, 60,$ and 90° (Figure 2). These data were obtained to substantiate the predicted theoretical aerodynamic heat-transfer rates based on tunnel air flow conditions and to establish an experimental base line for the series of tests. The stagnation point heat-transfer data derived from the hemisphere model exhibited excellent agreement with those predicted by the Fay and Riddell⁽⁴⁾ correlation. These values are $29.05 \text{ Btu/ft}^2\text{-sec}$ and $28.75 \text{ Btu/ft}^2\text{-sec}$, respectively. In addition, the ratio of local-to-stagnation heat-transfer rates ($\dot{q}_w/\dot{q}_0$) on the hemispherical nose are compared in Figure 5 to the theoretical distribution developed by Lees.⁽⁵⁾ Further validity of the results are expressed by the very good agreement between the accepted theory of Lees and the test data for the laminar heat-transfer distribution over an isothermal hemispherical nose.

Figure 5. Heat-Transfer Distribution Around a Hemisphere

B. SNAP 8 CONFIGURATION RESULTS

Heat-transfer data were acquired from the sensor locations noted on Figure 2 and Table 1. A series of 12 heat-transfer acquisition runs was made for the SNAP 8 configuration. These test runs were performed in 10° angle-of-attack steps from 0 to 70° with the piping in the shadow of the flow (zero roll), and for piping spatial roll positions of 90 and 180° at 30 and 60° angles of attack. All aerodynamic heat-transfer data obtained from the test⁽⁶⁾ have been normalized by the calibration hemispherical stagnation point value ($29.05 \text{ Btu/ft}^2\text{-sec}$). The ratios of local-to-stagnation point heat-transfer values are given in Table 2 for the 0 to 70°

TABLE 2
HEAT-TRANSFER RATE DISTRIBUTIONS OVER THE SNAP 8
CONFIGURATION PIPING IN AFT POSITION WITH RESPECT TO FLOW
(Roll = 0°)
(Sheet 1 of 2)

Heat- Transfer Gage Identifi- cation	Local Heat-Transfer Rate to Hemisphere Stagnation Point Rate ($\dot{q}_l/\dot{q}_o$) Angle-of-Attack (°)							
	0	10	20	30	40	50	60	70
HT-1	1.671	1.426	1.295	1.033	0.7792	0.4981	0.3285	0.1989
HT-2	0.848	1.062	1.265	1.397	1.4349	1.3679	1.2256	1.1086
HT-3	0.096	0.2480	0.4409	0.7593	1.2222	0.9283	0.9364	1.0502
HT-4	0.021	0.0680	0.1382	0.1740	0.1569	0.1872	0.3394	0.2849
HT-5	0.034	0.1054	0.0380	0.0093	0.0043	0.0028	-	0.0208
HT-6	-	0.2908	0.3810	0.0703	0.0501	0.0483	0.0416	0.0289
HT-7	0.053	0.0123	0.0498	0.0562	0.0348	0.0223	0.0131	0.0354
HT-8	-	-	1.143	0.8845	0.5486	0.7051	0.6741	0.6201
HT-9	0.028	0.0342	0.0407	0.0511	0.0535	0.0440	0.0342	0.0246
HT-10	-	-	-	0.6838	0.2893	0.2584	0.2057	0.1778
HT-11	-	-	-	0.5556	0.7590	0.7665	0.7347	0.7064
HT-12	0.080	0.0656	0.0591	0.0125	0.0132	0.0116	0.0101	0.0138
HT-13	0.070	0.0973	0.1262	0.1912	0.2694	0.3337	0.3897	0.4423
HT-14	0.082	0.0673	0.1191	0.2106	0.2526	0.3303	0.3749	0.4247
HT-15	0.086	0.0967	0.1630	0.2716	0.4175	0.6066	0.6595	0.7739
HT-16	0.0783	0.0793	0.1096	0.1588	0.2238	0.3116	0.3498	0.3926
HT-17	0.0783	0.1182	0.1328	0.2296	0.3842	0.5250	0.5665	0.6542
HT-18	0.0400	0.0871	0.0200	0.0157	0.0172	0.0139	0.0137	0.0154
HT-19	0.0615	0.0934	0.0611	0.0838	0.1058	0.1359	0.1473	0.1756
HT-20	0.0746	0.1246	0.0652	0.1398	0.2215	0.2626	0.2868	0.3552
HT-21	0.0346	0.0262	-	0.0230	0.0194	0.0181	0.0217	0.0347
HT-22	0.0723	0.1472	0.1391	0.2148	0.3263	0.3893	0.4839	0.5155

TABLE 2

HEAT-TRANSFER RATE DISTRIBUTIONS OVER THE SNAP 8
 CONFIGURATION PIPING IN AFT POSITION WITH RESPECT TO FLOW
 (Roll = 0°)
 (Sheet 2 of 2)

Heat- Transfer Gage Identifi- cation	Local Heat-Transfer Rate to Hemisphere Stagnation Point Rate ($\dot{q}_l/\dot{q}_o$) Angle-of-Attack (°)							
	0	10	20	30	40	50	60	70
HT-23	0.0187	-	0.0886	0.0291	0.0198	0.0125	0.0114	0.0209
HT-24	0.0351	0.0379	-	0.0377	0.0439	0.0522	0.0797	0.0892
HT-25	0.0453	0.1451	0.1929	0.2590	0.3716	0.4316	0.5900	0.5408
HT-26	0.0483	0.0683	-	0.0990	0.1390	0.1837	0.2570	0.1681
HT-27	0.0237	0.0737	0.0460	0.0279	0.0062	0.0067	0.0087	0.0101
HT-28	0.0544	0.0737	-	0.2134	0.3021	0.5188	0.3841	0.4642
HT-29	0.0552	0.1263	0.0457	0.1457	-	0.3968	0.1953	0.5604
HT-30	0.0475	-	0.2655	0.4237	0.1456	-	0.6531	-
HT-31	0.0438	-	0.5640	0.4475	0.1694	0.3169	0.4711	0.8997
HT-32	0.0385	-	-	0.1706	0.4215	0.4026	-	0.8477
HT-33	0.0350	0.1400	-	0.6260	0.3971	0.2925	0.3283	0.2895
HT-34	0.0347	-	0.4954	0.3789	0.2781	0.2943	0.3013	0.1254
HT-35	0.1760	-	0.3784	0.2591	0.2567	0.2494	0.2456	0.0819
HT-36	0.1293	0.0135	0.2769	0.0614	-	0.1352	0.1458	0.1215
HT-37	0.1332	0.0337	0.1124	0.2237	0.3640	0.4244	0.4531	0.4578
HT-38	0.0731	0.0374	0.0932	0.1328	0.1746	0.2023	0.2011	0.2095
HT-39	0.0458	0.1022	0.1069	0.1733	0.2451	0.2600	0.2799	0.3143
HT-40	0.0384	0.0474	0.0612	0.0684	0.0848	0.0922	0.0907	0.0940
HT-41	0.0451	0.0954	0.1106	0.1958	0.2725	0.2857	0.3112	0.3361
HT-42	0.0433	0.0290	0.0561	0.0359	0.0351	0.0387	0.0369	0.0343
HT-43	0.0251	0.0442	0.0818	0.1348	0.1782	0.2150	0.2693	0.3417
HT-44	0.068	0.0836	0.1189	0.0480	0.0462	-	0.0360	0.0264

angle-of-attack cases where the system piping is directly aft of the model stagnation point or line (zero-roll angle). Heat-transfer distributions on the system as a result of flow perturbations due to the piping are given in Table 3. The missing data in Tables 2 and 3 are due to off-scale output (both high and low theoretical predictions) and gage malfunctions. Data acquisition was accomplished at the very high rate of 92% of the total possible heat-transfer data output.

In addition to the tabular form, heat-transfer data are presented in a schematic distributional form on the reactor vessel and piping. These are given for flow impinging on the model at 0, 30, and 60° in Figures 6, 7, and 8, respectively. These heat-transfer distributions on the SNAP 8 configuration represent overall equilibrium conditions at the selected static orientations to the airflow. Moving one step further to an actual reentry case, the dynamic flight conditions where the spatial position of the system is continually changing must be considered. Hence, the effect of varying the angle of attack on the heat-transfer rates is demonstrated in Figures 9 through 11. The rates derived from sensors on the piping, upper vessel and head, and the vessel are given in these figures.

In general, all heat-transfer trends are substantiated by theory. Examples and an explanation of some of the flow phenomena are given in the following paragraphs. The heat-transfer on the forward areas of the piping (Sensors 1 and 2 in Figure 9) exhibit smooth correlations where the shock wave lies closely over the body; however, other portions of the piping show the effects of a changing secondary flow field. This can be seen on the piping segment just above the head (Sensor 3 in Figure 9) where heat transfer is influenced by the vessel head at high angles of attack. This correlation discontinuity between 40 and 50° angle of attack is a result of the increased shock standoff distance at this location at high angles of attack. Evidence of this phenomenon is seen in the Schlieren photograph (point A in Figure 12) taken at 50° angle of attack. Heating to the piping parallel to the reactor vessel is also directly influenced by the flow field. The effect of the flow changing from over the head to around the vessel is demonstrated by the discontinuity (Figure 9) in the heat-transfer correlation at the location of Sensor 6 at an angle between 20 and 30° to the airflow. The two-dimensional flow field occurs in Region B of Figure 12.

TABLE 3
HEAT-TRANSFER RATE DISTRIBUTIONS OVER THE SNAP 8
CONFIGURATION PIPING IN SIDE AND FORWARD
POSITIONS WITH RESPECT TO FLOW
(Sheet 1 of 2)

Heat-Transfer Gage Identification	$\alpha^* = 30^\circ$ Roll = 90°	$\alpha^* = 30^\circ$ Roll = 180°	$\alpha^* = 60^\circ$ Roll = 90°	$\alpha^* = 60^\circ$ Roll = 180°
HT-1	1.1092	1.1554	0.4520	0.4188
HT-2	-	0.2072	0.3515	0.0489
HT-3	0.1385	0.0242	0.1963	0.0300
HT-4	0.1097	0.0926	0.1623	0.0778
HT-5	0.0771	0.4573	0.1422	0.9764
HT-6	0.7275	0.1797	1.1840	0.2621
HT-7	0.1694	0.0963	-	0.1041
HT-8	1.5448	-	0.2525	0.0178
HT-9	1.5321	-	0.1855	0.0084
HT-10	0.6661	-	0.6712	0.1219
HT-11	0.4313	0.0315	0.1903	0.0146
HT-12	-	-	0.4098	0.1808
HT-13	0.1820	0.0415	0.4205	0.0105
HT-14	0.1645	-	0.3752	0.0074
HT-15	0.0575	0.0460	0.0680	0.0106
HT-16	0.1526	0.0246	0.3410	0.0092
HT-17	0.0481	0.0263	0.0599	0.0103
HT-18	0.1364	0.0742	0.3328	0.2151
HT-19	-	0.0389	0.4980	0.0212
HT-20	0.1366	0.0310	0.3224	0.0582
HT-21	0.2067	0.0732	0.5329	0.1680
HT-22	0.0756	0.0143	0.1946	0.0411

*Angle-of-Attack

TABLE 3
HEAT-TRANSFER RATE DISTRIBUTIONS OVER THE SNAP 8
CONFIGURATION PIPING IN SIDE AND FORWARD
POSITIONS WITH RESPECT TO FLOW
(Sheet 2 of 2)

Heat-Transfer Gage Identification	$\alpha^* = 30^\circ$ Roll = 90°	$\alpha^* = 30^\circ$ Roll = 180°	$\alpha^* = 60^\circ$ Roll = 90°	$\alpha^* = 60^\circ$ Roll = 180°
HT-23	0.0783	0.0767	0.2103	0.0231
HT-24	0.2474	0.0560	0.5573	0.0659
HT-25	0.0358	0.0182	0.0982	0.0086
HT-26	0.2147	0.0380	0.4184	0.0248
HT-27	0.0628	0.0135	-	0.2175
HT-28	0.0954	0.0075	0.2174	0.0090
HT-29	0.1863	0.0182	0.2362	0.0068
HT-30	0.1310	0.0481	0.1135	0.0079
HT-31	0.2706	0.0169	0.4513	0.0168
HT-32	0.1214	0.0393	0.0938	0.0053
HT-33	0.4839	0.0640	0.1237	0.0143
HT-34	0.3684	0.0176	0.2269	0.0435
HT-35	0.2417	-	0.2914	0.1081
HT-36	0.1746	0.0143	0.3972	0.0131
HT-37	0.0308	0.0393	0.0624	0.0035
HT-38	0.1201	0.0116	0.2038	0.0058
HT-39	0.0720	0.0131	0.0930	0.0024
HT-40	0.1668	0.0252	0.2708	0.0111
HT-41	0.0384	0.0251	0.0356	0.0022
HT-42	0.1852	0.0424	0.3194	0.0363
HT-43	0.0235	0.0140	0.0292	0.0063
HT-44	-	0.9438	0.2854	0.7142

*Angle-of-Attack

Data key:

Heat transfer gage number (dimensions in Table 1)

10-28-66 UNC

7700-2510

Figure 6. Aerodynamic Heat-Transfer Distributions on SNAP 8 Configuration at 0° Angle of Attack

Data key:

Heat transfer gage number (dimensions in Table 1)

Figure 7. Aerodynamic Heat-Transfer Distributions on SNAP 8 Configuration at 30° Angle of Attack

Data key:

Heat transfer gage number (dimensions in Table 1)

10-28-66 UNC

7700-2512

Figure 8. Aerodynamic Heat-Transfer Distributions on SNAP 8 Configuration at 60° Angle of Attack

Figure 9. Aerodynamic Heat-Transfer Distributions on SNAP 8 Configuration Piping

Figure 10. Aerodynamic Heat-Transfer Distributions on SNAP 8 Configuration Upper Vessel and Head

Figure 11. Aerodynamic Heat-Transfer Distributions on SNAP 8 Configuration Vessel

Figure 12. Schlieren Photograph of Typical Flow Field Over Aeroheating Model

For the most part, the local heat-transfer distributions on the reactor head and vessel exhibit smooth correlations with angle of attack. Selected heat-transfer gage locations are presented in Figures 10 and 11. The major flow separation influencing these data occurs at the low angles of attack where the forward piping and relatively blunt vessel head separates the flow from the vessel sides. The expected trend of higher heat-transfer rates with increasing angle of attack can be seen for all data in this area of the system. This is the result of each local body segment being translated to a position approaching normal with respect to free stream flow with increasing angle of attack. A very minor perturbation to the flow is seen to result from the rib between the reactor vessel and head. The flow separates at the rib with a corresponding decrease in heat transfer at, and directly aft of, the rib. These data are given by heat-transfer Gages 13, 14, and 16 (Figure 10), respectively. The effect of the blunt shield has a pronounced effect on the flow field in the vicinity of the reactor vessel. This can be seen graphically in Figure 12 at Point C where the shock wave generated by the shield stands off by approximately 40% of the vessel length at 50° angle of attack.

Heat-transfer correlations of the experimental data obtained from the cylindrical reactor vessel section were constructed for comparison with existing theory. The test was conducted at a nominal Reynolds number per foot of 34,000 to place the test in the hypersonic compressible boundary layer regime. However, this test point is also at the edge of rarefied hypersonic flow where the initial aerodynamic heating takes place in an actual reentry trajectory. Therefore, the heat-transfer correlations were generated to encompass both of these areas of application. The cylindrical stagnation streamline heat-transfer data are shown in Figure 13 as a function of rarefaction parameter defined by the following expression:

$$K_{\Lambda}^2 = \frac{\epsilon \rho_{\infty} U_{\infty} r}{\mu_o} \sec \Lambda$$

where Λ is the angle of yaw. The Stanton number, C_H , was used to define the coefficients of heat transfer and has the standard form shown below:

$$C_H = \frac{q}{\rho_{\infty} U_{\infty} (H_{\infty} - H_w)}$$

Figure 13. Comparison of Theory and Experiment for Stagnation Line Heat-Transfer to Yawed Cylindrical Reactor Section

Heat-transfer data derived from sensors 17 and 25 are presented in Figure 13 and exhibit very good agreement with the compressible boundary-layer solution

$$C_H = (0.512) \frac{(3.0 \epsilon)^{1/4}}{k}$$

from Cohen and Reshotko.⁽⁷⁾ The viscous layer theory of Cheng and Chang⁽⁸⁾ is included on Figure 13 for cylinder yaw angles of 0 and 45° to demonstrate the applicability of the heat-transfer correlations in this regime.

The theoretical comparisons were carried one step further to circumferential heat-transfer distribution on a cylindrical body. The local-to-stagnation stream-line heat-transfer ratios taken from test data obtained at 70° angle of attack are presented in Figure 14. The theoretical laminary boundary layer solution of Beckwith⁽⁹⁾ and an empirical extension to large body angles obtained from hypersonic test data⁽¹⁰⁾ are shown in Figure 14 for comparison purposes. The agreement between the Aeroheating data and the theoretical curve with empirical extension is exceedingly good considering the perturbing effects involved. These include the short length of the cylindrical section, end effects, a large aft body, and the use of 70° angle of attack data where the s/r distance is 3.2% larger than for the correlations.

Figure 14. Circumferential Heat Transfer on Cylindrical Reactor Section

IV. CONCLUSIONS

The heat-transfer data derived from the Aeroheating test provides a relatively complete heat-transfer distribution over the SNAP 8 system configuration in the range of 0 to 70° angle of attack. The data have been normalized to the stagnation point value of a 1.885-in. diam sphere (reactor radius at one-fifth scale) for convenience. However, these normalized data can be converted to a 1-ft sphere reference through a multiplication factor consisting of a square root of the radii ratio. In addition, this is the method for determining the absolute heating rates to a system along a theoretical flight trajectory. For example, this heating rate takes on the following expression:

$$\dot{q}_\ell = \left(\frac{\dot{q}_\ell}{\dot{q}_o} \right) \frac{\dot{q}_o, r = 1 \text{ ft (Trajectory output)}}{\sqrt{r}}$$

The primary emphasis of the test was placed on acquisition of data free from a piping-dependent flow field. This was done on the premise that piping will undergo early ablation and not contribute significantly to the overall heating received by the vessel. However, the test runs made at 30 and 60° angle of attack with piping directly in the flow should provide sufficient data to evaluate the thermal response of the piping to reentry heating.

The aerodynamic heating distributions obtained from the test can be extended throughout the hypersonic continuum regime with confidence. However, care must be exercised when application is extended to high-altitude low-density transitional flow. This includes investigating the rarefaction parameter, and Reynolds and Knudsen numbers.

In the event that a heating investigation be undertaken for a reactor reentering free from the shield, care must be taken to use the forward end vessel heating distribution over the entire vessel. This is due to the flow field generated around the lower portion of the vessel as a result of the aerodynamically blunt shape of the shield.

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APPENDIX: NOMENCLATURE

<u>Symbol</u>	<u>Description</u>	<u>Dimension</u>
C_H	Stanton Number	-
H	Total enthalpy	Btu/lb
K_Λ^2	Rarefaction parameter	-
$\dot{q}$	Rate of energy transported to body surface	Btu/sec-ft ²
r	Nose radius	ft
Re	Reynolds number = $\rho \frac{Ux}{\mu_o}$	-
s	Distance along surface, starting at stagnation point	ft
U	Velocity	ft/sec
α	Angle of attack	°
γ	Ratio of specific heat	-
$\epsilon \equiv \frac{\gamma-1}{2\gamma}$		-
θ	Angle between direction of flight velocity and normal to local surface of body	°
Λ	Yaw angle	°
μ	Viscosity	lb-sec/ft ²
ρ	Density	slug/ft ³
Subscripts		
∞	Pertaining to free stream conditions	
o	Pertaining to stagnation conditions	
l	Pertaining to local surface condition	