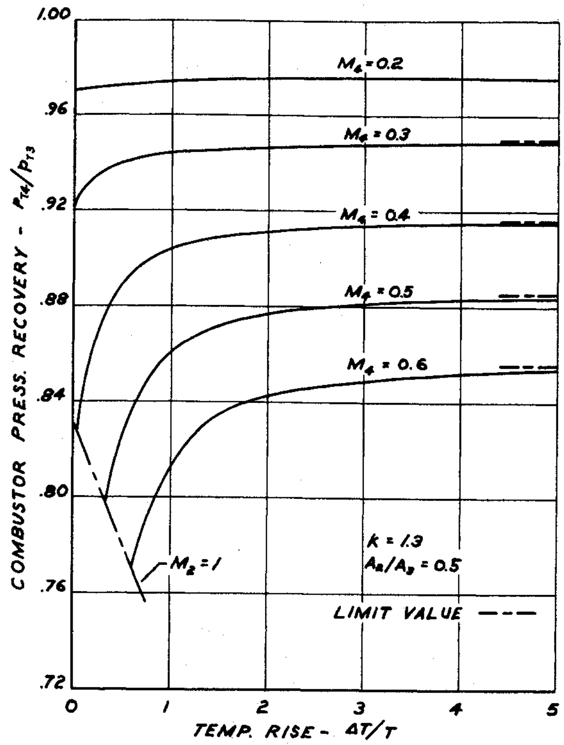

Fig. 3 Combustor total pressure recovery.

Rayleigh line pressure recovery for infinite heat addition, which can be obtained by setting $M_3 = 0$ in Eq. (4).

$$(p_{T_4}/p_{T_2})_{\max} = [1+(k-1)M_4{}^2/2]^{k/(k-1)}/[1+kM_4{}^2] \qquad (6)$$

This limiting value is noted on Fig. 3.

For a combustor operating with a choked constant area nozzle, M_4 is constant and independent of the combustor inlet conditions and fuel air ratios. M_4 is a function only of the exit nozzle area ratio A_5/A_4. The maximum combustor pressure recovery as defined by Eq. (6) is presented in Fig. 4 as a function of A_5/A_4.

Experimental data in Ref. 1 indicate that the over-all combustor pressure recovery p_{T_4}/p_{T_2} is independent of the combustor inlet conditions and fuel air ratio. The experimental values for p_{T_4}/p_{T_2} from Ref. 1 are presented in Fig. 4 for various exit nozzle area ratios. The data points presented in Fig. 4 represent an average of the measured pressure recovery over a range of fuel air ratios. The open points are for a coaxial dump and the closed points are for a 30° dump angle. The dump area ratios A_2/A_3 for the two combustors are noted on Fig. 4. The square point in Fig. 4 was determined from an empirical equation for the pressure drop across a turbojet combustor. The area ratio used in plotting this point is the turbine flow area to the total combustor flow area.

The agreement between experimental data and Eq. (6) in Fig. 4 is within 2%, which is within the accuracy of the experimental data. The degree of agreement is even more remarkable when one considers that the experimental data are for combustors with different geometries.

Closer agreement can be obtained by multiplying Eq. (6) by a combustor pressure efficiency η_p, which is defined by Eq. (7).

$$\eta_p = (p_{T_4}/p_{T_2})/(p_{T_4}/p_{T_2})_{\max} \qquad (7)$$

Experimental data, such as presented in Fig. 4, can be used to determine the value of η_p for a given combustor or a class of combustors. The combustor pressure efficiency η_p will account for frictional losses during the heat addition process which have so far been neglected. A curve for $\eta_p = 0.98$ is included in Fig. 4.

The advantage of the method, as described by Eqs. (6) and (7) for determining the combustor pressure recovery p_{T_4}/p_{T_2}, is that only one variable, A_5/A_4, is required to obtain a good estimate.

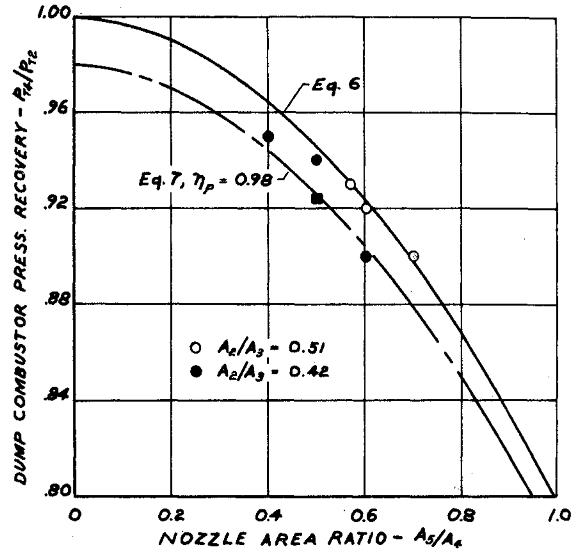

Fig. 4 Over-all combustor total pressure recovery.

Use of this method will greatly simplify the mathematic modeling of combustor performance. The use of this method should also reduce the required amount of combustor pressure recovery testing.

References

[1] Long, H. C. and Carlson, C. H., "Low Cost Ramjets," AFAPL-TR-72-104, Nov. 1972, Aero Propulsion Lab., Wright-Patterson Air Force Base, Ohio.

[2] Barclay, L. P., "Pressure Losses in Dump Combustors," AFAPL-TR-72-57, Oct. 1972, Aero Propulsion Lab., Wright-Patterson Air Force Base, Ohio.

[3] Beans, E. W., "Computer Solution to Generalized One-Dimensional Flow," *Journal of Spacecraft and Rockets*, Vol. 6, No. 12, Dec. 1970, pp. 1460–1464.

Performance Testing of a Transit Generator at JPL

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Introduction

A TRANSIT spacecraft, launched on September 2, 1972 into Earth orbit, was powered by a radioisotope thermoelectric generator (RTG). After approximately one month of operation in space, the loss of telemetry data precluded all verification of the RTG operative behavior.[2] In March 1973 a Transit-type generator Model QM-3 activated by radiant heat from an electrically heated source (ETG) was delivered to JPL for long-term parametric and life tests.

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Index category: Spacecraft Electrical Power Systems.

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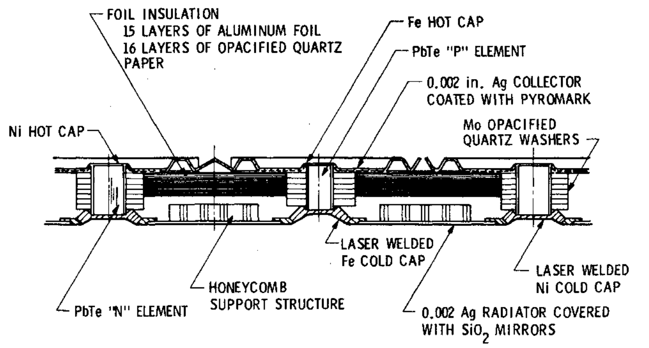

Fig. 1 Isotec panel cross section.

The Transit-type generator, as well as the generator used on the Transit spacecraft, was assembled with 12 lightweight panels using 2N-3P thermoelectric material. The panels were mounted to form a right (12-sided) dodecagonal prism with nonactive top and bottom covers. Each of the 12 panels consisted of 36 P-N couples interconnected in a series-parallel array of four couples in parallel connected to form a series string of nine quads. The hot and cold junctions of the individual thermoelements in a panel were attached, respectively, to a heat collecting and a radiating surface. Each element was surrounded by molybdenum opacified quartz washers to reduce the material sublimation and prevent short circuits between the elements and the multifoil insulation material. This latter was composed of alternate layers of aluminum foil and opacified quartz paper (Fig. 1). The electrical heat source used in the laboratory tests consisted of a stainless steel cylinder simulating the basic geometry and mass of the isotope fueled source. Two coaxially sheathed electrical heaters, with a total capacity of 900 w were spirally wound around the outer surface of the cylinder. The heat from the source was transmitted by radiation to the heat collecting surface of the generator. A highly reflective outer surface coating on the heat radiative outer surface, provided a low solar absorbence surface.

The main difference between ETG/QM-3 and the RTG flying on the Transit satellite, in addition to the difference in heat source, was the composition of the panels and the heat rejection ambient. QM-3 was assembled with three types of panels. The first group (M1) was composed of three panels similar to those used in the flight generator and assembled with thermocouples made by a vacuum warm-pressed process. The second group of three panels (M2) was composed of unused panels assembled with material made by the vacuum cold pressed process. The third group (M3) was composed of six panels assembled also with materials made by the cold-pressed process, but which were previously used for material tests. For test purposes, all panels in each group were connected in series and were operated as individual generators with individual load circuitry. The generator was put on test in a large diameter vacuum chamber with chilled water cooling.

After a prudent period of heat up and preliminary tests, the power input to the generator was increased to achieve the following stable test conditions on the flight-type panels (Group 1): average hot junction temperature $\bar{T}_h = 400°C$, current output in all three groups of panels, 6.0 amp. Maintaining the same value of input power and varying the load resistance, a set of parametric data was recorded under stable conditions at current values ranging between 7.0 amp and 5.0 amp at 0.50 amp intervals. A measurement was also made at a current output of 6.30 amp and at an average hot junction temperature of 400°C to enable a comparison between the data received from the Transit generator in flight. The results of the parametric test are presented in Figs. 2, 3, and 4 for the three groups of panels individually and in Fig. 5 for the generator in total, adding the values of the individual group of panels.

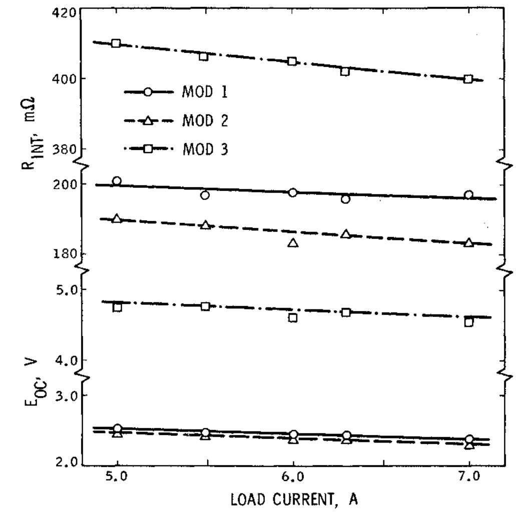

Fig. 3 Parametric tests 778 w in. (400°C H/J nom.).

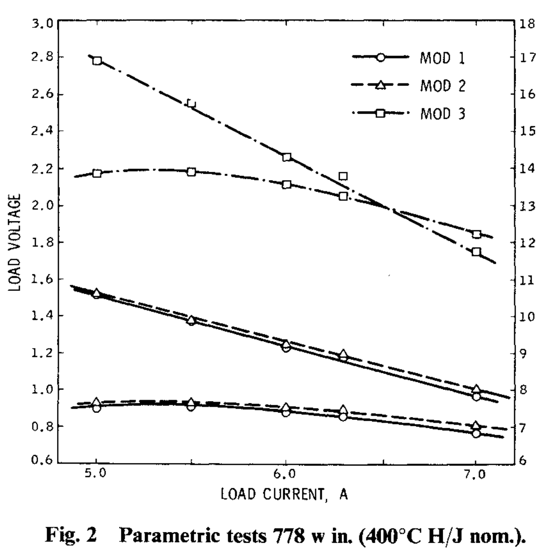

Fig. 2 Parametric tests 778 w in. (400°C H/J nom.).

Results of Analysis and Comparisons

It was observed that as a consequence of the differences in the cooling media of the test environments (LN_2 at the manufacturer and chilled water at JPL) the cold junction temperatures recorded at JPL were, on the average, 24°C higher than those observed at the manufacturer. This also resulted in a 75 w lower input power demand for similar hot junction and output current conditions (799 w vs 854 w) and a 20°C smaller ΔT with, as a

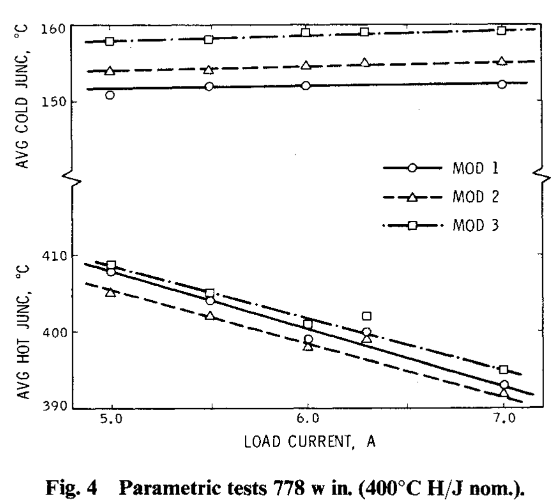

Fig. 4 Parametric tests 778 w in. (400°C H/J nom.).

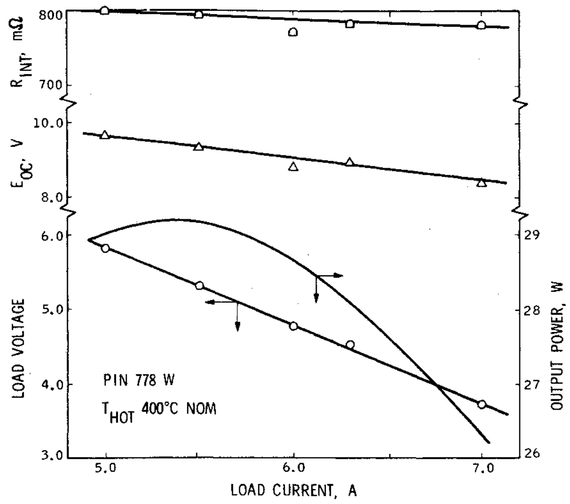

Fig. 5 Parametric tests 778 w in. (complete generator).

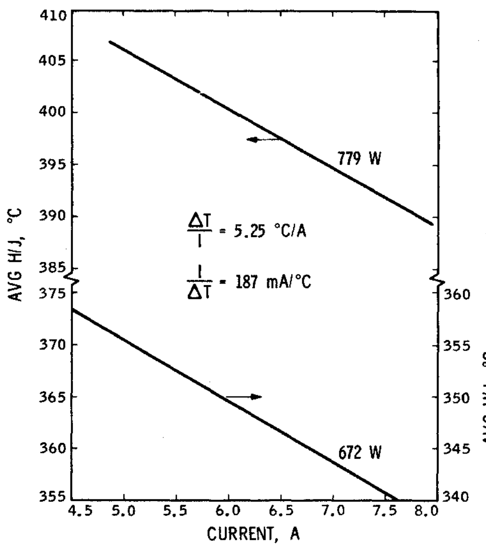

Fig. 6 Output current vs hot junction temperature (Group 1).

consequence, a lower power output. Comparison of the data after normalization is presented in Table 1. The normalization was based on $(\Delta T_2/\Delta T_1)^2 \times P_1 = P_2$. The output power was calculated from the current-voltage values and was normalized first to the ΔT observed at the manufacturer (value *A*) and second (for the three panel groups) to a ΔT of 265°C (value *B*). The internal resistance of the individual panels and that of the three panel groups are presented as those measured with alternating current and also as calculated at JPL by $(E_{oc} - E_L)/I_L$. No similar data were available from the manufacturer as no E_{oc} data were recorded for the selected conditions. It is surmized that the reasons for the discrepancies between the measurements may be attributed to the differences in measurement techniques and instrumentation between the two facilities and possible difference in the values of the internal resistance of the individual panels.

The influence of the output current on the M1 average hot junction temperature for Group 1 (composed of the three flight-type panels) is presented in Fig. 6 for two values of input power. At BOL of the generator, the Peltier effect corresponds to 5.25°C/amp. The individual values of the average Seebeck coefficient calculated at an input power of 779 w and at an output current of 6 amp, with a nominal hot junction temperature of 400°C, but a variable ΔT resulting from different values of cold junction in each panel were, respectively: Panel 112 $\bar{\alpha} = 3.29$ mv, Panel 116 $\bar{\alpha} = 3.39$ mv, and Panel 104 $\bar{\alpha} = 3.18$ mv, which resulted in an average value for the three flight-type panels of $\bar{\alpha} = 3.27$ mv. The Seebeck coefficient of Group M1, which consisted of the three flight panels connected in series, was $\bar{\alpha} = 9.814$ mv. No comparison could be made with values as observed at the manufacturer, since for this particular condition no open-circuit voltage values were available.

The effects of changes in the total input power on the output power of the individual groups of panels, and on the 12-panel generator (QM-III) are presented in Fig. 7. This effect has a value of 0.021 W_o/W_{in} (total) in the case of Groups M1 and M2 (flight-type panels and new cold-pressed panels), and 0.0355 W_o/W_{in} for Group M3 (assembled with used cold-pressed panels). The effect on the QM-III generator as a whole (computed by adding the output power from the three groups of panels) was calculated to be 0.0792 W_o/W_{in}, for a 50 w change (five years) in the input power (774 w–724 w). This data will allow one to differentiate during the long-term life test between the effects due to changes in material properties and the effects due to the thermal decrease of the radioisotopic fuel.

A comparison was made between the values observed at JPL for the three flight-type panels (Group M1), Panels 104, 113,

Table 1 Data comparison (test conditions: JPL – $P_{in} = 779$, $I_o = 6.00$; GGA – $P_{in} = 874$, $I_o = 6.018$)

Panel	$\bar{T}_h$ °C	$\bar{T}_c$ °C	ΔT°C	E_{oc} v^a	E_L v	P_o w	$P/P_o(A)$ w^b	$P/P_o \Delta T =$ 265$(B)^c$	*R* meas. $m\Omega^d$	*R* calcu. $m\Omega$	Location
112	395	146	249	0.819[a]	0.408	2.448	2.526		62.51	68.51[a]	JPL
	387.6	128.6	252.6		0.485	2.92	$\Delta P = 0.394$		54.78		GGA[e]
116	396	159	237	0.804[a]	0.406	2.436	2.863		60.47	60.3[a]	JPL
	391.1	133.4	257		0.472	2.842	$\Delta P = 0.021$		57.54		GGA[e]
104	408	152	256	0.806[a]	0.423	2.538	2.931		57.85	63.8[a]	JPL
	402.1	126.8	275.3		0.491	2.95	$\Delta P = 0.019$		55.93		GGA[e]
Group	399.6	152.3	247.3	2.427[a]	1.237	7.422	7.996	34.09	181.35	206.16[a]	JPL
I	394.0	137.33	256.7		1.448	8.738	$\Delta P = 0.742$	37.25	...		GGA[e]
93	396	161	235	0.791[a]	0.424	2.544	2.739		56.24	61.20[a]	JPL
	390	137	253		0.479	2.88	$\Delta P = 0.141$		53.54		GGA[e]
95	402	159	243	0.793[a]	0.421	2.526	2.864		56.56	62.00[a]	JPL
	393	134	259		0.480	2.89	$\Delta P = 0.026$		53.64		GGA[e]
96	397	144	253	0.796[a]	0.413	2.478	2.537		58.59	63.83[a]	JPL
	388	132	256		0.480	2.89	$\Delta P = 0.053$		53.34		GGA[e]
Group	398.3	154.6	243.7	2.356[a]	1.257	7.542	8.482	35.672	171.72	183.16[a]	JPL
II	392.7	134.26	258.44		1.44	8.66	$\Delta P = 0.178$	36.420	...		GGA[e]

[a] E_{oc} data not available.
[b] P_o normalized to GGA ΔT.
[c] P_o normalized to $\Delta T = 265$°C × 4 for values of 12-panel generator.
[d] a.c. measurements JPL 1 amp–GGA 3 amp.
[e] Gulf General Atomics, San Diego, Calif. GGA designed and assembled both the generator flown on the Transit satellite and the QM-III generator.

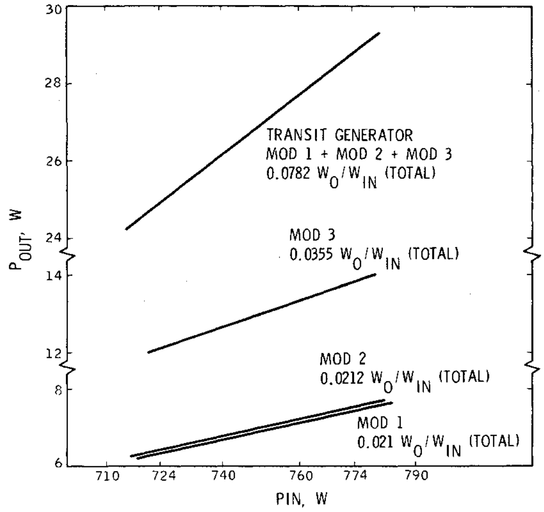

Fig. 7 Power output vs power input (QM-III generator).

and 116), and the data received from the generator flying on Transit (point 260 observed at 01.58). The comparison was made at an output current value of 6.30 amp and at a hot junction temperature of 400°C. In both cases, the power output was normalized for a ΔT of 265°C. In the case of the flight-type panels, the values were extrapolated to a hypothetical generator assembled with 12 panels. At JPL, Group M1 was operated under the following conditions: $\bar{T}_h = 400$°C, $\bar{T}_c = 147.2$°C, $\bar{\Delta T} = 253.3$°C, output voltage 1.180 v, output current 6.30 amp. For a 12-panel generator (hypothetical), the power output normalized for a $\bar{\Delta T} = 265$°C was 33 w with an output voltage $\Sigma_{12} = 4.72$ v. The generator on the Transit satellite had the following characteristics: $\bar{T}_h = 399.7$°C, $\bar{T}_c = 133.3$°C, $\Delta T = 266.4$°C, and $V_o = 5.581$ v. The output power normalized to $\Delta T = 265$°C was 35.6 w or 2.6 w higher than that extrapolated from the data observed at JPL from Group 1.

Life Test

After the 502 hr of operation required to perform the parametric test, the generator was adjusted for operation in a long-term life test mode. The conditions for this operation at BOL are $P_{in} = 744$ w, $\bar{T}_h = 400$°C nom. (for flight-type panels), $\bar{T}_c = 151.8$°C, $\bar{\Delta T} = 250.6$°C, $I_L = 5.301$ amp, $E_L = 1.40$ v, $P_o = 7.423$ v, normalized output power $P_{o265} = 33.20$ w. At the same input power and output voltage, Group 2 (new cold-pressed panels) operated at a $\bar{T}_h = 400.8$, $\bar{T}_c = 154.0$, $\bar{\Delta T} = 246.8$, $I_L = 5.354$ amps, while Group 3 (composed of used panels) for the same input power operated at $\bar{T}_h = 404.5$, $\bar{T}_c = 158.1$ $\Delta T = 246.3$, $V_L = 2.60$ v, and $I_L = 5.324$ amp.

The life test is performed at a fixed and constant output voltage from each group of panels and the input power is periodically decreased to follow the radioisotope decay scheme. At present, the generator has operated at JPL for a total accrued time of 4000 hr. During this time the degradation in output power of the different modules and that of the generator as a whole was calculated as: $M_1 = 1.25\%/1000$ hr, $M_2 = 2.21\%/1000$ hr, $M_3 = 1.44\%/1000$ hr, and generator total $= 1.6\%/1000$ hr. These values include both the material bulk property changes and the effects of the reduction in input power, simulating the isotope decay scheme. Discounting the latter indicates that the changes in thermoelectric material bulk properties *only* are $M_1 = 1\%/1000$ hr, $M_2 = 2.04\%/1000$ hr, $M_3 = 1.224\%/1000$ hr, generator total $= 1.37\%/1000$ hr. It should be remembered that M_1 was assembled with materials made by the warm vacuum-pressed process while M_2 and M_3 used couples made by the cold-press process. The difference between M_2 and M_3 is that M_2 was assembled with new material which had not experienced the "burn in" settling period, while the materials used in M_3, having been tested previously for long time periods, were settled and are more representative of the behavior of the cold pressed material.

Conclusions

A thermoelectric generator similar to the generator flown on Transit and assembled with 12 Isotec-type panels, three of which represent flight hardware, is presently on test at JPL. After extensive parametric tests, the generator is operating in a long-term life test mode, during which the input power will be reduced to simulate the radioisotopic decay. The panels in the test generator are electrically grouped as three independent generators, each with its independent load circuit. The life test is conducted at a constant output voltage from each group of panels. Comparison made between the data received from the generator mounted on the Transit spacecraft and the results observed at JPL from the group composed of the flight-type panels (extrapolated to 12 panels) indicated that for a normalized $\Delta T = 265$°C, the output of the test panels is slightly lower than that recorded from the flight generator.

References

[1] Bradshaw, G. and Postula, F., "Description and Status of the Transit Thermoelectric Converter," *7th IECEC Proceedings*, Sept. 1972, pp. 200–215.

Aerodynamic Heat Transfer to RSI Tile Surfaces and Gap Intersections

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THE design of a space shuttle orbiter, reusable for a hundred or more missions, dictates that the thermal protection system be lightweight, reliable, and last for many missions with minimal costs for refurbishment.[1] As currently envisioned, most of the orbiter surface will be covered with a nonmetallic, low-density refractory oxide. This material, referred to by the acronym RSI (Reusable Surface Insulation), both withstands (without degradation) the high heating rates and temperatures of repeated missions, and insulates the cold structure of the shuttle from the re-entry environment.[2] The material will be attached to the surface in 6-in. square tiles which vary in thickness from about ½-in. in the low heating areas to 3 in. where the heating is intense. Small gaps between the tiles will allow for differential expansions which result from the many varied thermal conditions to which the exterior surface and bondline between the tile and structural interface are exposed during a mission.[3] Heating inside the gaps and the change in the surface aerodynamic heating characteristics which results from the presence of the gaps are of serious concern to the designer and are the subject of this Note.

Aerothermal heating tests of a simulated RSI tile array were made on the sidewall of the Langley Research Center's Mach 10 Continuous Flow Hypersonic Tunnel[4] where the wall boundary layer was used to simulate a thick turbulent boundary-layer condition on the orbiter. The tile array, shown schematically in Fig. 1, consisted of actual RSI tiles 2.55 in. thick,

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