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SNAP 19 Generator
Heat Distribution Test at Mach 8

RELEASED FOR ANNOUNCEMENT
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MARTIN MARIETTA

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SNAP 19 Generator Heat Distribution Test at Mach 8

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FOREWORD

This report was prepared under United States Atomic Energy Commission Contract AT(30-1)-3607 and covers Item 3(c) of the proposed experimental program for SNAP 19, dated January 1966.

For convenience, Appendices A, B and C have been put in a separate volume of this report.

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SUMMARY

The purpose of this program was to obtain heating data for three 30% scale models of the SNAP 19 generator. The three models having different fin spans (full, two-third and one-third span) were tested at the Von Karman Facility, AEDC Tunnel B under the following conditions:

$M_\infty = 7.86$; $P_0 = 70$ psia; $T_0 = 1170^\circ$ R; $q_\infty = 0.35$ psia and $Re_\infty \times 10^{-6} = 0.4 \text{ ft}^{-1}$. The one-third span model was also tested under the following conditions to determine the effects of increased Reynolds number:

$M_\infty = 7.95$; $P_0 = 300$ psia; $T_0 = 1270^\circ$ R; $q_\infty = 1.42$ psia and $Re_\infty \times 10^{-6} = 1.5 \text{ ft}^{-1}$. The models were tested at roll angles of 0 and 30 degrees over the angle of attack range of 0 to 90 degrees.

Data obtained during the test were processed and presented in the form of $\dot{q}/\dot{q}_{FR}$ versus α plots for all thermocouples of each configuration and average heating rates for each thermocouple over a 90-degree angle of attack range obtained by integration of the $\dot{q}/\dot{q}_{FR}$ versus α curves.

The data presented in this report are sufficiently comprehensive and accurate to be used in a burnup analysis of the SNAP 19 generator during re-entry. The precision of the data was demonstrated by repeat runs to be within the reported accuracy.

The results indicate that the average heating rates decreased on both the generator body and fins as the fin span decreased, i. e. , during simulated fin disintegration. It was also observed that increasing the Reynolds number tends to increase the average heating rate on both the generator body and the fins.

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SYMBOLS AND DEFINITIONS

<u>Symbol</u>	<u>Definitions</u>	<u>Units</u>
α	angle of attack	degrees
b	model skin thickness	feet
g	gravitational constant	ft/sec ²
H	air enthalpy	Btu/lb
h_H	heat transfer coefficient	$\frac{\text{Btu/ft}^2\text{-sec}}{\text{Btu/lb}}$
M	Mach number	
n	number of points used to determine repeatability	
μ	air viscosity	lb-sec/ft ²
p	pressure	psia
ϕ	roll angle	degrees
q	dynamic pressure	psia
$\dot{q}$	heat transfer rate per unit area	Btu/ft ² -sec
$\bar{q}$	integrated heat rate per unit area for α between 0 and 90°	Btu/ft ² -sec
ρ	density	slugs/ft ³
R	universal gas constant	
r	arbitrary reference length based on a one-foot sphere	feet
Re/ft	Reynolds number per foot	ft ⁻¹
St	Stanton number	
T	temperature	°R
t	time	seconds
V	velocity	ft/sec
$\frac{dV_e}{dx}$	velocity gradient along the edge	1/sec

SubscriptsDefinitions

FR	computed from Fay-Riddell theory
0	tunnel stagnation conditions
w	model wall conditions
∞	tunnel free-stream conditions

Superscripts

' (prime)	conditions aft of a normal shock
-----------	----------------------------------

I. INTRODUCTION

The SNAP 19 radioisotope fueled thermoelectric generator has been designed for use on the Nimbus B satellite. It is required to establish and confirm the safety of the system as it re-enters the atmosphere.

Calculations performed at the Martin Marietta and Sandia Corporations indicate the potential existence of aerodynamic and aerothermodynamic conditions under which the fuel particulate would not maintain integrity. This causes a downward shifting of the particle size distribution and leads to an unsatisfactory condition from the safety aspect. The potentiality of fuel size degeneration emphasizes the need for an accurate description of the aerodynamic and aerothermodynamic properties of systems and subsystems housing the fuel.

The aerodynamic burnup analysis of the SNAP 19 generator involves three configurations representing various degrees of ablation (full, two-thirds and one-third fins) which are difficult to analyze insofar as the aeroheating distributions are concerned. The available theoretical methods are usually applied to more conventional type configurations, and attempting to apply such methods to other configurations could be misleading. Therefore, experimental data are required to substantiate any theoretical analysis of aeroheating distributions on the generator.

The objective of this test was to obtain the experimental data required to perform an aeroheating analysis of the generator during re-entry. The Mach 8 heat transfer test of three 30% scale models of the SNAP 19 generator (full span, two-thirds span, one-third span fin models) was conducted at the Arnold Engineering Development Center, VKF, Tunnel B. Testing was initiated on July 11, 1966 and completed on July 16, 1966.

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II. MODEL DESCRIPTION AND INSTRUMENTATION

Three 30% scale models of the SNAP 19 generator were tested. To simulate fin ablation, each model had a different fin span as shown in Figs. 1, 2 and 3.

The models are constructed of thin-skin Inconel. The generator body wall thickness is 0.050 inch and the fins are 0.062 inch constant thickness. The chromel-alumel thermocouples, made of 28 gage wire, were welded to the skin at the locations shown in Figs. 4a through 4e.

Thermocouples 1 through 13 are positioned on the front face of the model, and Thermocouples 14 through 58 are located on the body. The remaining thermocouples are on the fins. The full span and two-thirds span models have 98 thermocouples, while the one-third span model has 78 thermocouples.

The typical installation of a thermocouple is illustrated in Fig. 5. Thermocouple wires leading to the mounting hole are fastened down as shown in the figure. The wires are passed through an insulating disk before they are twisted to ensure that the final twist occurs at the point where the desired temperature measurement is to be made. The thermocouple is inserted in a hole bored for the wires and welded in place.

The model configurations are defined as follows:

<u>Configuration No.</u>	<u>Description</u>	<u>Re/ft</u>
100	Full span model at 0° roll	0.4×10^6
130	Full span model at 30° roll	0.4×10^6
200	Two-thirds span model at 0° roll	0.4×10^6
230	Two-thirds span model at 30° roll	0.4×10^6
300	One-third span model at 0° roll	0.4×10^6
330	One-third span model at 30° roll	0.4×10^6
400	One-third span model at 0° roll	1.5×10^6
430	One-third span model at 30° roll	1.5×10^6

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III. TEST FACILITY DESCRIPTION

This test was conducted at the VKF 50-Inch Hypersonic Tunnel B (Figs. 6 and 7) at Arnold Research Development Center, Tullahoma, Tennessee. The tunnel is a continuous, variable density wind tunnel equipped with axisymmetrical contoured Mach 6 and 8 nozzles. The tunnel is served by the main VKF compressor system and utilizes a propane-fired air heater to provide stagnation temperatures up to 900° F, required to prevent liquefaction in the main airstream. The entire tunnel--throat, nozzle, test section, model support section and diffuser--is cooled by integral, external water jackets. The test section is equipped with fused quartz windows of optical quality with two viewing areas of 17.4 inches in diameter.

The facility is equipped with a Schlieren system for making photographs of the shock wave patterns around the model. Typical results can be seen in Figs. 8 through 21.

The model and support system can be retracted into the installation chamber below the test section. During heat transfer tests, the model is cooled between runs by an airstream blowing over it.

The tunnel is sealed from the installation chamber allowing the tunnel to maintain airflow while the model is being prepared for the next run.

In either the retracted or extended positions, the model support (sting) can be remotely pitched about the attachment point of the model through a range of ± 15 degrees with a straight sting, and ± 12 degrees with any of the AEDC prebent stings. The system can also be rolled ± 180 degrees about the sting support axis.

Once the model is cooled, the attitude set and the airflow established, the model is injected into the stream. The model takes approximately two seconds to reach the centerline of the tunnel.

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IV. TEST PROCEDURE

The test in the AEDC Tunnel B was conducted under the following conditions:

M_∞	$P_0(\text{psia})$	$T_0(^{\circ}\text{R})$	$q_\infty(\text{psia})$	Re/ft
7.86	70	1170	0.35	0.4×10^6
7.95	300	1270	1.42	1.5×10^6

All fin configurations were tested at the first set of tunnel conditions. In addition, the one-third fin generator model with $\phi = 0$ and 30 degrees was tested under the second set of conditions. The complete run program is presented in Table 1 (Appendix A* provides a complete list of tunnel conditions for each run).

The general procedure for performing this test, under both sets of tunnel conditions, is as follows:

- (1) The model was placed in the installation chamber at initial α (15, 45 or 75 degrees with respect to the sting) and ϕ (0 or 30 degrees) settings.
- (2) The chamber was sealed, and pressure in the chamber was reduced to the tunnel static pressure.
- (3) The model was injected into the test section and remained in the flow for five seconds.
- (4) The data recording process started approximately two seconds before the injected model reached the centerline of the tunnel.
- (5) After each five-second test run, the model was retracted into the installation chamber and cooled by blowing cold air over the model.
- (6) After cooling the model to the point where the time-temperature variations become negligible, necessary angle of attack and roll angle changes were made in preparation for the next run.

*See Volume 2.

TABLE 1
Heat Transfer Run Program

ϕ (deg)	α (deg)	Full Fin	Two-thirds Fin	One-third Fin	One-third Fin
		Re/ft = 0.4×10^6 Group No.	Re/ft = 0.4×10^6 Group No.	Re/ft = 0.4×10^6 Group No.	Re/ft = 1.5×10^6 Group No.
0 ↑	0	27, 28	82	130	156, 163
	5	26	81	129	157
	10	25, 29	80	128	158
	15	24	79, 83	127, 131	159, 164
	20	23, 30	78	126	160
	25	22	77	125	161
	30	18, 21	74, 76	122, 124	162, 165
	35	17	73	121	166
	40	16, 19	72	120	167
	45	15	71, 75	119, 123	168, 172
	50	14, 20	70	118	169
	55	13	69	117	170
	60	8, 12	66, 68	114, 116	171, 173
	65	7	65	113	174
	70	6, 11	64	112	175
	75	5	63, 67	111, 115	176, 180
	80	4, 10	62	110	177
	85	3	61	109	178
0 ↓	90	1, 2, 9	60	108	179
30 ↑	0	31, 40	84	132	181
	5	32	85	133	182
	10	33, 39	86	134	183
	15	34	87, 91	135, 139	184, 188
	20	35, 38	88	136	185
	25	36	89	137	186
	30	37, 41	90, 92	138, 140	187
	35	42	93	141	--
	40	43, 49	94	142	--
	45	44	95, 99	143, 147	--
	50	45, 48	96	144	--
	55	46	97	145	--
	60	47, 50	98, 100	146, 148	189
	65	51	101	149	190
	70	52, 59	102	150	191
	75	53	103, 107	151, 155	192
	80	54, 58	104	152	193
	85	55	105	153	194
30 ↓	90	56, 57	106	154	195

V. DATA PRESENTATION

Data were recorded at the AEDC Tunnel B facility in the form of temperature-time histories for each model configuration tested. Temperature values measured with the model thermocouples were recorded on magnetic tape and processed at the facility. During the data processing at the facility, the temperature-time histories were converted by digital computer program to useful parameters. The following describes the methods and equations used in the AEDC data processing.

For each thermocouple, at each data reduction time, T_w in $^{\circ}\text{R}$ and dT_w/dt in $^{\circ}\text{R}/\text{sec}$, were computed from the center of a least-squares parabola through 21 consecutive wall temperature points. Using the dT_w/dt computed at each reduction time, the following equation yields $\dot{q}$:

$$\dot{q} = wbc \frac{dT_w}{dt} (\text{Btu}/\text{ft}^2\text{-sec}) \quad (1)$$

where:

w , density of model material = $526 \text{ lb}/\text{ft}^3$ (Ref. 5)

b , model skin thickness = (ft)

c , constant specific heat of model material
(Inconel 600) = $0.113 \text{ Btu}/\text{lb-}^{\circ}\text{R}$ (Ref. 5)

Using $\dot{q}$ from Eq (1), the enthalpy, heat transfer coefficient and Stanton number are determined by the standard heat transfer equation used at AEDC (Ref. 6) as follows:

$$H_w = 4.875 + 0.2235 T_w + 0.0000135 T_w^2 \text{ Btu}/\text{lb} \quad (2)$$

$$H_0 = 4.875 + 0.2235 T_0 + 0.0000135 T_0^2 \text{ Btu}/\text{lb} \quad (3)$$

Now:

$$h_H = \frac{\dot{q}}{H_0 - H_w} \frac{\text{Btu}/\text{ft}^2\text{-sec}}{\text{Btu}/\text{lb}} \quad (4)$$

$$T_{\infty} = \frac{T_0}{1 + \frac{\gamma-1}{2} M_{\infty}^2} = \frac{T_0}{(1 + 0.2 M_{\infty}^2)} \quad ^{\circ}\text{R} \quad (5)$$

$$p_{\infty} = \frac{p_0}{(1 + \frac{\gamma-1}{2} M_{\infty}^2)^{3.5}} = \frac{p_0}{(1 + 0.2 M_{\infty}^2)^{3.5}} \quad \text{psia} \quad (6)$$

Using Eqs 5 and 6, solve for ρ_{∞} and V_{∞} :

$$V_{\infty} = 49 M_{\infty} (T_{\infty})^{1/2} \quad \text{fps} \quad (7)$$

$$\rho_{\infty} = 0.0839 p_{\infty} (T_{\infty})^{-1} \quad \text{slugs/ft}^3 \quad (8)$$

The Stanton number can be evaluated:

$$ST = \frac{h_H}{\rho_{\infty} V_{\infty}} \quad \frac{1}{g} \quad (9)$$

where:

$$g = 32.17 \text{ ft/sec}^2$$

The parameter, St/St_{FR} , is also computed. In order to perform this calculation, St_{FR} must first be evaluated. To find ST_{FR} , the Stanton number based on the Fay-Riddell heat transfer equation, μ'_0 and p'_0 (where the prime indicates conditions aft of a normal shock) must be evaluated:

$$\mu'_0 = 2.270 T_0'^{1.5} (T_0' + 198.6)^{-1} \times 10^{-8} \text{ lb-sec/ft}^2 \quad (10)$$

$$p'_0 = p_0 \left(\frac{6M_{\infty}^2}{M_{\infty}^2 + 5} \right)^{3.5} \left(\frac{6}{7M_{\infty}^2 - 1} \right)^{2.5} \text{ psia} \quad (11)$$

Equations (10) and (11) are easily solved since p_0 , T_0 and M_{∞} are known from tunnel operating conditions and $T_0 = T_0'$. Now compute ST_{FR} :

$$St_{FR} = \frac{0.254}{\rho_{\infty} V_{\infty} r^{0.5}} \frac{\mu_0'^{0.4}}{T_0^{0.15}} (p_0')^{0.5} \quad (12)$$

where:

r , arbitrary reference length based on a one-foot sphere equals one foot.

The data obtained from the AEDC facility computation is presented in Table 2.

A digital computer program was developed at the Martin Marietta Corporation using the data from AEDC, Table 2, to compute $\dot{q}/\dot{q}_{FR}$ and to correct the data for conduction effects.

The data in this report are presented in tabulated and graphical form. The plotted data describes the variation of $\dot{q}/\dot{q}_{FR}$ with angle of attack for the different fin lengths and roll angles under consideration. The following description indicates the theory and mathematics involved in modifying the facility data to obtain the desired $\dot{q}/\dot{q}_{FR}$ ratio.

The Fay-Riddell heat transfer equation yielding $\dot{q}_{FR}$ is obtained from the basic equation:

$$\dot{q}_{FR} = 0.94 (\rho_w \mu_w)^{0.1} (\rho_0' \mu_0')^{0.4} (H_0' - H_w) \sqrt{\left(\frac{dVe}{dx}\right)_0} g \quad (13)$$

where:

$$\left(\frac{dVe}{dx}\right)_0 = \frac{1}{r} \sqrt{\frac{2(p_0' - p_{\infty})}{\rho_0'}} \quad (14)$$

(from Newtonian theory for a hemisphere)

since:

$$\rho_0' = \frac{p_0'}{R T_0'}$$

Eq. (15) becomes:

$$\left(\frac{dVe}{dx}\right)_0 = \frac{1}{r} \sqrt{2 R T_0' \left(1 - \frac{\rho_{\infty}}{\rho_0'}\right)} \quad (15)$$

TABLE 2
Average Heating Rates

$$\bar{q}/q_{FR} = \int_0^{90} \dot{q}/\dot{q}_{FR} d\alpha/90^\circ$$

Gage No.	Configuration		Configuration		Configuration		Configuration	
	100	130	200	230	300	330	400	430
1	2.69	2.66	2.86	2.88	3.38	3.15	2.89	
2	1.27	1.42	1.22	1.14	1.16	1.36	1.42	
3	0.96	0.98	0.97	1.17	1.20	1.10	1.34	
4	0.97	1.13	0.98	1.07	1.08	1.07	1.06	
5	0.97	1.11	1.03	1.17	0.96	1.20	1.26	
6	2.01	3.01	2.11	3.16	2.19	3.06	2.10	
7	1.28	1.58	0.81	1.00	1.26	1.38	1.20	
8	1.02	1.08	0.91	1.06	1.06	1.09	1.10	
9	1.08	1.02	1.13	1.10	1.26	1.03	1.23	
10	1.64	2.81	1.67	2.58	2.04	2.83	2.19	
11	1.18	1.40	1.06	1.28	1.19	1.46	1.38	
12	1.09	1.12	0.87	1.02	1.06	1.13	1.18	
13	1.66	0.94	1.60	1.01	1.76	1.12	1.86	
14	2.71	3.17	2.70	3.14	3.21	2.86	4.07	
15	0.96	1.52	0.56	1.69	0.29	0.91	0.44	
16	1.64	1.54	1.58	2.18	0.86	1.96	1.41	
17	1.84	1.75	1.27	1.95	0.97	1.62	1.28	
18	1.88	2.38	1.78	2.54	0.97	1.20	1.41	
19	1.77	2.08	1.63	1.73	1.11	1.36	1.56	
20	0.43	0.80	0.42	0.52	0.26	0.32	0.47	
21	1.72	2.25	1.24	1.46	1.06	1.27	1.33	
22	1.20	1.60	0.92	1.27	0.76	1.04	1.07	
23	1.42	1.84	1.00	1.72	0.90	1.16	1.30	
24	1.06	1.30	0.92	1.17	1.06	1.06	1.46	
25	2.73	2.49	2.87	2.81	3.19	3.17	2.98	
26	0.58	1.20	0.47	1.04	0.38	0.83	0.67	
27	1.17	2.03	1.01	1.74	0.88	1.71	1.32	
28	1.34	2.23	1.07	1.79	0.99	1.77	1.41	
29	1.73	2.28	1.55	2.46	1.06	1.61	1.66	
30	1.48	1.81	1.31	1.26	1.48	1.45	1.97	
31	0.42	0.72	0.36	0.53	0.30	0.38	0.61	
32	1.54	1.65	1.01	1.24	0.87	1.11	1.31	
33	1.27	1.53	1.02	1.69	0.99	1.26	1.32	
34	1.86	2.71	1.39	2.46	1.24	1.79	1.72	
35	0.78	1.49	0.81	1.02	1.30	1.40	1.79	
36	2.73	2.91	2.89	3.26	3.10	3.57	3.13	
37	0.97	0.68	0.72	0.64	0	0	0.27	

TABLE 2 (continued)

Gage No.	Configuration		Configuration		Configuration		Configuration	
	100	130	200	230	300	330	400	430
38	1.86	1.24	1.57	1.07	0.83	1.01	1.36	
39	2.19	1.29	1.29	0.94	0.90	0.01	1.24	
40	1.97	2.09	2.00	1.43	1.01	1.19	1.46	
41	1.90	1.07	1.57	1.03	1.27	1.20	1.62	
42	0.38	0.41	0.46	0.43	0.26	0.27	0.50	
43	1.42	1.05	1.26	0.86	1.01	0.92	1.39	
44	0.91	0.81	0.79	0.93	0.81	0.73	1.07	
45	1.56	1.71	1.06	1.31	0.92	1.01	1.46	
46	1.05	0.27	1.14	0.61	0.92	0.95	1.31	
47	0.68	1.52	0.66	1.52	0.51	0.84	0.78	
48	1.32	1.88	1.08	1.89	0.83	1.50	1.31	
49	1.57	2.16	1.18	2.14	0.82	1.47	1.24	
50	0.18	0.69	0.22	0.54	0.26	0.42	0.57	
51	0.79	0.78	0.81	1.31	0.17	0.14	1.70	
52	0.97	1.77	0.68	1.28	0.64	0.98	1.16	
53	0	0.09	0	0.07	0	0.10	0.03	
54	0	0.19	0.07	0.27	0	0.36	0.128	
55	0	0.31	0	0.37	0	0.18	0.12	
56	0	0.05*	0	0	0	0.06	0.03	
57	0	0.27	0.04	0.34	0.12	0.30	0.20	
58	0	0.26	0.01	0.24	0.03	0.16	0.23	
59	6.21*	2.62	0.55	12.39	3.41	5.67	3.59	
60	1.84	--	0.79	1.63	0.47	1.36	0.76	
61	1.31*	--	0.56	0.92	0	--	--	
62	5.78	7.86	4.46	5.89	--	--	--	--
63	0.48	0.81	0.72	1.11	--	--	--	--
64	0.38	0.77	0.20	0.48	--	--	--	--
65	1.83	4.03	1.21	2.33	0.96	1.63	1.42	
66	0.60	0.92	0.66	1.14	0.61	1.06	0.81	
67	0.41	0.78	0.43	1.07	0.41	0.58	0.63	
68	1.07	2.59	0.71	2.16	--	--	--	--
69	0.58	0.75	0.42	0.48	--	--	--	--
70	0.49	0.46	0.32	0.43	--	--	--	--
71	9.00	8.61	7.96	--	9.40	8.33	8.77	
72	4.21	2.22*	4.98	3.53	3.29	3.43	4.17	
73	4.07*	--	3.59	2.80	2.60	3.13	2.88	
74	10.33	9.02	8.84	8.21	--	--	--	--
75	2.19	3.11	2.03	2.36	--	--	--	--
76	1.47	2.17*	1.37	2.87	--	--	--	--
77	8.30	7.33*	4.61	4.47	3.96	6.50	4.53	
78	2.45	2.50	2.74	2.44	2.19	2.13	2.43	
79	2.29	3.28	2.19	2.12	1.89	2.31	2.33	
80	4.03	7.22	4.69	7.11	--	--	--	--

TABLE 2 (concluded)

Gage No.	Configuration		Configuration		Configuration		Configuration	
	100	130	200	230	300	330	400	430
81	0.78	1.50	0.91	1.38	--	--	--	--
82	0.71	1.61	1.01	1.93	--	--	--	--
83	9.30*	--	6.87*	6.62	8.96	9.71	8.93	
84	5.73*	--	6.35	--	3.73	5.74	5.07	
85	4.93*	--	4.33	6.29	3.42	6.78	5.07	
86	5.28*	--	4.39*	5.63	3.79	6.64	5.44	
87	7.10	9.22	9.72	10.61	--	--	--	--
88	2.90	3.61	4.82	7.02	--	--	--	--
89	3.42	4.89	2.95	4.47	--	--	--	--
90	3.71	5.13	3.77	5.30	--	--	--	--
91	8.63*	--	--	--	7.99	9.29	7.66	
92	3.82	7.67	3.67	6.72	2.74	6.21	3.82	
93	3.62	6.28*	3.34*	6.06	2.21	5.43	3.08	
94	3.91*	--	3.96*	3.44	3.18	5.24	4.28	
95	7.09	--	7.56	7.67	--	--	--	--
96	2.56	4.74	2.81	6.00	--	--	--	--
97	2.30	4.11	3.56	5.33	--	--	--	--
98	3.71	6.61	2.88	4.76	--	--	--	--

*Estimated values, test data incomplete

Neglecting $\frac{\rho_{\infty}}{\rho_0'}$ is a simplifying assumption which introduces a maximum error in $\dot{q}$ of +0.3% for a Mach number of 8. With this assumption, Eq (15) is:

$$\left(\frac{dVe}{dx}\right)_0 = \frac{1}{r} \sqrt{2 R T_0'} \quad (16)$$

Noting the following relations:

$$\rho_w = \frac{p_0'}{R T_w'} \quad (17)$$

$$\rho_0' = \frac{p_0'}{R T_0'} \quad (18)$$

Equations (16), (17) and (18) are used in Eq (14) to give:

$$\dot{q}_{FR} = \quad (19)$$

$$0.94 \left(\frac{p_0' \mu_w'}{R T_w'}\right)^{0.1} \left(\frac{p_0' \mu_0'}{R T_0'}\right)^{0.4} H_0' - H_w' \left[\frac{1}{r} (2 R T_0')^{0.5}\right]^{0.5} g$$

Manipulation of Eq (19) yields:

$$\dot{q}_{FR} = \frac{0.94 (p_0')^{0.5} (\mu_0')^{0.4} (H_0' - H_w') g (2)^{0.25}}{r^{0.5} (T_0')^{0.15} (R)^{0.25}} \left(\frac{\mu_w'}{T_w'}\right)^{0.1} \quad (20)$$

where:

$$\left(\frac{\mu_w'}{T_w'}\right)^{0.1} = 0.1214 \text{ for } T_w' = 540^\circ R \quad (21)$$

Rearrange Eq (21) and use Eq (22):

$$\dot{q}_{FR} = \frac{0.94 (0.1214) (2)^{0.25} (32.17)}{(1716)^{0.25}} \frac{(P_0')^{0.5} (\mu_0')^{0.4} (H_0' - H_w)}{(r)^{0.5} (T_0')^{0.15}} \quad (22)$$

Assuming: $T_0' = T_0$
 $H_0' = H_0$

Equation (22) simplifies to:

$$\dot{q}_{FR} = 8.138 \left[\frac{(P_0')^{0.5} (\mu_0')^{0.4} (H_0 - H_w)}{(r)^{0.5} (T_0')^{0.15}} \right] \quad (23)$$

Using Eq (4) and (9), an expression for the Stanton number, St , is found:

$$St = \frac{\dot{q}}{\rho_\infty V_\infty g (H_0 - H_w)} \quad (24)$$

Based on the Fay-Riddell heat transfer equation, the Fay-Riddell Stanton number is:

$$St_{FR} = \frac{\dot{q}_{FR}}{\rho_\infty V_\infty g (H_0 - H_w)} \quad (25)$$

Divide Eq (25) by Eq (26):

$$\frac{\dot{q}}{\dot{q}_{FR}} = \frac{St}{St_{FR}} \frac{(H_0 - H_w)}{(H_0 - H_w)} \quad (26)$$

In Eq (28) the last term containing the $(H_0 - H_w)$ expressions will not cancel because the wall enthalpy, H_w , in the denominator is an arbitrary reference constant based on a wall temperature of $540^\circ R$; where H_w of the numerator is a variable dependent upon the local wall temperature, T_w , at each thermocouple. Since $H_w = 129.5$ at $540^\circ R$

(see Eq (2)), Eq (26) takes the form:

$$\frac{\dot{q}}{\dot{q}_{FR}} = \frac{St}{St_{FR}} \frac{(H_0 - H_w)}{(H_0 - 129.5)} \quad (27)$$

Equation (27) indicates how $\frac{\dot{q}}{\dot{q}_{FR}}$ was obtained from the AEDC data which were presented as $\frac{St}{St_{FR}}$.

Data were recorded over a span of approximately seven seconds, at a rate of 20 times per second for each run. The time breakdown is as follows: Two seconds recording time while the model is in the chamber, 0.25 second recording time while the model is in transit to the tunnel centerline, and five seconds recording time after the model reaches the centerline. The time chosen to evaluate the data is $t = 0.25$ second after the model reaches the centerline of the tunnel. Choosing $t = 0.25$ second eliminates undesirable transient effects in the data which occur before this time and keep conduction effects, which increase with time, to a minimum.

The parameter, $\dot{q}/\dot{q}_{FR}$, defines (for the reference time) the quantity of heat that is being retained at a given point on the model. However, a thermocouple located near a heat sink or local hot spot will incur a heat loss because heat will be conducted to a surrounding area at a lower temperature. The conduction loss will cause values of $\dot{q}$ to be lower than the actual values. Conversely, thermocouples near a local cool spot will yield $\dot{q}$ values higher than the actual values because heat is being conducted to the cool spot from the surrounding region at a higher temperature. Thermocouples located in a region where temperature variations are linear (see the sketch) in each direction (which is the most common case) require no conduction correction because heat flux to and from the thermocouple location remains balanced.

It should be noted that the thermocouple numbering used in AEDC does not agree with the Martin Marietta Corporation numbering system for Configurations 300, 330, 400 and 430. The differences are in the fin instrumentation only (TC numbers greater than 59). The relation of the Martin Marietta numbers to AEDC numbers are listed in Table 2. The data given in Appendices B and C use the AEDC numbering system. All other references to TC number used in this report are with respect to the Martin Marietta system.

The uncorrected values of the heat inputs for each thermocouple at the reference time (0.25 second after the model reaches the tunnel centerline) and 0.50 second later (0.75 second after the model reaches the tunnel centerline) are recorded in Appendix B. * Heat conduction to and from each thermocouple location is proportional to the difference between the uncorrected heat input values measured at the times mentioned. A $\dot{q}$, which decreases the time, indicates a conduction of heat away from the location being considered, and a $\dot{q}$ increasing

*The modified data were computed and are presented in Appendix B under the following headings:

(a)	(b)	(c)	(d)	(e)	(f)	(g)
<u>TC</u>	<u>ALPHA</u>	<u>Q1/QFR</u>	<u>Q2/QFR</u>	<u>COR/QFR</u>	<u>QC1/QFR</u>	<u>QC. 5/QFR</u>

where:

- (1) TC = thermocouple number
- (2) ALPHA = angle of attack
- (3) Q1/QFR uncorrected $\dot{q}/\dot{q}_{FR}$ ratio, calculated with Eq (27) for a reduction time at 0.25 second after the model reaches the centerline of the tunnel.
- (4) Q2/QFR is the uncorrected $\dot{q}/\dot{q}_{FR}$ ratio, calculated with Eq (27) for a reduction time at 0.75 second after the model reaches the centerline of the tunnel.
- (5) COR/QFR represents the conduction correction increment which is evaluated as : $COR/QFR = (c) - (d) = \Delta\dot{q}/\dot{q}_{FR}$
- (6) QC1/QFR is the corrected $\dot{q}/\dot{q}_{FR}$: $QC1/QFR = (c) + (e)$.
- (7) QC. 5/QFR represents $\dot{q}/\dot{q}_{FR}$ corrected by one-half the conduction correction, (e): $QC. 5/QFR = (c) + 1/2 (e)$.

TABLE 3

Relationship of Test Thermocouple Numbers to
Model Thermocouple Numbers

<u>TC of</u> <u>Appendices B & C</u>	<u>Correct TC No.</u> <u>(Configurations</u> <u>300, 330, 400, 430)</u>
1 to 58	1 to 58
59	59
60	60
61	61
62	65
63	66
64	67
65	71
66	72
67	73
68	77
69	78
70	79
71	83
72	84
73	85
74	86
75	91
76	92
77	93
78	94

with time indicates that heat is being conducted to the considered location. A $\dot{q}$ value, which has negligible variation, shows that heat conduction to and from the location in question is approximately equal.

Most of the plotted data presented in this report required little or no correction for the effects of conduction. However, a conduction correction was determined and applied to all the uncorrected data. The determination of this correction is best explained with the aid of the following sketch.

It is estimated that the conduction values at $t = 0.25$ second is one-third the value at $t = 0.75$ second. Therefore, the difference between the values for these two times would be double the conduction value at $t = 0.25$ second. For this reason, the difference in the heating rate ratios (given as COR/Q_{FR} in Appendix B) is multiplied by 0.5 to determine the final correction increment which is then added to the uncorrected value for $t = 0.25$ second. The result (given as $QC.5/Q_{FR}$ in Appendix B) is considered to be the corrected value of $\dot{q}/\dot{q}_{FR}$ and this parameter was plotted versus α for all model configurations in Figs. 22 through 260.

The actual procedure for reducing the test data to final form was as follows:

- (1) Tunnel data were processed at the AEDC facility, recorded on magnetic tape and listed. Schlieren pictures (Figs. 8 to 21) were also obtained at the facility.
- (2) The AEDC data were modified by a digital program, at the Martin Marietta Corporation, to yield the desired parameter, $\dot{q}/\dot{q}_{FR}$.
- (3) The $\dot{q}/\dot{q}_{FR}$ values were listed and put onto the tape for use on the plotter (see Appendix B).
- (4) The magnetic plotting tape was used to make the plots of $\dot{q}/\dot{q}_{FR}$ versus α (see Figs. 22 through 260) on the Benson-Lehner STE electronic plotter.
- (5) The $\dot{q}/\dot{q}_{FR}$ versus α plots were integrated with a planimeter to determine the average heat inputs to selected thermocouples over the angle of attack range 0 to 90 degrees. The integrated values are presented in Appendix C and in Figs. 261 through 288.

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VI. ACCURACY OF DATA

The plotted data given in Figs. 22 through 260 have three sources of errors that may be significant; the data recording system at the test site; the conduction correction; and the plotting accuracy. The estimates and effects of each of these sources are shown in the following table:

<u>Source</u>	<u>Error</u>	<u>Value in $\dot{q}/\dot{q}_{FR}$</u>	<u>Limits</u>
Measurement	$\pm 0.2^\circ \text{ R/sec}$	± 0.04	$0 < \dot{q}/\dot{q}_{FR} < 2.0$
	or $\pm 0.02 (\Delta T/\Delta t)$	$\pm 0.02 \dot{q}/\dot{q}_{FR}$	$\dot{q}/\dot{q}_{FR} > 2.0$
Conduction	$\pm 0.20 (\Delta \dot{q}_{cond}/\dot{q}_{FR})$	± 0.10	$0 < \dot{q}/\dot{q}_{FR} < 10$
		$\pm 0.01 \dot{q}/\dot{q}_{FR}$	$\dot{q}/\dot{q}_{FR} > 10$
Plotting	$\pm 0.015 \text{ in. to center of symbol}$	± 0.02	TC 1-58
		± 0.04	TC 59-98
Total		± 0.30	$0 < \dot{q}/\dot{q}_{FR} < 10$
		$\pm 0.03 \dot{q}/\dot{q}_{FR}$	$\dot{q}/\dot{q}_{FR} > 10$

The average heating rate values, $\bar{\dot{q}}/\dot{q}_{FR}$, have another source of error in that they were obtained by integrating the plotted values of $\dot{q}/\dot{q}_{FR}$ over the 90-degree α range with a planimeter, which has a probable error of $\pm 3\%$. The accuracy of the average heating data (found by taking the square root of the sum of the squares of the $\dot{q}/\dot{q}_{FR}$ error and the planimeter error) is approximately within $\pm 4\%$ of the $\bar{\dot{q}}/\dot{q}_{FR}$ values.

During the tests, the data were obtained at every 5 degrees of α with repeat points at every 10 degrees. The repeatability of the data was estimated by taking the root mean square of the differences at the repeat points.

$$\dot{q}/\dot{q}_{FR} = \pm \sqrt{\Sigma \Delta \dot{q}/\dot{q}_{FR} / n}$$

for each thermocouple on Configuration 100.

The body data (TC 1 through 58) gave $\Delta \dot{q}/\dot{q}_{FR} = \pm 0.125$.

The fin data (TC 59 through 98) gave $\Delta \dot{q}/\dot{q}_{FR} = \pm 0.246$.

Certain thermocouples were found to be giving faulty readings that were caused by loose or broken wires. A list of the faulty thermocouples and the range over which they were malfunctioning is given in Table 4.

When the model was rolled 30 degrees (Configurations 130, 230, 330 and 430), the data on Thermocouples 83 through 98 may be inaccurate because the fins on which they were located are parallel to the stream and therefore were subject to heating on both sides. The thermocouple wires were also open to the free stream and may have disturbed the flow so that the heating on one surface of the fin may not be equal to one half the total indicated.

TABLE 4

Damaged Thermocouples

<u>Configuration</u>	<u>Thermocouple</u>	<u>α Range (deg)</u>	<u>Comment</u>
100	59	0 to 25	
	61	0 to 35	
	73	0 to 25	
	77		
	83	0 to 55	
	84	0 to 35	
	85	0 to 35	
	86	0 to 40	
	91	0 to 60	
	94	0 to 60	
130	26	55	
	34	30	
	59		TC is out
	61		TC is out
	72	60 to 90	
	73		TC is out
	74	0 to 10	
	76	60 to 90	
	77	55 to 90	
	79	75 to 90	
	83		TC is out
	84		TC is out
	85		TC is out
	86		TC is out
	87	0	
	91		TC is out
	93	55 to 90	
	94		TC is out
200	95	60 to 90	
	78	60 to 80	
	86		Questionable data
	83	30 to 60	
	91		TC is out
	93	30 to 65	
	94		Questionable data
230	61	65 to 90	
	71	30 to 90	
	84	30 to 90	
	87		
300	61		TC is out
330	61		TC is out

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VII. DISCUSSION OF RESULTS

The purpose of this test was to obtain heating data on the SNAP 19 generator configuration with three simulated degrees of fin ablation (full, 2/3, 1/3 span fins). These data are to be used in a burnup analysis of the generator.

Each of the three models tested in the program had uniform span fins positioned at 60-degree intervals around the generator. Three pairs of fins were instrumented such that for 0-degree roll, the instrumented fins were located at 30, 90 and 150 degrees (see Figs. 4D and 4E). For the model at 30 degrees roll, the fin locations were 0, 60 and 120 degrees. Testing at 0 and 30 degrees roll yields fin data for a ϕ range of 0 to 150 degrees.

With the exception of the front face, all the instrumentation was symmetrical about the fore and aft midpoint of the model, thus allowing simulation of data through 180-degree alpha polars, while only testing through 90-degree alpha polars. Recording data on the front face of the model for angles of attack greater than 90 degrees are unnecessary since the front face will be in the shadow of the body beyond the 90-degree position.

The data for a row of thermocouples along the body such as Thermocouples 26 through 29 (see Fig. 261 and Figs. 94 through 101) point up the effects of shadowing and flow deflection due to the flanges. Thermocouple 26 is in the shadow of the flange of the front cover plate and therefore has a generally low heat input; TC 29, located near the center flange, incurs a high heating rate as the result of flow deflection near the flange.

The data presented in Figs. 22 through 260 ($\dot{q}/\dot{q}_{FR}$ versus α) can be used to determine the heating distribution on the generator for any given angle of attack. These data also indicate that local areas of high heating rates exist that change in both location and intensity with a change in angle of attack.

The average heat inputs over the α range of 0 to 90 degrees (Figs. 261 through 288) are more useful in describing the general effects of ablation on the heat distribution on the generator.

Figure 261 may be used as a typical example of the effects of fin ablation on the body heating. The decreased fin spans had little effect on the front face heating (TC 2, 3, 4 and 5); the heating on the front flange (TC 1 and 25) increased as the fin span was decreased, but the heating on the rest of the body (TC 26 through 35) decreased as the fin span decreased.

As expected, the heating rates on the fins are much higher than on the body. In general, the heating rates on the fins decreased as the fin span was decreased.

The Schlieren photograph shown here indicates the occurrence of turbulent flow during one of the test runs (Configuration 100 at $\alpha = 30$ deg). The flow in this case appears to be in the process of breaking down. The tabulated data for this particular run yield extremely high heating rates, $\dot{q}/\dot{q}_{FR}$, which may be attributed to the turbulence.

Data acquired during this run were not used. However, a duplicate run was made (Group 21, Fig. 10) and the data from the duplicate run were used.

Configurations 400 and 430 were tested to determine the effects of changing the Reynolds number. Configuration 400 is a one-third span generator model tested at $Re \times 10^{-6} = 1.5 \text{ ft}^{-1}$ (other configurations had $Re \times 10^{-6} = 0.4 \text{ ft}^{-1}$; Appendix A contains all tunnel conditions). A comparison of average heating values, $\dot{q}/\dot{q}_{FR}$, for Configurations 300 and 400 shows that heating on the body and fins of the model is higher for the larger Reynolds number (Figs. 274 and 284). It is noted that the change in Reynolds number has little effect on the average heating rates of the front cover plate (see TC 2 through 5, Fig. 263). However, an increased Reynolds number appears to decrease the average heating values on the flange of the front cover (see TC 1 and 25, Fig. 263). The flange area is near a stagnation point which is subjected to high heating input. However, an increase of Reynolds number causes the bow shock standoff distance to increase (the increase is too small to be noticed in the Schlieren pictures), resulting in the lower heating values on the flange.

The burnup analysis will be based upon the heating data obtained at the lower Reynolds number ($Re \times 10^{-6} = 0.4 \text{ ft}^{-1}$). This Reynolds number is within the flight regime of the generator, and it is the lowest Reynolds number obtainable in the AEDC Tunnel B.

VIII CONCLUSIONS

Based on the test results presented in this report, the following conclusions are drawn.

- (1) Local areas of high heating rates exist on the fins and the body that vary in both position and intensity with changes in angle of attack.
- (2) The average heating rates on the body decrease as the fin span is decreased.
- (3) Generator fin disintegration is accompanied by a decrease in the average heating on the fins.
- (4) Increasing the Reynolds number tends to increase values of the average heating rates ($\bar{q}/\dot{q}_{FR}$) on both the body and the fins.

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IX. REFERENCES

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4. Dagold, R. G., "Test Plan Report SNAP 19 Generator Force and Stability Test, Mach 8," Martin Company, MND-3607-59, Revised June 1966.
5. "The Heat Capacity and Thermal Conductivity of Inconel 600," Union Carbide Nuclear Division, 7933-1865-I, August 1966.

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Fig. 3. One-Third Span Model

Fig. 1. Full Span Model

Fig. 2. Two-Thirds Span Model

SHOWN C-C 59 THRU 70 N 94 9 ASSY 59 THRU 64 N 29 ASSY
SIMILAR D-D 71 THRU 82 IN 94 19 ASSY 65 THRU 70 N 29 ASSY
SIMILAR E-E 83 THRU 98 N 94 9 ASSY 71 THRU 78 N 29 ASSY

TE THERMOCOUPLES FWD OF SECT FF NTO
BUNDLE INSULATE BUNDLE WITH GLASS OR TEFLON
TAPE TO SNUG FT N 75 DMMOLE TE OTHER
THERMOCOUPLES AFT SECT FF TO BUNDLE

$$F - F$$

Fig. 4a. Thermocouple Locations

H-H

-39 ASSY SHOWN
-49 ASSY SIMILAR
-59 ASSY SIMILAR

-69 ASSY SHOWN
-79 ASSY SIMILAR
-89 ASSY SIMILAR

SEE SHEET 1 FOR NOTES AND LIST OF MATERIALS

Fig. 4c. Thermocouple Locations

MODEL #1, FULL SPAN FIN

Fig. 4d. Thermocouple Locations

B-B
MODEL #2, $\frac{2}{3}$ SPAN
SAME AS MODEL #1 EXCEPT AS SHOWN

B-B
MODEL #3, $\frac{1}{3}$ SPAN
SAME AS MODEL #1 EXCEPT AS SHOWN

Fig. 4e. Thermocouple Locations

Fig. 5. Thermocouple Installation

Fig. 6. Diagram of Tunnel B and Test Section

Fig. 7. Photograph of Tunnel B

Full fin
 $Re = 0.4 \times 10^6 / ft$

Two-thirds fin
 $Re = 0.4 \times 10^6 / ft$

One-third fin
 $Re = 0.4 \times 10^6 / ft$

One-third fin
 $Re = 1.5 \times 10^6 / ft$

Fig. 8. Schlieren Photographs

Full fin
 $Re = 0.4 \times 10^6 / ft$

Two-thirds fin
 $Re = 0.4 \times 10^6 / ft$

One-third fin
 $Re = 0.4 \times 10^6 / ft$

One-third fin
 $Re = 1.5 \times 10^6 / ft$

Fig. 9. Schlieren Photographs

Full fin
 $Re = 0.4 \times 10^6 / ft$

Two-thirds fin
 $Re = 0.4 \times 10^6 / ft$

One-third fin
 $Re = 0.4 \times 10^6 / ft$

One-third fin
 $Re = 1.5 \times 10^6 / ft$

Fig. 10. Schlieren Photographs

Full fin
 $Re = 0.4 \times 10^6 / ft$

Two-thirds fin
 $Re = 0.4 \times 10^6 / ft$

One-third fin
 $Re = 0.4 \times 10^6 / ft$

One-third fin
 $Re = 1.5 \times 10^6 / ft$

Fig. 11. Schlieren Photographs

Full fin
 $Re = 0.4 \times 10^6 / ft$

Two-thirds fin
 $Re = 0.4 \times 10^6 / ft$

One-third fin
 $Re = 0.4 \times 10^6 / ft$

One-third fin
 $Re = 1.5 \times 10^6 / ft$

Fig. 12. Schlieren Photographs

Full fin
 $Re = 0.4 \times 10^6 / ft$

Two-thirds fin
 $Re = 0.4 \times 10^6 / ft$

One-third fin
 $Re = 0.4 \times 10^6 / ft$

One-third fin
 $Re = 1.5 \times 10^6 / ft$

Fig. 13. Schlieren Photographs

Full fin
 $Re = 0.4 \times 10^6 / ft$

Two-thirds fin
 $Re = 0.4 \times 10^6 / ft$

Gp 60 $\alpha = 90$

One-third fin
 $Re = 0.4 \times 10^6 / ft$

Gp 108 $\alpha = 90$

One-third fin
 $Re = 1.5 \times 10^6 / ft$

Gp 156 $\alpha = 90$

Fig. 14. Schlieren Photographs

Full fin
 $Re = 0.4 \times 10^6 / ft$

Two-thirds fin
 $Re = 0.4 \times 10^6 / ft$

One-third fin
 $Re = 0.4 \times 10^6 / ft$

One-third fin
 $Re = 1.5 \times 10^6 / ft$

Fig. 15. Schlieren Photographs

Full fin
 $Re = 0.4 \times 10^6 / ft$

Two-thirds fin
 $Re = 0.4 \times 10^6 / ft$

One-third fin
 $Re = 0.4 \times 10^6 / ft$

One-third fin
 $Re = 1.5 \times 10^6 / ft$

Fig. 16. Schlieren Photographs

Full fin
 $Re = 0.4 \times 10^6/ft$

Two-thirds fin
 $Re = 0.4 \times 10^6/ft$

One-third fin
 $Re = 0.4 \times 10^6/ft$

One-third fin
 $Re = 1.5 \times 10^6/ft$

Fig. 17. Schlieren Photographs

Full fin
 $Re = 0.4 \times 10^6 / ft$

Two-thirds fin
 $Re = 0.4 \times 10^6 / ft$

One-third fin
 $Re = 0.4 \times 10^6 / ft$

One-third fin
 $Re = 1.5 \times 10^6 / ft$

Fig. 18. Schlieren Photographs

Fig. 19. Schlieren Photographs

Full fin
 $Re = 0.4 \times 10^6 / ft$

Two-thirds fin
 $Re = 0.4 \times 10^6 / ft$

One-third fin
 $Re = 0.4 \times 10^6 / ft$

One-third fin
 $Re = 1.5 \times 10^6 / ft$

Fig. 20. Schlieren Photographs

Full fin
 $Re = 0.4 \times 10^6 / ft$

Two-thirds fin
 $Re = 0.4 \times 10^6 / ft$

One-third fin
 $Re = 0.4 \times 10^6 / ft$

One-third fin
 $Re = 1.5 \times 10^6 / ft$

Fig. 21. Schlieren Photographs

Fig. 22. Heat Transfer, TC 1 - 5, Configuration 100

Fig. 23. Heat Transfer, TC 1 - 5, Configuration 200

Fig. 24. Heat Transfer, TC 1 - 5, Configuration 300

Fig. 25. Heat Transfer, TC 1 - 5, Configuration 400

Fig. 26. Heat Transfer, TC 1 - 5, Configuration 130

Fig. 27. Heat Transfer, TC 1 - 5, Configuration 230

Fig. 28. Heat Transfer, TC 1 - 5, Configuration 330

Fig. 29. Heat Transfer, TC 1 - 5, Configuration 430

Fig. 30. Heat Transfer, TC 6 - 9, Configuration 100

Fig. 31. Heat Transfer, TC 6 - 9, Configuration 200

Fig. 32. Heat Transfer, TC 6 - 9, Configuration 300

Fig. 33. Heat Transfer, TC 6 - 9, Configuration 400

Fig. 34. Heat Transfer, TC 6 - 9, Configuration 130

Fig. 35. Heat Transfer, TC 6 - 9, Configuration 230

Fig. 36. Heat Transfer, TC 6 - 9, Configuration 330

Fig. 37. Heat Transfer, TC 6 - 9, Configuration 430

Fig. 38. Heat Transfer, TC 10 - 13, Configuration 100

Fig. 39. Heat Transfer, TC 10 - 13, Configuration 200

Fig. 40. Heat Transfer, TC 10 - 13, Configuration 300

Fig. 41. Heat Transfer, TC 10 - 13, Configuration 400

Fig. 42. Heat Transfer, TC 10 - 13, Configuration 130

Fig. 43. Heat Transfer, TC 10 - 13, Configuration 230

Fig. 44. Heat Transfer, TC 10 - 13, Configuration 330

Fig. 45. Heat Transfer, TC 10 - 13, Configuration 430

Fig. 46. Heat Transfer, TC 14, Configuration 100

Fig. 47. Heat Transfer, TC 14, Configuration 200

Fig. 48. Heat Transfer, TC 14, Configuration 300

Fig. 49. Heat Transfer, TC 14, Configuration 400

Fig. 50. Heat Transfer, TC 14, Configuration 130

Fig. 51. Heat Transfer, TC 14, Configuration 230

Fig. 52. Heat Transfer, TC 14, Configuration 330

Fig. 53. Heat Transfer, TC 14, Configuration 430

Fig. 54. Heat Transfer, TC 15 - 18, Configuration 100

Fig. 55. Heat Transfer, TC 15 - 18, Configuration 200

Fig. 56. Heat Transfer, TC 15 - 18, Configuration 300

Fig. 57. Heat Transfer, TC 15 - 18, Configuration 400

Fig. 58. Heat Transfer, TC 15 - 18, Configuration 130

Fig. 59. Heat Transfer, TC 15 - 18, Configuration 230

Fig. 60. Heat Transfer, TC 15 - 18, Configuration 330

Fig. 61. Heat Transfer, TC 15 - 18, Configuration 430

Fig. 62. Heat Transfer, TC 19, Configuration 100

Fig. 63. Heat Transfer, TC 19, Configuration 200

Fig. 64. Heat Transfer, TC 19, Configuration 300

Fig. 65. Heat Transfer, TC 19, Configuration 400

Fig. 66. Heat Transfer, TC 19, Configuration 130

Fig. 67. Heat Transfer, TC 19, Configuration 230

Fig. 68. Heat Transfer, TC 19, Configuration 330

Fig. 69. Heat Transfer, TC 19, Configuration 430

Fig. 70. Heat Transfer, TC 20 - 23, Configuration 100

Fig. 71. Heat Transfer, TC 20 - 23, Configuration 200

Fig. 72. Heat Transfer, TC 20 - 23, Configuration 300

Fig. 73. Heat Transfer, TC 20 - 23, Configuration 400

Fig. 74. Heat Transfer, TC 20 - 23, Configuration 130

Fig. 75. Heat Transfer, TC 20 - 23, Configuration 230

Fig. 76. Heat Transfer, TC 20 - 23, Configuration 330

Fig. 77. Heat Transfer, TC 20 - 23, Configuration 430

Fig. 78. Heat Transfer, TC 24, Configuration 100

Fig. 79. Heat Transfer, TC 24, Configuration 200

Fig. 80. Heat Transfer, TC 24, Configuration 300

Fig. 81. Heat Transfer, TC 24, Configuration 400

Fig. 82. Heat Transfer, TC 24, Configuration 130

Fig. 83. Heat Transfer, TC 24, Configuration 230

Fig. 84. Heat Transfer, TC 24, Configuration 330

Fig. 85. Heat Transfer, TC 24, Configuration 430

Fig. 86. Heat Transfer, TC 25, Configuration 100

Fig. 87. Heat Transfer, TC 25, Configuration 200

Fig. 88. Heat Transfer, TC 25, Configuration 300

Fig. 89. Heat Transfer, TC 25, Configuration 400

Fig. 90. Heat Transfer, TC 25, Configuration 130

Fig. 91. Heat Transfer, TC 25, Configuration 230

Fig. 92. Heat Transfer, TC 25, Configuration 330

Fig. 93. Heat Transfer, TC 25, Configuration 430

Fig. 94. Heat Transfer, TC 26 - 29, Configuration 100

Fig. 95. Heat Transfer, TC 26 - 29, Configuration 200

Fig. 96. Heat Transfer, TC 26 - 29, Configuration 300

Fig. 97. Heat Transfer, TC 26 - 29, Configuration 400

Fig. 98. Heat Transfer, TC 26 - 29, Configuration 130

Fig. 99. Heat Transfer, TC 26 - 29, Configuration 230

Fig. 100. Heat Transfer, TC 26 - 29, Configuration 330

Fig. 101. Heat Transfer, TC 26 - 29, Configuration 430

Fig. 102. Heat Transfer, TC 30, Configuration 100

Fig. 103. Heat Transfer, TC 30, Configuration 200

Fig. 104. Heat Transfer, TC 30, Configuration 300

Fig. 105. Heat Transfer, TC 30, Configuration 400

Fig. 106. Heat Transfer, TC 30, Configuration 130

Fig. 107. Heat Transfer, TC 30, Configuration 230

Fig. 108. Heat Transfer, TC 30, Configuration 330

Fig. 109. Heat Transfer, TC 30, Configuration 430

Fig. 110. Heat Transfer, TC 31 - 34, Configuration 100

Fig. 111. Heat Transfer, TC 31 - 34, Configuration 200

Fig. 112. Heat Transfer, TC 31 - 34, Configuration 300

Fig. 113. Heat Transfer, TC 31 - 34, Configuration 400

Fig. 114. Heat Transfer, TC 31 - 34, Configuration 130

Fig. 115. Heat Transfer, TC 31 - 34, Configuration 230

Fig. 116. Heat Transfer, TC 31 - 34, Configuration 330

Fig. 117. Heat Transfer, TC 31 - 34, Configuration 430

Fig. 118. Heat Transfer, TC 35 and 36, Configuration 100

Fig. 119. Heat Transfer, TC 35 and 36, Configuration 200

Fig. 120. Heat Transfer, TC 35 and 36, Configuration 300

Fig. 121. Heat Transfer, TC 35 and 36, Configuration 400

Fig. 122. Heat Transfer, TC 35 and 36, Configuration 130

Fig. 123. Heat Transfer, TC 35 and 36, Configuration 230

Fig. 124. Heat Transfer, TC 35 and 36, Configuration 330

Fig. 125. Heat Transfer, TC 35 and 36, Configuration 430

Fig. 126. Heat Transfer, TC 37 - 40, Configuration 100

Fig. 127. Heat Transfer, TC 37 - 40, Configuration 200

Fig. 128. Heat Transfer, TC 37 - 40, Configuration 300

Fig. 129. Heat Transfer, TC 37 - 40, Configuration 400

Fig. 130. Heat Transfer, TC 37 - 40, Configuration 130

Fig. 131. Heat Transfer, TC 37 - 40, Configuration 230

Fig. 132. Heat Transfer, TC 37 - 40, Configuration 330

Fig. 133. Heat Transfer, TC 37 - 40, Configuration 430

Fig. 134. Heat Transfer, TC 41, Configuration 100

Fig. 135. Heat Transfer, TC 41, Configuration 200

Fig. 136. Heat Transfer, TC 41, Configuration 300

Fig. 137. Heat Transfer, TC 41, Configuration 400

Fig. 138. Heat Transfer, TC 41, Configuration 130

Fig. 139. Heat Transfer, TC 41, Configuration 230

Fig. 140. Heat Transfer, TC 41, Configuration 330

Fig. 141. Heat Transfer, TC 41, Configuration 430

Fig. 142. Heat Transfer, TC 42 - 45, Configuration 100

Fig. 143. Heat Transfer, TC 42 - 45, Configuration 200

Fig. 144. Heat Transfer, TC 42 - 45, Configuration 300

Fig. 145. Heat Transfer, TC 42 - 45, Configuration 400

Fig. 146. Heat Transfer, TC 42 - 45, Configuration 130

Fig. 147. Heat Transfer, TC 42 - 45, Configuration 230

Fig. 148. Heat Transfer, TC 42 - 45, Configuration 330

Fig. 149. Heat Transfer, TC 42 - 45, Configuration 430

Fig. 150. Heat Transfer, TC 46, Configuration 100

Fig. 151. Heat Transfer, TC 46, Configuration 200

Fig. 152. Heat Transfer, TC 46, Configuration 300

Fig. 153. Heat Transfer, TC 46, Configuration 400

Fig. 154. Heat Transfer, TC 46, Configuration 130

Fig. 155. Heat Transfer, TC 46, Configuration 230

Fig. 156. Heat Transfer, TC 46, Configuration 330

Fig. 157. Heat Transfer, TC 46, Configuration 430

Fig. 158. Heat Transfer, TC 47 - 49, Configuration 100

Fig. 159. Heat Transfer, TC 47 - 49, Configuration 200

Fig. 160. Heat Transfer, TC 47 - 49, Configuration 300

Fig. 161. Heat Transfer, TC 47 - 49, Configuration 400

Fig. 162. Heat Transfer, TC 47 - 49, Configuration 130

Fig. 163. Heat Transfer, TC 47 - 49, Configuration 230

Fig. 164. Heat Transfer, TC 47 - 49, Configuration 330

Fig. 165. Heat Transfer, TC 47 - 49, Configuration 430

Fig. 166. Heat Transfer, TC 50 - 52, Configuration 100

Fig. 167. Heat Transfer, TC 50 - 52, Configuration 200

Fig. 168. Heat Transfer, TC 50 - 52, Configuration 300

Fig. 169. Heat Transfer, TC 50 - 52, Configuration 400

Fig. 170. Heat Transfer, TC 50 - 52, Configuration 130

Fig. 171. Heat Transfer, TC 50 - 52, Configuration 230

Fig. 172. Heat Transfer, TC 50 - 52, Configuration 330

Fig. 173. Heat Transfer, TC 50 - 52, Configuration 430

Fig. 174. Heat Transfer, TC 53 - 55, Configuration 100

Fig. 175. Heat Transfer, TC 53 - 55, Configuration 200

Fig. 176. Heat Transfer, TC 53 - 55, Configuration 300

Fig. 177. Heat Transfer, TC 53 - 55, Configuration 400

Fig. 178. Heat Transfer, TC 53 - 55, Configuration 130

Fig. 179. Heat Transfer, TC 53 - 55, Configuration 230

Fig. 180. Heat Transfer, TC 53 - 55, Configuration 330

Fig. 181. Heat Transfer, TC 53 - 55, Configuration 430

Fig. 182. Heat Transfer, TC 56 - 58, Configuration 100

Fig. 183. Heat Transfer, TC 56 - 58, Configuration 200

Fig. 184. Heat Transfer, TC 56 - 58, Configuration 300

Fig. 185. Heat Transfer, TC 56 - 58, Configuration 400

Fig. 186. Heat Transfer, TC 56 - 58, Configuration 130

Fig. 187. Heat Transfer, TC 56 - 58, Configuration 230

Fig. 188. Heat Transfer, TC 56 - 58, Configuration 330

Fig. 189. Heat Transfer, TC 56 - 58, Configuration 430

Fig. 190. Heat Transfer, TC 59 - 61, Configuration 100

Fig. 191. Heat Transfer, TC 59 - 61, Configuration 200

Fig. 192. Heat Transfer, TC 59 - 61, Configuration 300

Fig. 193. Heat Transfer, TC 59 - 61, Configuration 400

Fig. 194. Heat Transfer, TC 59 - 61, Configuration 130

Fig. 195. Heat Transfer, TC 59 - 61, Configuration 230

Fig. 196. Heat Transfer, TC 59 - 61, Configuration 330

Fig. 197. Heat Transfer, TC 59 - 61, Configuration 430

Fig. 198. Heat Transfer, TC 62 - 64, Configuration 100

Fig. 199. Heat Transfer, TC 62 - 64, Configuration 200

Fig. 200. Heat Transfer, TC 62 - 64, Configuration 130

Fig. 201. Heat Transfer, TC 62 - 64, Configuration 230

Fig. 202. Heat Transfer, TC 65 - 67, Configuration 100

Fig. 203. Heat Transfer, TC 65 - 67, Configuration 200

Fig. 204. Heat Transfer, TC 65 - 67, Configuration 300

Fig. 205. Heat Transfer, TC 65 - 67, Configuration 400

Fig. 206. Heat Transfer, TC 65 - 67, Configuration 130

Fig. 207. Heat Transfer, TC 65 - 67, Configuration 230

Fig. 208. Heat Transfer, TC 65 - 67, Configuration 330

Fig. 209. Heat Transfer, TC 65 - 67, Configuration 430

Fig. 210. Heat Transfer, TC 68 - 70, Configuration 100

Fig. 211. Heat Transfer, TC 68 - 70, Configuration 200

Fig. 212. Heat Transfer, TC 68 - 70, Configuration 130

Fig. 213. Heat Transfer, TC 68 - 70, Configuration 230

Fig. 214. Heat Transfer, TC 71 - 73, Configuration 100

Fig. 215. Heat Transfer, TC 71 - 73, Configuration 200

Fig. 216. Heat Transfer, TC 71 - 73, Configuration 300

Fig. 217. Heat Transfer, TC 71 - 73, Configuration 400

Fig. 218. Heat Transfer, TC 71 - 73, Configuration 130

Fig. 219. Heat Transfer, TC 71 - 73, Configuration 230

Fig. 220. Heat Transfer, TC 71 - 73, Configuration 330

Fig. 221. Heat Transfer, TC 71 - 73, Configuration 430

Fig. 222. Heat Transfer, TC 74 - 76, Configuration 100

Fig. 223. Heat Transfer, TC 74 - 76, Configuration 200

Fig. 224. Heat Transfer, TC 74 - 76, Configuration 130

Fig. 225. Heat Transfer, TC 74 - 76, Configuration 230

Fig. 226. Heat Transfer, TC 77 - 79, Configuration 100

Fig. 227. Heat Transfer, TC 77 - 79, Configuration 200

Fig. 228. Heat Transfer, TC 77 - 79, Configuration 300

Fig. 229. Heat Transfer, TC 77 - 79, Configuration 400

Fig. 230. Heat Transfer, TC 77 - 79, Configuration 130

Fig. 231. Heat Transfer, TC 77 - 79, Configuration 230

Fig. 232. Heat Transfer, TC 77 - 79, Configuration 330

Fig. 233. Heat Transfer, TC 77 - 79, Configuration 430

Fig. 234. Heat Transfer, TC 80 - 82, Configuration 100

Fig. 235. Heat Transfer, TC 80 - 82, Configuration 200

Fig. 236. Heat Transfer, TC 80 - 82, Configuration 130

Fig. 237. Heat transfer, TC 80 - 82, Configuration 230

Fig. 238. Heat Transfer, TC 83 - 86, Configuration 100

Fig. 239. Heat Transfer, TC 83 - 86, Configuration 200

Fig. 240. Heat Transfer, TC 83 - 86, Configuration 300

Fig. 241. Heat Transfer, TC 83 - 86, Configuration 400

Fig. 242. Heat Transfer, TC 83 - 86, Configuration 230

Fig. 243. Heat Transfer, TC 83 - 86, Configuration 330

Fig. 244. Heat Transfer, TC 83 - 86, Configuration 430

Fig. 245. Heat Transfer, TC 87 - 90, Configuration 100

Fig. 246. Heat Transfer, TC 87 - 90, Configuration 200

Fig. 247. Heat Transfer, TC 87 - 90, Configuration 130

Fig. 248. Heat Transfer, TC 87 - 90, Configuration 230

Fig. 249. Heat Transfer, TC 91 - 94, Configuration 100

Fig. 250. Heat Transfer, TC 91 - 94, Configuration 200

Fig. 251. Heat Transfer, TC 91 - 94, Configuration 300

Fig. 252. Heat Transfer, TC 91 - 94, Configuration 400

Fig. 253. Heat Transfer, TC 91 - 94, Configuration 130

Fig. 254. Heat Transfer, TC 91 - 94, Configuration 230

Fig. 255. Heat Transfer, TC 91 - 94, Configuration 330

Fig. 256. Heat Transfer, TC 91 - 94, Configuration 430

Fig. 257. Heat Transfer, TC 95 - 98, Configuration 100

Fig. 258. Heat Transfer, TC 95 - 98, Configuration 200

Fig. 259. Heat Transfer, TC 95 - 98, Configuration 130

Fig. 260. Heat Transfer, TC 95 - 98, Configuration 230

Fig. 261. Averaged Heating Values, TC 1 - 35, Configurations 100, 200, 300

Fig. 262. Averaged Heating Values, TC 1 - 35, Configurations 130, 230, 330

Fig. 263. Averaged Heating Values, TC 1 - 35, Configurations 300, 400

Fig. 264. Averaged Heating Values, TC 14 - 24, Configurations 100, 200, 300

Fig. 265. Averaged Heating Values, TC 14 - 24, Configurations 130, 230, 330

Fig. 266. Averaged Heating Values, TC 14 - 24, Configurations 300, 400

Fig. 267. Averaged Heating Values, TC 36 - 46, Configurations 100, 200, 300

Fig. 268. Averaged Heating Values, TC 36 - 46, Configurations 130, 230, 330

Fig. 269. Averaged Heating Values, TC 36 - 46, Configurations 300, 400

Fig. 279. Averaged Heating Values, TC 74 - 82, Configurations 100, 200, 300

Fig. 280. Averaged Heating Values, TC 74 - 82, Configurations 130, 230, 330

Fig. 281. Averaged Heating Values, TC 83 - 94,
Configurations 100, 200, 300

Fig. 282. Averaged Heating Values, TC 83 - 94,
Configurations 130, 230, 330

Fig. 283. Averaged Heating Values, TC 83 - 94,
Configurations 300, 400

Fig. 284 Averaged Heating Values, TC 71 - 79, Configurations 100, 200, 300

Fig 285 Averaged Heating Values, TC 71 - 79, Configurations 130, 230, 330

Fig 286 Averaged Heating Values, TC 71 - 79, Configurations 300, 400

Fig. 287. Averaged Heating Values, TC 87 - 98, Configurations 100, 200

Fig. 288. Averaged Heating Values, TC 87 - 98, Configurations 130, 230