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ABLATION TEST RESULTS ON MATERIALS EVALUATED
IN THE AVCO 10 MW ARC FACILITY FOR SANDIA
LABORATORIES

MASTER

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August 4, 1967

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for

Sandia Laboratories
Albuquerque, New Mexico

under

Contract Number 48-5902

ABSTRACT

Ablation test data for graphite materials (ATJ, AXF5Q, ACF-4Q, Graphitite "G" and PO-3) tested in the AVCO 10 MW Arc Facility are presented. Each material was tested at two conditions; nominally $H/RT_0 = 270$ - import pressure 4.8 atmos and $H/RT_0 = 190$ import pressure 7.0 atmos. Jet calibration data, gross material recession, surface temperature and post test pictures are given.

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TABLE OF CONTENTS

	<u>Page</u>
I. GENERAL DISCUSSION	5
A. Test Program	5
B. Facility Description and Instrumentation	5
II. TEST RESULTS	6
1. Impact Pressure Measurements	6
2. Stagnation Region Heat Transfer	6
3. Ablation Tests	10
APPENDIX A - Enthalpy Probe Measurements	43
APPENDIX B - Gas Sampling and Analysis	51
APPENDIX C - Exit Nozzle Flow Coefficient	59

ABLATION TEST RESULTS ON MATERIALS EVALUATED IN THE AVCO 10 MW ARC FACILITY FOR SANDIA LABORATORIES

I. GENERAL DISCUSSION

A. Test Program

The following discussion presents the results of a splash test program conducted in the Avco 10 Megawatt Arc Facility for the Sandia Laboratories, Albuquerque, New Mexico under Contract No. 48-5902. The tests were run during the time period between 16 May and 15 June 1967. Mr. D. F. McVey was Contract Monitor.

Several grades of graphite were subjected to the environments produced by the 10 Megawatt Arc Facility. Gas stream enthalpy and gas composition of the jet was checked by means of the Avco split flow enthalpy probe and the results are reported in Appendix A and B, respectively. Further checks on the sonic nozzle method of obtaining gas enthalpy were made by obtaining flow coefficients of the nozzles and recomputing gas enthalpy. These results are reported in Appendix C.

B. Facility Description and Instrumentation

The 10 Megawatt Arc Facility, fully described in reference 1, consists basically of a 4-inch diameter spherical plenum chamber into which four arc heads exhaust radially. The heated air mixes in the plenum and exits in a direction perpendicular to the plane of the arcs through an exit nozzle. For the tests two different exit nozzles were utilized, one being a nominal Mach 2.0 nozzle with a throat diameter of 0.931 inch and the other a Mach 2.2 nozzle with a throat diameter of 0.765 inch.

Photographic coverage of the tests included a 35 mm Nikon camera set at a frame speed of approximately 4 frames/second and a 128 frame/second Bell & Howell movie camera.

Surface temperatures of the ablating specimens were obtained by means of a calibrated (Therm-dot, Model TD9F) high resolution pyrometer. The pyrometer operation is based on the fact that an object emits thermal radiation as a function of its temperature. A lens focuses this radiation onto a sensitive detector which generates a signal voltage proportional to the radiation intensity. This signal is amplified to drive a meter calibrated in degrees centigrade. The pyrometer is sighted on the object by means of a straight through nonparallax telescopic sight. A circular reticle in the telescopic sight exactly defines the area of the object being measured. For these tests the spot diameter was 0.15 inch. Quoted accuracy of the instrument is 1% of the temperature span. The pyrometer contains an emittance compensation from 0.1 to 1.0 which automatically corrects the direct reading temperature scales as well as the recorder output voltage. For all tests this was set at $\epsilon = 1.0$ since the emissivity was unknown. In an attempt to

obtain values of stagnation temperature, the pyrometer was aimed at a point downstream of the front face of the model such that near the end of the run, the front face of the model would have receded into the field of view of the pyrometer. For these tests the meter was set at the high temperature range. Therefore, temperatures below 3800°F were not obtainable.

II. TEST RESULTS

High Pressure Tip Tests

1. Impact Pressure Measurements

Impact pressure measurements were obtained in the free jet for both nozzles at 0.5, 1.0 and 1.5 inches downstream of the nozzle exit plane utilizing an Avcomet (copper impregnated tungsten) probe (Figure 1). The data obtained is presented in Table I.

NOZZLE - .931 THROAT DIA

Figure 1. Schematic - Impact Pressure Probe

The Mach numbers shown in the table were obtained using $\gamma = 1.2$ and assuming an isentropic expansion to 1.0 atmosphere at the nozzle exit. In an attempt to achieve the desired levels of impact pressure and H/RT_0 , the 0.765 inch diameter nozzle was run at plenum pressures slightly higher than design pressure and therefore the nozzle ran slightly under expanded. The data, however, indicates good repeatability of test conditions for both exit nozzles.

2. Stagnation Region Heat Transfer

Stagnation region heat transfer rates were obtained 1.0 inch downstream of the nozzle exit plane on the jet centerline and 0.15 inch

TABLE I

10 Megawatt Arc Impact Pressure Data

Run No.	D* (inch)	X (inch)	H/RT ₀	P _{plenum} (atmos)	$\dot{m}$ (lb/sec)	P _{impact} (atmos)	Mach No.
7474	0.931	1.0	271	7.06	0.247	4.72	1.92
7475	0.931	1.5	277	7.20	0.250	4.95	1.97
7480	0.931	1.0	270	7.06	0.248	4.68	1.91
7481	0.931	1.5	269	7.06	0.248	4.77	1.93
7509	0.931	1.0	271	7.05	0.247	4.52	1.87
7510	0.931	0.5	271	7.05	0.247	4.67	1.91
7513	0.765	1.0	211	13.28	0.343	7.36	2.49
7514	0.765	0.5	193	12.9	0.344	6.67	2.32
7515	0.765	1.0	190	12.7	0.341	6.39	2.27
7539	0.765	0.5	197	12.97	0.343	6.81	2.34
7540	0.765	1.0	196	13.00	0.345	6.56	2.30

off centerline for 0.931 inch diameter nozzle. Measurements with the 0.765 inch diameter nozzle were made at 0.5 inch and 0.75 inch downstream of the nozzle exit plane on the jet centerline. The calorimeter used was a 3/16 inch diameter right circular cylinder by 1.5 inch long Avco transient null point copper calorimeter press fitted into a graphite shroud of similar size and shape to the ablation specimens. It should be noted that the calorimeter face was flat and not contoured to radius of the specimen. A chromel alumel thermocouple is embedded 0.010 inch from the surface of the slug. The resulting calorimeter time-temperature history is taken as the input to a computer program where a simple one-dimensional heat transfer calculation is performed.

At the extremely high heat transfer rates obtained in the facility, the melting point of the calorimeters was exceeded prior to the time at which the gas enthalpy and plenum pressure achieved steady state values. Careful examination of the transients in the arc current, voltage and plenum pressure for any particular operating condition clearly indicated that the time required for the plasma generator to achieve steady state was reproducible. Hence, it is possible to generate calorimeter response curves which will allow one to determine the heat transfer rate which would be achieved under steady state operating conditions by plotting the instantaneous calorimeter heat flux (normalized with the indicated flux at an arbitrary time of 0.10 second) as a function of time (Figures 2 and 3). The excellent agreement of the calorimeter response curves are clearly evident when presented in this manner. The steady state heat transfer rates may then be obtained by multiplying the heat flux at 0.10 second by the asymptotic value of the normalized flux at any particular arc condition. Heat transfer rates obtained in this fashion are listed in Table 2 and are presented in Figure 4 as a function of calorimeter nose radius.

The effect of offsetting the calorimeter 0.15 inch from the jet centerline is probably small although it is difficult to assess from the scatter in the limited number of data points obtained with the 0.931

Figure 2. Nondimensional heating vs time
Nozzle throat diameter = 0.765 inch

Figure 3. Nondimensional heating vs time
Nozzle throat diameter = 0.931 inch

TABLE 2

10 Megawatt Arc Stagnation Region Heat Flux Data

Run No.	D* (inch)	X (inch)	Y (inch)	Shroud shape	P _{plenum} (atmos)	$\dot{m}$ (lb/sec)	H/RT ₀	$\dot{q}_{cw}$ (Btu/ft ² -sec)
7476	0.931	1.0	0.0	0.2 nose radius	7.06	0.248	270	9280
7477	0.931	1.0	0.0	Flat face	7.06	0.248	270	6460
7478	0.931	1.0	0.15	0.2 nose radius	7.06	0.248	270	11900
7479	0.931	1.0	0.15	Flat face	7.06	0.248	270	7950
7506	0.931	1.0	0.0	Flat face	7.16	0.252	268	8380
7508	0.931	1.0	0.0	0.2 nose radius	7.09	0.248	271	11650
7517	0.765	0.50	0.0	0.2 nose radius	12.70	0.341	190	11400
7518	0.765	0.75	0.0	Flat face	12.83	0.343	192	6900
7520	0.765	0.50	0.0	Flat face	12.70	0.341	190	7570
7521	0.765	0.75	0.0	0.2 nose radius	12.70	0.341	190	11060
7535	0.765	0.50	0.0	0.2 nose radius	12.83	0.341	194	9000
7538	0.765	0.50	0.0	Flat face	13.00	0.343	196	7300

Figure 4. Heat transfer calibration data

inch exit nozzle. However, since q varies directly as $\sqrt{P} H/RT_0$, and such excellent repeatability was obtained with the flat face calorimeter on centerline with the 0.765 inch diameter nozzle, an approximate level is calculated at 8500 Btu/ft²-sec for the 0.931 nozzle. This would tend to indicate that the heat transfer rate across the jet is relatively constant at least out to 0.15 inch.

Tests conducted with the 0.765 inch diameter nozzle indicates that axial movement of the calorimeter has essentially no effect on the q levels.

3. Ablation Tests

Ablation tests were run at two nominal test conditions. Condition 1 corresponded to an H/RT_0 of 270 and plenum pressure of 7.0 atm. Condition 2 corresponded to an H/RT_0 of 190 and a plenum pressure of 12.5 atm.

All ablation test specimens were supplied by Sandia Laboratories. The basic design features of the specimens are shown in Figure 5. For the flat faced models a plug containing three (3) tungsten 5% versus tungsten 26% rhenium thermocouples was inserted into the outer shell such that the thermocouples were located 0.1, 0.2 and 0.4 inch from the front face. The 0.20 inch nose radius models were solid models with a thermocouple hole in the rear containing one tungsten versus tungsten 26% rhenium thermocouple located 0.5 inch back from the front face.

② FLAT FACED SPECIMEN ASSY (SHIELDED)

① BLUNT NOSE SPECIMEN ASSY

Figure 5. High pressure ablation test specimens

The various grades of graphite tested included ATJ, P-03, POCO AXF-5Q, POCO AXF-5Q (hot isostatically compacted), POCO ACF-4Q, and graphite "G".

Table 3, the run summary, presents test conditions, length and weight losses and comments as to any unusual occurrences during the run. Figures 6 through 26 present time-temperature histories obtained from the thermocouple and the surface brightness temperature ($\epsilon = 1.0$) recorded by the pyrometer. True surface temperature can be obtained by using the correct value of emissivity for the material. Note that values of surface temperature below 3800°F were not obtainable with the high resolution pyrometer.

Post test photographs of the samples are shown in Figures 27 through 33.

TABLE 3
10 MEGAWATT ARC TIP TEST SUMMARY

Rur No.	* Sample No.	Sample description	Sample instr.	Gas enthalpy H/RT ₀	Test time (sec)	Heat flux q_{cw} (Btu/ft ² sec)	Gas mass flow (lb/sec)	Plenum pressure (atms)	Power to air (MW)	Sonic nozzle dia. (in.)	Total mass loss of sample (grams)	Sample length Pre-run (in.)	Post-run (in.)	Remarks
CONDITION 1														
7482	G-3	Graphitite R _N = 0.20	---	264	7.05	---	0.248	7.03	2.34	0.931	1.00	1.602	1.411	
7481	A-5	ATJ Graphite	---	264	6.60	---	0.248	7.03	2.34	0.931	1.30	1.600	1.38	
7482	P-3	PO-3 Graphite	---	264	6.44	---	0.248	7.03	2.34	0.931	1.25	1.605	1.417	
7485	P-4	PO-3 Graphite	---	262	6.43	---	0.248	6.99	2.32	0.931	1.50	1.606	1.401	
7486	5Q-4	5Q POCO Graphite	---	262	6.43	---	0.248	6.99	2.32	0.931	1.00	1.604	1.398	
7487	5Q-5	5Q POCO Graphite	---	271	6.44	---	0.247	7.06	2.39	0.931	1.10	1.604	1.396	
7488	5Q-14	5Q POCO Graphite	---	269	7.05	---	0.248	7.06	2.38	0.931	0.90	1.607	1.429	
7489	5Q-15	5Q POCO Graphite	---	262	7.33	---	0.248	6.99	2.32	0.931	1.00	1.606	1.421	
7490	4Q-4	4Q POCO Graphite	---	263	7.59	---	0.247	6.99	2.32	0.931	1.90	1.608	1.151	Arc water leak wet model prior to run. Model dried out in oven.
7491	A-6	ATJ Graphite	1 T/C	259	7.59	---	0.246	6.92	2.28	0.931	1.25	1.605	1.370	
7492	P-5	PO-3 POCO Graphite	1 T/C	257	7.57	---	0.248	6.96	2.28	0.931	1.35	1.605	1.368	
7493	G-4	Graphitite	---	261	7.60	---	0.248	6.99	2.31	0.931	0.75	1.605	1.418	Arc water leak at end of run.
7494	4Q-5	4Q POCO Graphite	---	269	6.93	---	0.248	7.06	2.38	0.931	2.40	1.604	0.903	Tip broke 0.82 seconds into the run.
7495	A-7	ATJ Graphite	---	271	7.56	---	0.248	7.09	2.40	0.931	0.95	1.604	1.376	
7497	5Q-6	5Q POCO Graphite	1 T/C	268	2.76	---	0.248	7.05	2.37	0.931	--	1.603	--	Run cut--arc water leak.
7493	5Q-16	5Q POCO Graphite	1 T/C	272	6.94	---	0.249	7.12	2.42	0.931	1.60	1.608	1.310	No pyrometer reading--model tip broke.
7499	G-5	Graphitite	1 T/C	268	6.98	---	0.248	7.06	2.37	0.931	1.05	1.608	1.421	
7501	5Q-7	5Q POCO Graphite	1 T/C	276	6.94	---	0.248	7.12	2.44	0.931	1.20	1.605	1.326	
7502	4Q-10	4Q POCO Graphite	1 T/C	276	6.98	---	0.248	7.12	2.44	0.931	--	1.608	--	Model tip broke off. Remainder of model cracked.
7503	4Q-22	4Q POCO Graphite	3 T/C's	268	5.05	---	0.252	7.16	2.41	0.931	--	---	--	Model broke. Run cut.
7504	A-13	ATJ Graphite	3 T/C's	274	7.01	---	0.246	7.06	2.41	0.931	--	---	--	No pyrometer reading. Model dished.
7505	A-15	ATJ Graphite	3 T/C's	271	4.00	---	0.248	7.09	2.40	0.931	--	---	--	Model dished.
CONDITION 2														
7522	A-8	ATJ Graphite	---	192	7.03	---	0.343	12.83	2.35	0.765	1.20	1.607	1.243	
7523	A-9	ATJ Graphite	1 T/C	186	4.97	---	0.341	12.59	2.27	0.765	0.60	1.605	1.429	
7524	P-7	POCO Graphite	1 T/C	186	5.95	---	0.338	12.48	2.24	0.765	0.80	1.607	1.416	
7525	P-6	POCO Graphite	---	198	6.01	---	0.343	12.97	2.43	0.765	1.50	1.608	1.186	
7526	5Q-9	5Q POCO Graphite	1 T/C	198	5.96	---	0.343	12.97	2.43	0.765	1.25	1.602	1.292	
7527	5Q-18	5Q POCO Graphite	1 T/C	198	5.08	---	0.345	13.04	2.44	0.765	--	1.609	1.455	Sample broke. Run cut.
7528	4Q-7	4Q POCO Graphite	1 T/C	195	5.95	---	0.341	12.83	2.38	0.765	1.10	1.607	1.276	
7529	G-6	Graphitite	1 T/C	198	5.99	---	0.343	12.97	2.43	0.765	0.40	1.604	--	
7530	5Q-8	5Q POCO Graphite	1 T/C	198	5.97	---	0.343	12.97	2.43	0.765	0.90	1.604	1.294	
7531	A-20	ATJ Graphite	3 T/C's	198	4.02	---	0.343	12.97	2.43	0.765	--	1.59	--	Gas flow through sample.
7532	A-21	ATJ Graphite	3 T/C's	196	3.98	---	0.345	13.00	2.42	0.765	--	1.59	--	Gas flow through sample.
7533	4Q-8	4Q POCO Graphite	---	195	5.96	---	0.343	12.90	2.39	0.765	1.00	1.603	1.279	Model tip broke 2.55 seconds into run.
7534	5Q-17	5Q POCO Graphite	---	194	5.95	---	0.341	12.83	2.36	0.765	1.40	1.608	1.224	Model chipped during run.

* Material Code - G = Graphitite G
A = ATJ
P = PO-3
5Q = AIF-5Q
4Q = ACF-4Q

Figure 6. Temperature vs time

Figure 7. Temperature vs time

Figure 8. Temperature vs time

Figure 9. Temperature vs time

Figure 10. Temperature vs time

Figure 11. Temperature vs time

Figure 12. Temperature vs time

Figure 13. Temperature vs time

Figure 14. Temperature vs time

Figure 15. Temperature vs time

Figure 16. Temperature vs time

Figure 17. Temperature vs time

Figure 18. Temperature vs time

Figure 19. Temperature vs time

Figure 20. Temperature vs time

Figure 21. Temperature vs time

Figure 22. Temperature vs time

Figure 23. Temperature vs time

Figure 24. Temperature vs time

Figure 25. Temperature vs time

Figure 26. Temperature vs time

Figure 27. High pressure tip specimens - Graphitite "G" post test
Condition 1: $H/RT_0 \approx 270$ $P_{\text{impact}} \approx 4.8$ atmos
Condition 2: $H/RT_0 \approx 190$ $P_{\text{impact}} \approx 7.0$ atmos

Figure 28. High pressure tip specimens - ATJ post test
Condition 1: $H/RT_0 \approx 270$ $P_{\text{impact}} \approx 4.8$ atmos
Condition 2: $H/RT_0 \approx 190$ $P_{\text{impact}} \approx 7.0$ atmos

Figure 29. High pressure tip specimens - P0-3 post test
Condition 1: $H/RT_0 \approx 270$ $P_{\text{impact}} \approx 4.8$ atmos
Condition 2: $H/RT_0 \approx 190$ $P_{\text{impact}} \approx 7.0$ atmos

Figure 30. High pressure tip specimens - AXF-5Q post test
Condition 1: $H/RT_0 \approx 270$ $P_{\text{impact}} \approx 4.8$ atmos
Condition 2: $H/RT_0 \approx 190$ $P_{\text{impact}} \approx 7.0$ atmos

Figure 31. High pressure tip specimens - ACF-5Q post test
Condition 1: $H/RT_0 \approx 270$ $P_{\text{impact}} \approx 4.8$ atmos
Condition 2: $H/RT_0 \approx 190$ $P_{\text{impact}} \approx 7.0$ atmos

Figure 32. High pressure tip specimens - ACF-4Q post test
 Condition 1: $H/RT_0 \approx 270$ $P_{\text{impact}} \approx 4.8$ atmos
 Condition 2: $H/RT_0 \approx 190$ $P_{\text{impact}} \approx 7.0$ atmos

Figure 33. High pressure tip specimens - ATJ post test
Condition 1: $H/RT_0 \approx 270$ $P_{\text{impact}} \approx 4.8$ atmos
Condition 2: $H/RT_0 \approx 190$ $P_{\text{impact}} \approx 7.0$ atmos

APPENDIX A

Enthalpy Probe Measurements

APPENDIX A

ENTHALPY PROBE MEASUREMENTS

General

In order to check the sonic throat method of calculating gas enthalpy in the Avco 10 Megawatt Arc Facility, tests were performed utilizing the Avco split flow enthalpy probe. It was intended to make several runs gradually increasing the enthalpy of the jet by increasing the number of arcs fired. Enthalpy checks were obtained for 1, 2, and 3 arc firings. Due to a large difference (greater than 10 percent) at the 3 arc condition in results obtained via probe data and sonic throat calculations, it was decided not to run the 4 arc condition for an enthalpy check but to obtain gas samples at the 3 arc condition instead. It would have been desirable to have taken gas samples and enthalpy data during the same run. However, this was not possible since the volume of gas collected during the enthalpy measurement was so low as to make detection of the species impossible. Separate runs therefore were made. During a gas sampling run, the probe began leaking cooling water thereby putting a halt to further testing.

Probe Setup

The Avco enthalpy probe is a split flow type consisting of four concentric tubes (Figure A-1). The incoming coolant splits at the tip of the probe, part flowing through the inner annulus adjacent to the gas sampling tube and part through the outer annulus. The probe operates on an energy balance technique, i.e., it collects a known amount of gas sample and then determines its heat content by measuring the temperature rise of the inner coolant stream. Since a substantial amount of heat is transferred to the inner coolant near the probe tip from the external stream when the probe is immersed in the hot gas stream it is necessary to record the temperature rise of the coolant prior to drawing the gas sample (a "tare" measurement).

The gas enthalpy is computed by equating the energy transferred to the coolant per unit time to the energy extracted from the gas sample per unit time.

$$h_s = \frac{\dot{m}_{H_2O}}{\dot{m}_g} C_{PH_2O} \left\{ (\Delta T_{H_2O})_{FLOW} - (\Delta T_{H_2O})_{NO FLOW} \right\} + C_{Pg} T_g \quad (1)$$

where

$$\dot{m}_{H_2O} = \frac{W_{H_2O}}{t} \quad (2)$$

Figure A-1. Schematic diagram of split flow enthalpy probe

and

$$\dot{m}_g = \frac{V}{Rt} \left(\frac{P_2}{T_2} - \frac{P_1}{T_1} \right) \quad (3)$$

Since the temperature rise in the collecting tank is negligible; $T_1 = T_2 = \text{room temperature}$. Therefore

$$\dot{m}_g = \frac{V}{Rt} \left(\frac{P_2 - P_1}{T_1} \right) \quad (4)$$

Substituting (2) and (4) into (1) we obtain:

$$h_s = \frac{W_{H_2O}(R)T_1}{V} (C_{PH_2O}) \frac{(\Delta T_{H_2O})_{\text{FLOW}} - (\Delta T_{H_2O})_{\text{NO FLOW}}}{(P_2 - P_1)} + C_{Pg} T_g \quad (5)$$

Therefore, by measuring the amount of coolant (inner) flow (W_{H_2O}), pressure and temperature of the gas in a known volume before and after admitting the gas sample (P_1 , P_2 , and T_1), the temperature rise of the coolant during the tare and sampling modes of operation, and the temperature of the gas as it leaves the probe, the gas enthalpy is easily computed. The exit nozzle used was a nominal $M = 2$ contoured nozzle installed at the end of a 10 inch long water cooled extension. The throat and exit diameters for all probe tests were 0.931 inch and 1.278 inches, respectively.

Discussion of Results

A. Enthalpy Probe

Six enthalpy probe runs were made, three at the 1 arc condition, two at the 2 arc condition, and one at the 3 arc condition. The results are shown tabulated below compared to sonic throat enthalpy calculations.

Run number	Number of arcs fired	Probe H/RT_0	Sonic throat H/RT_0	Plenum pressure (atm)	Stream* Mach number
7545	1	57.2	57	4.04	1.16
7546	1	62.2	64	4.04	1.16
7547	1	66.3	66	4.04	1.16
7549	2	112.7	130	5.354	1.48
7550	2	112.9	126	5.354	1.48
7551	3	136.1	175	6.016	1.62

*Mach numbers calculated assuming stream static pressure of 1 atmos.

Agreement was excellent for the 1 arc cases but became poorer as the number of arcs was increased. A possible explanation of this discrepancy can be obtained by considering the heat transfer to the tip of the probe. Ideally, the heat transferred to the coolant from external

sources should remain constant during the times the probe is in the gas stream during the tare and when flow is admitted to the probe. As such, an accurate measure can be made of the "tare" and therefore an accurate calculation of energy transferred to the coolant from the gas sample. Should this not be the case, the measured value of

$$(\Delta T_{H_2O})_{\text{FLOW}} - (\Delta T_{H_2O})_{\text{NO FLOW}}$$

in Equation 5 of the previous section is in error.

At Mach numbers close to unity where the shock in front of the probe is relatively weak, the heat transfer to the probe with and without flow is expected to be approximately equal and good results can be expected. At higher Mach numbers the shock detachment distance decreases and the flow characteristics around the probe can change from conical flow when taking the tare reading, to wedge flow when taking a sample as shown in the sketch below. The effect of this is to reduce the heat transfer to the tip of the probe by approximately 30%. Since the tare reading is about 1/2 the total ΔT of the coolant, a 30% increase in computed H/RT_0 would be obtained. For the 3 arc condition, an increase of this magnitude would bring the probe value of H/RT_0 up to sonic throat value. At the intermediate Mach numbers when the shock is not attached while drawing the sample it would be expected that the heat transfer rate at the tip of the probe would be somewhere between the cone and wedge value. If we assume, therefore a 15% drop in heat transfer to the probe for the 2 arc runs one can again explain the differences between probe measurements and sonic throat calculations.

Conclusions

The following conclusions are based on the tests described above:

1. The results obtained with the probe design used in this test compare favorably with sonic throat calculations of gas enthalpy when the stream Mach number is near unity.
2. At higher Mach numbers ($1 < M < 2$), as the shock detachment distance decreases, the possibility exists that the shock becomes attached while taking the gas sample, thereby reducing the heat transfer rate to the probe tip. This invalidates the tare reading and results in erroneous enthalpy measurements.
3. At high Mach numbers where the shock is always attached, this probe design would be expected to yield good results.

Recommendations

The following recommendations are made regarding enthalpy measurement techniques for the 10 Megawatt Arc Facility.

1. Since probe measurements will be compared directly to sonic throat calculations it is deemed unnecessary to make probe measurements with a supersonic exit nozzle. A simple sonic nozzle with the desired D^* would alleviate the problems involved in obtaining accurate tare measurements. Further, the probe should be located as close to the nozzle exit plane as practical in order to minimize any enthalpy decay effects.

2. It was noted that the sharp tip of the probe blunted slightly as the series of runs progressed until eventually the probe leaked. It is recommended that the probe tip be hemispherical rather than conical in order to provide more adequate cooling to the tip. Further, the hemispherical probe would increase the shock detachment distance which is desirable from a tare measurement standpoint.

APPENDIX B
Gas Sampling and Analysis

APPENDIX B
GAS SAMPLING AND ANALYSIS

General

Two gas samples were collected from the 10 MW Arc exhaust jet by means of the enthalpy probe described in Section A, and were analyzed in the F&M Model 720 Dual Column Programmed Temperature Gas Chromatograph. The samples were taken from Runs 7552 and 7553 (Table B-1).

Procedure

In gas chromatography, a sample is injected into the instrument and swept by a flow of inert gas (helium) onto a separating column. The column is generally a length of 1/4 inch diameter tubing packed with either a nonvolatile liquid coated on a solid support, or an adsorbent solid. The various species of the sample have different affinities toward the column packing, and separate into discrete moving bands as they are flushed through the column by the carrier gas (helium). As each specie band emerges from the column it enters a thermal conductivity detector which, by means of a Wheatstone bridge network, generates an electrical signal proportional to the concentration of the component in the carrier gas. This signal feeds a potentiometric recorder which produces the chromatogram.

Calibration is accomplished by injection of gas standards of known concentration from which elution time, (identification of species) and signal strength, (concentration) are determined.

The two gas samples were analyzed utilizing the following columns:

<u>Gas</u>	<u>Column type</u>	<u>Column length</u>	<u>Column temperature</u>
O ₂	#5A Molecular seive	20 ft	0°C
N ₂	Molecular seive	20 ft	0°C
Ar	Molecular seive	20 ft	0°C
CO ₂	Silica gel	20 ft	150°C
CO	Silica gel	20 ft	20°C
NO	Poropak	12 ft	27°C
N ₂ O	Poropak	12 ft	27°C

Results

The following average gas concentrations were determined from several sample injections.

A. 10 MW Arc Run 7552 (Probe located on jet centerline)

$$N_2 = 77.02\%$$

$$O_2 = 12.26\%$$

$$CO = 3.90\%$$

$$CO_2 = 0.73\%$$

$$Ar = 0.94\%$$

$$TOTAL\ MOLE\ PERCENT = 94.85$$

The dissociation of nitrogen tetroxide is represented by the equation

and would constitute the remaining 5.15%. Let α represent the fraction dissociated, then $1 - \alpha$ = fraction undissociated. For partially dissociated N_2O_4 at 1 atm pressure at 25°C, $\alpha = 0.185^{(1)}$ and

$$N_2O_4 = \frac{1-\alpha}{1+\alpha} (5.15)^{(1)}$$

and

$$NO_2 = \frac{2\alpha}{1+\alpha} (5.15)^{(1)}$$

The oxygen to nitrogen atom ratio is give by

$$\frac{O}{N} = \frac{2(12.26) + 3.90 + 2(0.73) + \frac{4(5.15)}{1.185}}{2(77.02) + \frac{2(5.15)}{1.185}} = 0.291$$

B. 10 MW Arc Run 7553 (0.12 inch from jet centerline)

$$N_2 = 78.86\%$$

$$O_2 = 12.36\%$$

$$CO_2 = 1.17\%$$

$$CO = 2.89\%$$

$$Ar = 0.94\%$$

$$TOTAL\ MOLE\ PERCENT = 96.22\ (N_2O_4 + NO_2) = 3.78$$

(1) Physical Chemistry, Farrington Daniels, Robert A. Alberty, J. Wiley & Sons, New York, New York, p 241.

$$\frac{O}{N} = \frac{2(12.36) + 2.89 + 2(1.17) + \frac{4(3.78)}{1.185}}{2(78.86) + \frac{2(3.78)}{1.185}} = 0.260$$

Discussion

A sample of gas from each of the two arc runs was passed through a 12 foot Poropak P column at 27°C to determine if any nitric oxide (NO), or nitrous oxide (N₂O) was present. None was detected. One would expect to find some nitric oxide present in the high temperature jet exhaust since the reaction

is extremely endothermic. However, in air, NO is rapidly oxidized by NO₂ which is brown in color. Since N₂O decomposes to N₂ and O₂ at high temperatures it would not likely be present in the jet exhaust.

The presence of nitrogen dioxide (NO₂) was confirmed by the characteristic brown color of the collected gas samples. Since NO₂ exists in equilibrium with nitrogen tetroxide (N₂O₄), the concentration of both these gases was determined analytically and their contribution to the oxygen-nitrogen atom ratio was quantitatively defined.

In addition to the foregoing analysis of gas species in the arc exhaust, carbon cathodes were weighed before and after several arc firings in order to determine the amount of carbon contamination in the arc exhaust (Table B-1). Since these were four arc firings, 75% of the carbon mass loss was plotted as a function of time in order to obtain the amount of carbon eroded for the three arc runs made when collecting the gas samples. The carbon mass loss rate for a three arc run was determined to be 0.01575 lb/sec (Figure B-1). The carbon contamination, therefore, for 10 MW Arc Runs 7552 and 7553 was calculated to be 6.32% by weight.

The amount of carbon contamination was then determined using the data obtained from the gas analyses. The atom ratios of C/N, O/N, and Ar/N were computed and the carbon contamination determined as follows:

$$\frac{LB \text{ (Carbon)}}{LB \text{ (air)}} = \frac{12(C/N)}{14(N/N) + 16(O/N) + 40(Ar/N)}$$

The results of this calculation indicates 1.8% and 2.16% carbon contamination by weight for Runs 7552 and 7553, respectively. All of the carbon lost as a result of cathode erosion is obviously not converted to CO₂ and CO. Some passes through the arc exhaust as free carbon particles and would not be detected in the gas analysis.

Conclusions

1. The oxygen to nitrogen atom ratios obtained through gas analysis are well within 10% of the known ratio for air; 0.269.

2. Great care was taken to insure that gas samples at pressures of slightly over 1 atm would be obtained for the purposes of preventing contaminating leakage into the sample bottle and facilitating the

TABLE B-1

Summary of 10 MJ Arc Run Conditions

Run No.	Plenum pressure (atm)	Throat diameter (inch)	Number cf arcs	H/RT_0	Air mass flow (lb/sec)	Carbon cathode weight loss (grams)	Time (sec)
7502	7.124	0.931	4	276	0.248	51.5	6.98
7503	7.159	0.931	4	268	0.252	32.9	5.05
7505	7.089	0.931	4	271	0.248	23.3	4.00
7552*	6.050	0.931	3	172	0.250	--	10.08
7553*	6.085	0.931	3	178	0.248	--	10.02

*Gas sampling run.

Figure B-1. Carbon cathode weight loss as a function of time
10 MW arc facility - 3 active arcs

detection of small concentrations of carbon dioxide, carbon monoxide, and argon. The total amount of combined carbon in the gas samples was approximately 2% by weight. Since only very small traces of carbon dioxide (approximately 0.02% by volume) are present in air it can be concluded that all of the carbon found in the gas samples came from cathode erosion. The difference in carbon to air ratios obtained using both the cathode weight loss from prior runs and gas analysis techniques reasonable in that one would not expect all of the carbon loss from the cathodes to become combined with the limited supply of oxygen found in air.

APPENDIX C

Exit Nozzle Flow Coefficient

APPENDIX C

EXIT NOZZLE FLOW COEFFICIENT

Gas enthalpy in the 10 Megawatt Arc Facility is determined from isentropic relationships utilizing measured values of plenum pressure (P_{plen}), mass flow rate ($\dot{m}$), and exit nozzle throat diameter (D^*). The nozzle flow coefficient is assumed to be unity. As a further check on quoted enthalpy, flow coefficients were obtained for a nominal 0.931 inch throat diameter exit nozzle. Since the flow coefficient is a function of Reynolds Number, cold flow tests at very low mass flow rates (0.01-0.03 lb/sec) were required in order to achieve Reynolds Numbers in the range obtained during hot flow runs with this nozzle. This necessitated use of the Avco 10 MW Wind Tunnel where the test chamber could be evacuated to very low pressures in order to maintain choked conditions at the nozzle. With this apparatus installed, several calibrated orifice plates were placed in the air line to the arc and accurate measurements of mass flow rate obtained. Plenum pressures and temperatures were obtained utilizing standard techniques and the exit nozzle diameter was measured with micrometers. Choked flow conditions were maintained both at the orifice and the exit nozzle. A schematic of the apparatus is shown below.

A series of cold flow runs was made on the nominal 0.931 inch throat diameter exit nozzle and flow coefficients calculated from the analysis below.

Since the flow coefficient is defined as

$$C_D = \frac{\dot{m}}{\dot{m}_{\text{IDEAL}}} \quad (1)$$

where

$$\dot{m}_{\text{IDEAL}} = \frac{P A}{\sqrt{T}} \left[\frac{g_0 \gamma}{R} \right]^{1/2} \left(\frac{2}{\gamma+1} \right)^{\frac{\gamma+1}{2(\gamma-1)}} \quad (2)$$

For $\gamma = 1.4$ and air, (1) and (2) reduce to

$$C_D = \frac{\dot{m} \sqrt{T}}{6.146 P D^{*2}} \quad (3)$$

where

$\dot{m}$ = mass flow (lb/sec)

P = plenum pressure (atmospheres)

T = plenum temperature ($^{\circ}R$)

D^* = nozzle throat diameter (inch)

The results are shown plotted in Figure C-1 as a function of Reynolds Number. In the range of Reynolds Number covered very little variation in discharge coefficient was obtained and a value of 0.99 is indicated. The effect on enthalpy is a reduction of 2-3% from the quoted value.

Figure C-1. Nozzle flow coefficient versus Reynolds Number

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