TG–881
DECEMBER 1966
Copy No. 2

Technical Memorandum

HIGH-PRESSURE ARC-JET ABLATION CHARACTERISTICS OF TEFLON

N. G. PAUL
F. FALK
L. O. KAUFFMAN

THE JOHNS HOPKINS UNIVERSITY • APPLIED PHYSICS LABORATORY

TG-881
DECEMBER 1966

Technical Memorandum

HIGH-PRESSURE ARC-JET ABLATION CHARACTERISTICS OF TEFLON

N. G. PAUL
F. FALK
L. O. KAUFFMAN

THE JOHNS HOPKINS UNIVERSITY • APPLIED PHYSICS LABORATORY
8621 Georgia Avenue, Silver Spring, Maryland 20910

Operating under Contract NOw 62-0604-c, Bureau of Naval Weapons, Department of the Navy

THE JOHNS HOPKINS UNIVERSITY
APPLIED PHYSICS LABORATORY
SILVER SPRING MARYLAND

ABSTRACT

Experimental data and the results of analyses are presented for Teflon ablation runs carried out in the Re-Entry Studies Project Mach 2 arc-jet tunnel at the Applied Physics Laboratory Propulsion Research Laboratory. Data were obtained under the following arc chamber conditions: 25 to 140 psia and 1500 to 4000 Btu/lb. These simulate stagnation region re-entry heating environments of 8500 to 14,000 ft/sec at altitudes of 64,000 to 114,000 feet.

A comparison of the data with three major theories showed that the analytical treatment of S. M. Scala closely predicted the levels and trends of the results. Teflon appears to be a considerably less efficient heat absorption material, by a factor of almost 2, than is conventionally anticipated.

TABLE OF CONTENTS

THE JOHNS HOPKINS UNIVERSITY
APPLIED PHYSICS LABORATORY
SILVER SPRING, MARYLAND

LIST OF ILLUSTRATIONS

LIST OF TABLES

LIST OF SYMBOLS

C_1	recombination rate parameter, dimensionless
H_{eff}	effective heat of ablation, Btu/lb
$H_{t_{arc}}$	total arc effluent enthalpy, Btu/lb
$\dot{m}$	mass loss rate, lbs/ft^2-sec
$P_{t_{arc}}$	total pressure in arc chamber, psia
q_o	calorimetric heat flux, Btu/ft^2-sec
q_{stag}	stagnation point heat flux, hot wall, Btu/ft^2-sec
Re_θ	momentum thickness Reynolds number, dimensionless
R_N	radius of curvature in stagnation region, inches
T_{surf}	model surface temperature, °F
V_{-m}	ablation velocity, in/sec
W	overall mass loss, lbs or gms
$\dot{w}_a$	air flow rate, lbs/sec
Y	total surface regression, inches
Z	compressibility factor, dimensionless
τ	time, seconds
τ_{ss}	time to steady state, seconds
γ	ratio of specific heats, dimensionless

INTRODUCTION

Teflon* has been investigated both experimentally and analytically for some time in respect to its reaction to high temperature environments. As an ablator, Teflon not only possesees some excellent heat protection capabilities, but is also one of the simplest materials to describe analytically. It is frequently used as a standard material, even though some major disagreements exist concerning its properties (Ref. 1,2, 3 and esp. Ref. 4), and is also used when other aspects of heat and mass transfer, rather than gross ablation per se, are being examined.

It is well known that most ballistic objects of a reasonable shape decelerate and thus experience maximum heating at the lower altitudes where combustion effects, high pressure levels, and high shearing forces take on increased significance in respect to material performance. It is also a fact that ablating materials, and their attendant reactions, are quite sensitive to the local environment ~ and that little data have been obtained under simulated lower altitude conditions. For example, in respect to Teflon, Ref. 1 points out that the effects of combustion could be quite severe at the lower stagnation enthalpy conditions ~ although, again, lack of data in this region has caused some doubt to exist concerning the size of these effects.

For practical purposes, three major theories exist concerning the ablation mechanisms of Teflon[1, 2, 3] ~ and one of their basic differences lies in the manner in which either the gas phase, or gas phase-solid phase coupling, is considered. Two of the theories[2,3] include combustion specifically while the third,[1] a simplified theory, gives only an upper limit for these effects.

---

*Trade name of the E.I. duPont de Nemours Corp. for its fluorocarbon product, polytetrafluoroethylene.

The Johns Hopkins University
APPLIED PHYSICS LABORATORY
Silver Spring, Maryland

Thus, the present series of experimental runs were conducted to both obtain a "standard" set of results with the APL/JHU arc-jet tunnel setup and also to investigate the simulated lower altitude environment where the combustion effects on Teflon are of particular importance.*

EXPERIMENTAL SETUP AND TEST CONDITIONS

The tests were conducted in the Re-Entry Studies Project arc-jet tunnel in cell 3A at the Propulsion Research facility at this Laboratory; a schematic of the experimental setup is shown in Figure 1. Only a brief account will be given of the apparatus, procedures, and measurement techniques since they will be covered in detail elsewhere (Ref. 5).

The air flow is metered upstream of the arc chamber by an ASME-contoured sonic nozzle. Pressures in the arc chamber are determined from static tap measurements which have been correlated with pressures obtained by a free-stream probe. Current and voltage to the arc unit are measured in a conventional manner. With these basic measurements, the real gas enthalpy level is determined based on a choked condition at the nozzle throat[18]; checks on the enthalpy levels have been made with both heat balances on the arc components (measured water flow rates and the corresponding increases in water temperature) and by means of aerodynamic copper-slug model probes placed downstream of the arc exhaust nozzle[6].

The arc effluent flow leaves the chamber, passes thru an 11" long water-cooled settling section and then thru a water-cooled Mach 2 (γ = 1.4)

*A very brief (unclassified) summary of the present work has been given in the Oct-Dec. 1965 issue of the APL/JHU Quarterly Progress Report series, AQR/65-4.

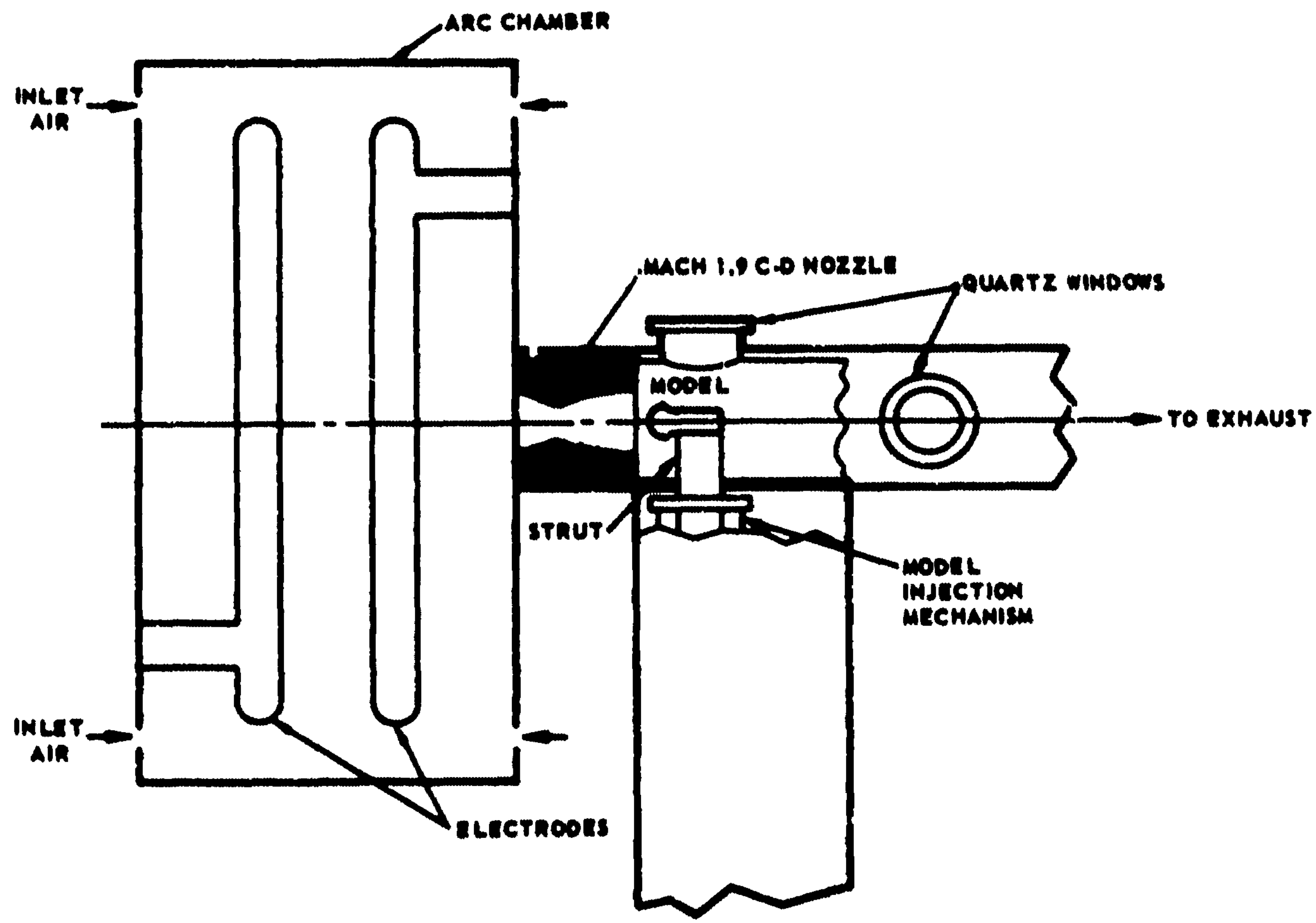

Fig. 1 EXPERIMENTAL SETUP–RE-ENTRY STUDIES PROJECT

exhaust nozzle. The nozzle, which has been especially contoured (Clippinger design) to give parallel flow conditions at the exit, exhausts into a 6" tunnel. The latter, containing suitable windows for schlieren, Fastax and Bolex photography, and other associated measurements, connects the complete arc unit to the exhaust system. Tunnel conditions are set according to the required real gas pressure ratio needed to start the nozzle. The data are obtained on strip chart recorders as well as magnetic tape using the facility data acquisition system.

The axisymmetric mushroom-shaped test models ($R_N \sim 0.4"$), with typical dimensions as shown in Figure 2, are very rapidly injected into the hot gas stream when arc conditions have stabilized. Every effort was made to hold arc chamber conditions constant during the test runs. Both injection and retraction times are in the order of 0.01 - 0.03 seconds; the result is essentially a square wave heat input to the test model with almost negligible errors introduced in respect to the determined ablation characteristics. The models are positioned in the stream in such a fashion that the entire face is within the Mach rhombus, i.e., no shock lines or waves impinge on the model face. A protective sleeve covers the model body, or stem, so that ablation or mass losses occur only from the face of the model. Figure 3 shows typical models before and after testing (1 model before testing, the others are after Runs 111, 114 and 122, respectively); Table I gives a brief summary of the more significant model measurements made before and after the runs. Length changes were generally determined with micrometer calipers* and weight changes with a chain balance. Nose radius changes were determined by the use of both precision radius gauges and an optical comparator.

*A specially-designed method of measurement (by L.O. Kauffman), utilizing precision height gauges, was employed on some of the later test models.

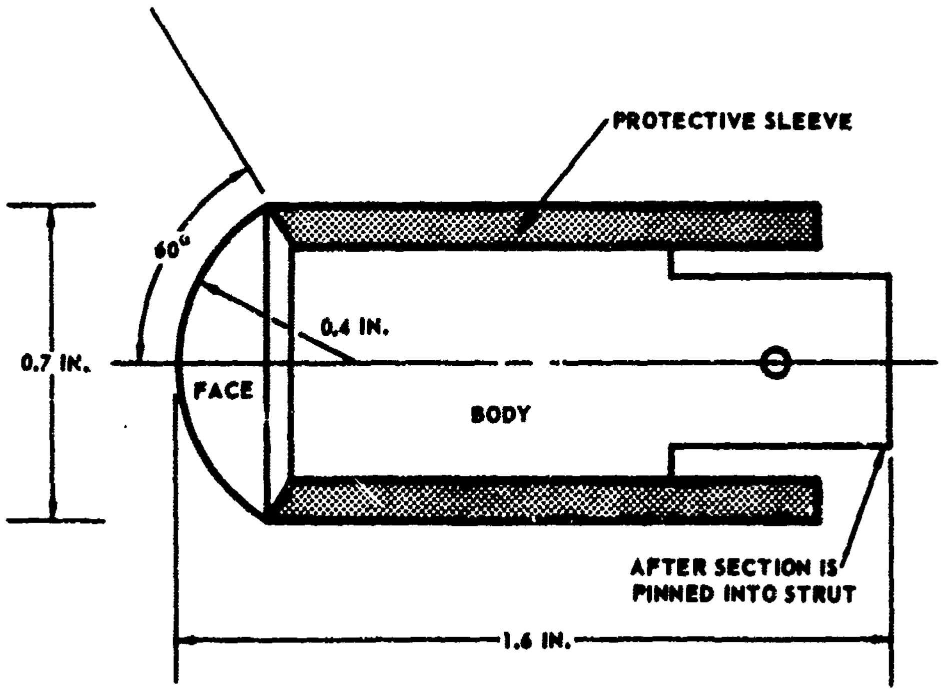

Fig. 2 TYPICAL TEST MODEL

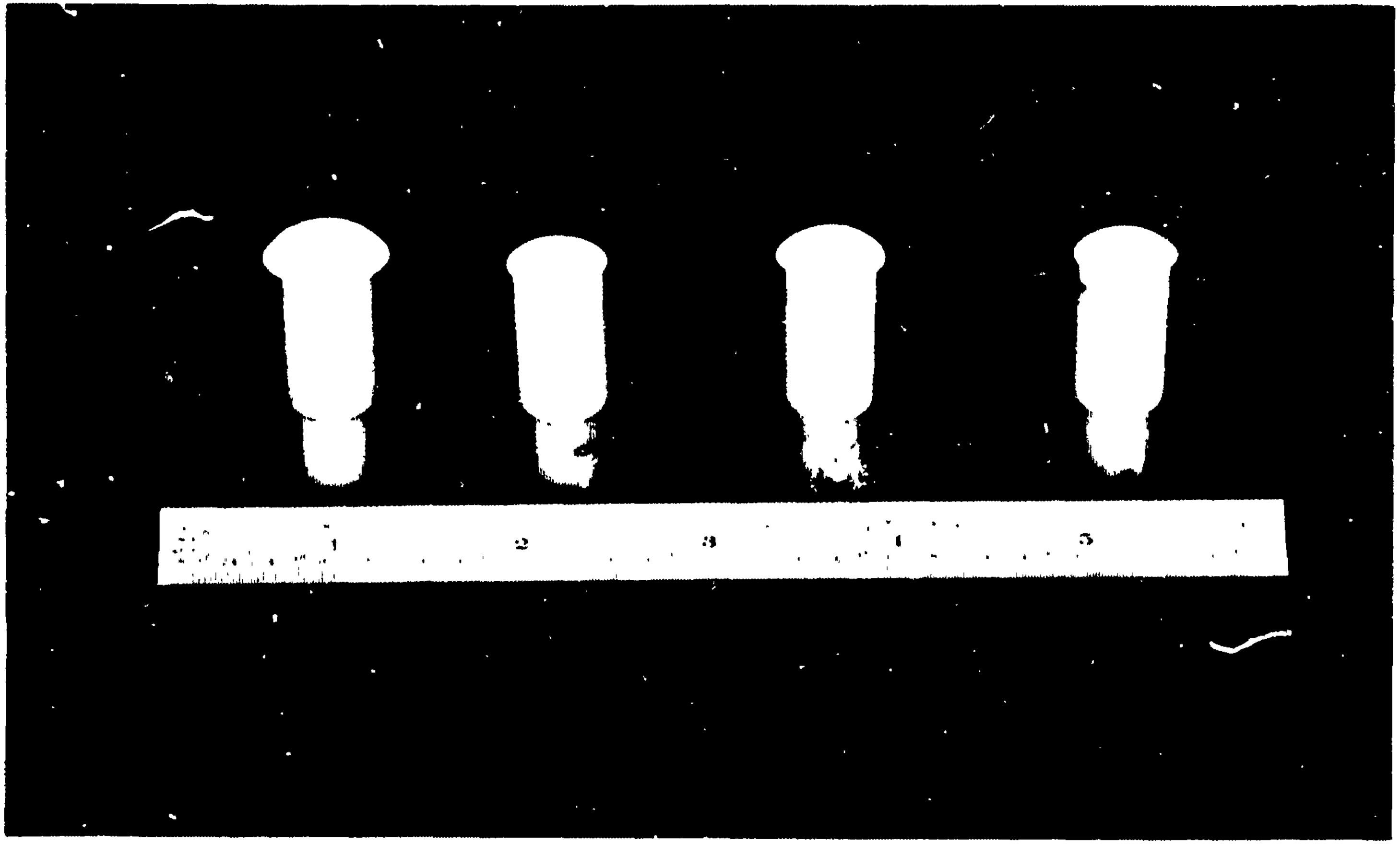

Fig. 3 TEFLON MODELS BEFORE AND AFTER TESTING

TABLE I

MODEL MEASUREMENTS

Run No.	Meas. Stag. Pt. Recession (in)	Meas. Overall Wt. Loss (gms)	Meas.(3) Gross $V_{-\infty}$ (in/sec)	Model Nose Radius Initial (in)	Model Nose Radius Final(1) (in)
145	.097	1.0816	.0357	.398	.41-.44
146	.102	1.1463	.0347	.402	.42-.44
147	.114	1.2508	.0403	.397	.44
148	.094	0.9468	.0376	.400	.42-.46
111	.106	1.0285	.0546	.400	.41-.5
122	.104	1.0335	.0559	"	.41-.45
112	.087	0.9350	.0613	"	.39-.44
205	.183	1.8428(2)	.0635	.394	.41
119	.065	0.8827(2)	.0591	.400	.41-.44
114	.057	0.6202	.0567	"	.41-.44
117	.088	1.4657(2)	.0815	.400	.41-.44
241	.131	1.7492(2)	.0868	.41	.41
127	.073	0.7576	.0830	.400	.41-.44

NOTES:

(1) Radius can vary as a function of angle

(2) Including body mass loss

(3) Stagnation point values

Run conditions for the various tests are given in Table II including the simulated flight conditions based on the environment existing in the stagnation region of the model face. The runs are grouped in respect to both increasing pressure and increasing enthalpy. Some rather brief, and general, comments on both the experimental data and the runs are given in Appendix A.

TEST RESULTS AND ANALYSES*

As can be seen from Table II, the range of test conditions utilized,

$P_{t_{arc}}$: 25 - 141 psia

$H_{t_{arc}}$: 1540 - 4000 Btu/lb

Run time : 0.88 - 2.94 sec.,

resulted in simulated re-entry stagnation region heating environments on the models corresponding to flight conditions of:

altitudes : 64,400 - 114,000 ft.

velocities : 8,500 - 14,000 ft/sec.

The corresponding changes in the models are shown in Table I; overall ranges of measured values of:

stagnation point recession : .057 - .183 in.

overall mass loss : 0.62 - 1.25 grams**

nose radius change : 0 - 25%

---

* A more detailed discussion of the techniques used in analysis, the assumptions and limitations, and certain calculated parameters obtained in addition to those presented here are presented in Ref. 7.

** Those models with body mass loss were excluded.

TABLE II

TEST CONDITIONS AND STAGNATION REGION SIMULATION

Run No.	$P_{t_{arc}}$ (psia)	$H_{t_{arc}}$ (Btu/lb)	Run Time (sec.)	Stagnation Region Conditions Simulated: Alt. (ft.)	Stagnation Region Conditions Simulated: Vel. (ft./sec.)
145	25.1	2640	2.72	109,600	11,700
146	25.3	3000	2.94	110,700	12,000
147	26.0	3030	2.83	110,200	12,100
148	29.1	4000	2.50	114,100	14,000
111	73.0	2100	1.94	82,400	10,000
122	69.5	2130	1.86	83,700	10,100
112	76.3	2470	1.42	85,100	10,900
205	71.5	2640	2.88	88,200	11,300
119	120.5	1540	1.1	64,200	8,500
114	122.5	1580	1.01	64,400	8,600
117	136	2120	1.08	68,800	10,100
241	138	2250	1.51	69,800	10,400
127	141	2270	0.88	69,500	10,400

were noted. The measured stagnation point loss and the measured run times gave gross* ablation velocities of

$$V_{-\infty} \ : \quad .0357 - .0868 \text{ in/sec.}$$

For the analyses of the runs, calculations were carried out using an IBM 7094 (FORTRAN) program which combined the fluid flow, heat and mass transfer considerations; a very brief accounting of this is given in the following paragraph.

The determined $P_{t_{arc}}$, $H_{t_{arc}}$, and $\dot{w}_a$ were used as the basic inputs. Employing continuity as a boundary condition, the real gas flow thru the nozzle was calculated, in an iterative manner, by a modified gamma technique**. Conditions behind the bow shock were found from standard (real gas) air tables; an isentropic compression was assumed from the shock to the stagnation point. From these results the local heat transfer was determined[9,10], the simulated flight conditions found (iteratively), and the mass transfer was calculated based on results given in Ref. 3.*** At the non-stagnation regions on the model face, the flow was determined (iteratively) by the use of a modified Newtonian pressure gradient with an isentropic expansion. The local heat transfer, which is dependent on the stagnation conditions, was calculated based on the work of Ref. (12). As a first approximation, the mass loss was determined locally, at two positions on the model face using equal surface areas, by an extension of Ref. (3). The resulting mass loss was summed and compared to the measured

* No corrections were made for time to approach the steady state ablation condition (as will be seen later, such times are small compared to the run time) or for model injection times (also small).

** Typical results compare very favorably with standard references (Ref. 8).

*** Fay and Riddell's, rather than Scala's, work was used for the heat transfer (coupled with Scala's ablation results). Ref. 11 shows the differences between the two methods are small at the given test conditions.

overall loss in weight by the model. Thus, the complete solution to the problem was effected in three separate parts in order to obtain the comparisons between both calculated and measured stagnation point regression and overall mass loss. All results were based on the average conditions occurring in the mid-portion of the steady state (ablation) part of the runs.

The final results, involving the comparison between the analytical and experimental findings, are shown in two different forms in Fig. 4 and Table III. In Figure 4, predictions of material performance are shown (after Scala[3]) for the three major theories. It can be noted that factors of up to 2 exist between the basic theory of Georgiev, Hidalgo and Adams[1] and that of Scala[3]; Sutton's work[2] gives results very near to the lower limit predicted by Georgiev et al[1] when combustion is considered. While plots of this nature (Figure 4) show the practical aspect of Teflon, i.e., its heat absorption capabilities as a function of enthalpy difference*, and are, in fact, a standard method of comparison, they are not too well suited for our investigations since the "data" reported are actually a combination of analytical and experimental results. For example, it can be shown quite easily from the basic definition of effective heat of ablation, at steady state conditions,

$$H_{eff} = \frac{q_o}{\dot{m}}$$

that

$$H_{eff} = \frac{q_o}{\rho} \frac{\tau}{Y}$$

where q_o is the calorimetric heat flux, τ is the time, ρ is the material

---

*Since the (calculated) Teflon surface temperature did not vary appreciably (1350-1400°F) in these tests, the resulting enthalpy of the air, at the wall, was essentially constant at a value of ~ 460 Btu/lb.

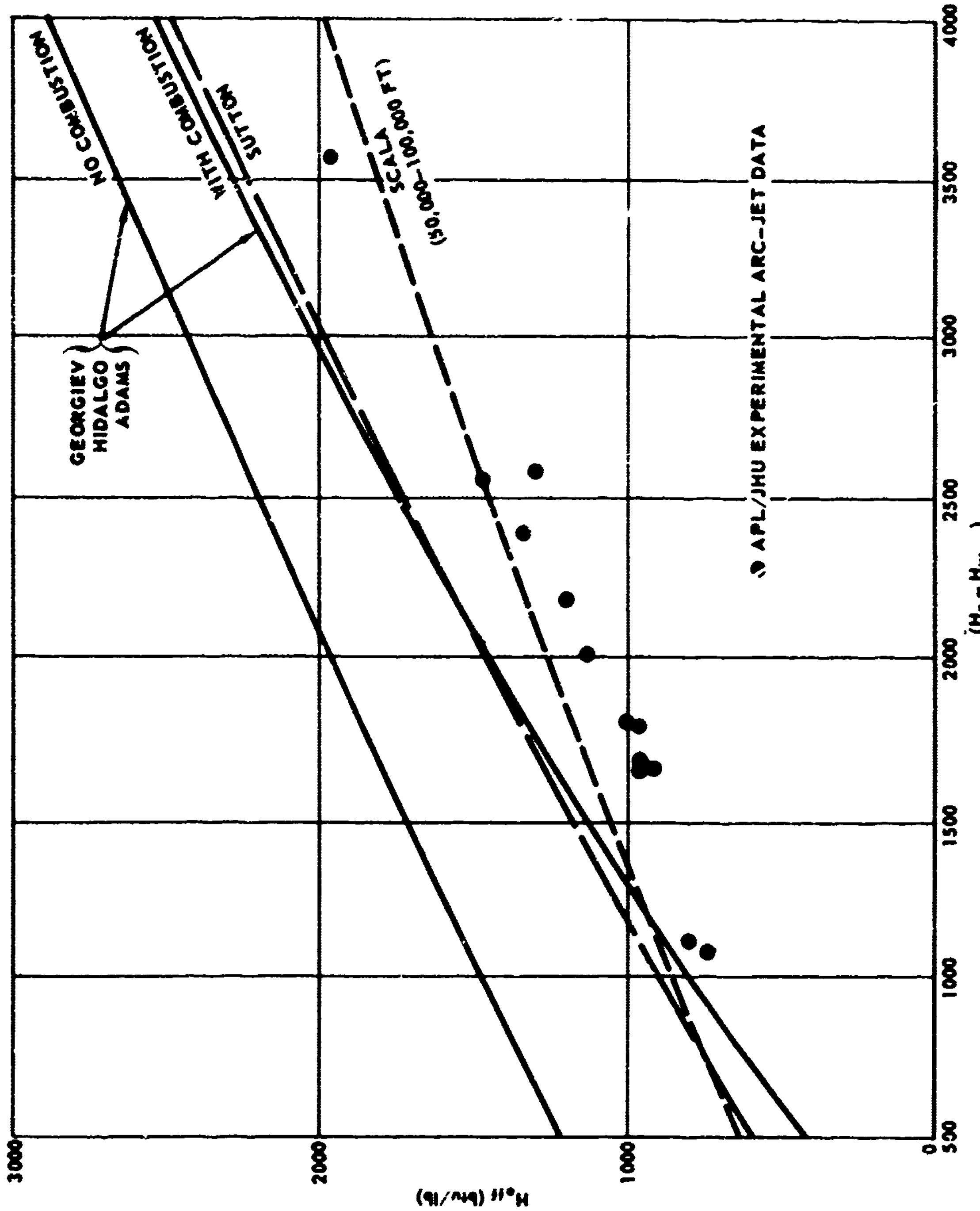

Fig. 4 A COMPARISON OF THEORETICAL ANALYSES FOR THE ABLATION OF TEFLON
(AFTER S.M. SCALA, REF. 3)

TABLE III

A COMPARISON OF CALCULATED AND EXPERIMENTAL RESULTS

Run No.	Stagnation Point Recession $\left(\frac{Y_{anal(Scala)}}{Y_{exptl}}\right)$	Overall Model Mass Loss $\left(\frac{W_{anal(Scala)}}{W_{exptl}}\right)$
145	.93	.98
146	.98	1.04
147	.86	.91
148	1.06	1.18
111	.87	.99
122	.86	.95
112	.89	.90
205	.89	---
119	.90	---
114	.95	1.01
117	.82	---
241	.82	---
127	.85	.94

density and Y is the total surface regression.* In our present series of tests all of the above quantities were measured with the exception of the heat flux. Calculation of H_{eff} values in this manner with the heat flux calculated as described in the preceding paragraph gave values to within 1-2 percent of those shown in Figure 4.

The "data" shown in Figure 4 were actually obtained in a somewhat different manner which involved the use of simulated flight conditions with compensations for the actual material loss. Scala's results, including his thermal diffusivity and specific heat, were assumed correct; an average value of our measured density was used (~ 135 lb/ft^3) and the conductivity (of necessity) was implied from

$$\alpha = \frac{k}{\rho\, c_p}.$$

Time to steady state and temperature distribution thru the model were obtained with finite difference numerical techniques. An analytical check on the times to steady state ablation were made and results compared within a few percent to those determined numerically. Also, at the time when steady state ablation began, the gradient thru the material (determined by finite differences) was checked for its necessary exponential nature. This was found to be approximately so, although a finer slab subdivision would have shown the gradient better. Using the net run time, and the given values of Scala's H_{eff}, the "data" in Fig. 4 were determined from

$$H_{eff(exptl)} = H_{eff(anal)} \times \frac{Y_{(anal)}}{Y_{(exptl)}} .$$

*A semi-infinite material is implied, with a square wave heat flux and use of a "net" time (or insignificant non-steady state times). All three can be shown to be good assumptions for these test runs.

As can be seen from the figure, values of H_{eff} of from 750-2000 Btu/lb were obtained over an enthalpy difference range of 1100-3600 Btu/lb. The results are quite clearly near the level predicted by Scala and show the trends he advocates.

The above method of presentation, while conventional, has some obvious drawbacks in any comparison of data with theory since analytical and experimental results are mixed. A different manner of presentation (with the necessary separation) is shown in Table III where measured and calculated stagnation point loss and overall mass loss are compared. This has the effect of lumping all errors (experimental and analytical) in with the analytical treatment since both physically occurring losses (mass and distance) are easily measurable. As can be seen the stagnation point losses, predicted from the theory of Scala, are generally 10-15 percent below those measured. The predicted mass losses, which are analytically only a first approximation*, are within ± 10 percent of those measured.**

There can be a number of possible explanations for the differences seen between the calculated and experimental values:

1) loss of material due to scouring of the model by fine solid particles from the steel arc chamber walls,

2) increased heat transfer in the stagnation region due to the turbulence level in the arc-effluent stream.

---

*While the non-stagnation, non-ablating (calorimetric) heat fluxes are analytically correct, Scala's analysis is for the stagnation region only. Thus it is an increasingly poor approximation to use the results of such an analysis at body angles greater than 15°-20°.

**As further refinements in the non-stagnation ablation analysis are available, more accurate results can be obtained by subdividing the model face into a number of zones, and then summing the mass losses.

3) inexactitudes in the determination of arc chamber conditions,

4) inexactitudes in the analysis both from the point of view of Scala's theory and from the techniques used in the present work or in the analytical description of the actual physical processes.

To discuss these points briefly, it can be stated that the evidence in respect to possible scouring of the models, by either arc electrode or arc body slag, is at the best inconclusive and interpretations are presently somewhat subjective. There is no doubt, from both Fastex movies and the copper calorimeter test model results[6], that some material comes from the arc chamber at least sporadically. On one of the model runs (#117) definite striations were noted on the model protective sleeve (of Teflon); occasionally other runs show signs of such evidence. When quartz was used as a protective sleeve, hard black deposits occurred on the sleeves ~ very similar to the deposits seen on the calorimeter models. On one aborted run (#113), where the arc blew out at the beginning of the model ablation period ~ and where conditions (i.e., gas temperature), dropped off very rapidly, black marks were noted on the model face. It actually is not too surprising if such marks are not seen on the other model faces since any further surface combustion of the Teflon, after it is removed from the stream, would tend to loosen small embedded particles causing them to drop out and be lost. Since the surface is hot, some combustion will occur, although the loss with materials such as Teflon will be small due to their low thermal diffusivities (i.e., small thermal thicknesses). Future use of a completely copper arc (arc model XIV) will minimize these problems, but in any event attempts will be made to quantitatively determine the effects of scouring and the new models will be more completely examined after each run for adverse effects.

In respect to turbulence the phenomena seems to be possibly present in two forms: i.e., in the basic turbulence in the stream and/or in its enhancement in the stagnation region. The first form arises from the swirling motion of the arc effluent stream ~ and while there is conclusive proof that such an effect occurs in the entrance region to the settling section (and thus the nozzle), the evidence is not conclusive as to whether or not such an effect persists to any degree downstream of the bow shock wave. In fact, the melt formations from glassy ablators do not show any such expected effects ~ although after the bow shock, which tends to damp disturbances, the tangential velocity could be too small to affect the melt and yet large enough to slightly increase the heat transfer. In respect to the second form Ref. 13 shows very clearly, as do a number of other experimental results*, the enhancement of the heat transfer or turbulence level in the region of a body where a favorable pressure gradient exists. However, the theoretical work is not very well developed for cases of the type we are examining, and at this stage it appears that all one can say is that the apparent higher heat flux that we see could reasonably (in both qualitative and quantitative senses) be due to either of the two, or both, turbulence effects.

In respect to the third item mentioned, it is possible that minor discrepancies or inconsistencies could occur in the determination o arc chamber environmental conditions. For example, our examination of the measured ablation velocities and their corresponding arc chamber environments shows slight inconsistencies as a function of enthalpy level. (This is discussed somewhat further in Appendix A).

---

*A study of impinging jets has been undertaken at APL/JHU; a summary of turbulence effects and heat transfer for such cases is expected to be published in the near future.

Finally, in respect to the analytical treatment a number of errors are always possible. First, in Scala's treatment, certain property data and simplifying assumptions were employed; attempts are being made to determine all their implications. Second, the possibility of numerical errors, or small discrepancies due to oversimplifications, are always possible ~ especially in long, involved computer programs. Third is the question of the accurate simulation, analytically, of the actual physical situation ~ and this will be covered in some detail in Ref. 7. Finally, there are small known errors present, due to approximations made; their sum conceivably could be the difference between the noted analytical and experimental findings. Parametric examinations, and error investigations, are being made on the analyses.

In order to show, both specifically and generally, the levels of certain calculated parameters without going into the details of their derivations or the implications of their results, values are presented in strictly tabular form in Tables IV-VI. Values in Tables IV and V apply to specific run conditions for stagnation and non-stagnation regions on the model, respectively, and Table VI shows overall ranges.

Briefly, the results show, for example, that the time to steady state ablation is small ~ at the most only 5 percent of the total run time. The recombination rate coefficient shows the degree of chemical equilibrium or "frozenness" in the local flow; the conditions reported here can be considered as being in the non-equilibrium to "well frozen" range*. The levels of shear stress, while numerically low, are for example a good order of magnitude higher than those usually seen in the literature. As could be expected from a pure sublimor (ablating material), no noticeable deleterious effects on the material could be seen from the shearing forces. Since both the given heat flux and shear stress are "calorimetric" values, preliminary estimates of their reduction (by mass

---

*the latter occurring at the lower pressures

TABLE IV

SELECTED CALCULATED PARAMETERS
(Stagnation Region Values)

Run No.	$\dot{q}_{STAG}$ (Btu/ft^2-sec)	T_{SURF} (°F)	H_{eff} (Btu/lb)	$\dot{m}$ $\frac{lbs}{ft^2\text{-sec}}$	$V_{-\infty}$ (in/sec)	τ_{ss} (sec)	C_1 (1)
145	540	1330	1440	.385	.0345	.12	.0015
146	580	1330	1510	.395	.0353	.11	.0014
147	600	1330	1520	.403	.0361	.11	.0014
148	830	1340	1860	.459	.0411	.08	.0008
111	570	1370	1100	.547	.0490	.06	.0195
122	600	1370	1120	.553	.0495	.06	.0167
112	780	1380	1270	.626	.0560	.04	.0149
205	860	1370	1350	.640	.0573	.04	.0112
119	500	1390	820	.620	.0555	.05	.0928
114	520	1390	840	.632	.0566	.04	.0895
117	840	1400	1110	.771	.0690	.03	.0575
241	950	1400	1170	.809	.0724	.03	.0541
127	950	1400	1180	.811	.0726	.03	.0510

NOTES:

(1) recombination rate parameter of Fay and Riddell (Ref. 10)

TABLE V

SELECTED CALCULATED PARAMETERS

(Non-Stagnation Region Values)

Run No.	$\dot{q}_{local}$ (Btu/ft^2-sec)	Shear Stress (lbf/ft^2
145	400 - 500	5.4 - 7.0
146	420 - 530	6.0 - 7.7
147	440 - 550	6.2 - 8.0
148	630 - 770	11.4 -15.1
111	470 - 550	7.0 -11.0
122	460 - 570	7.4 -11.5
112	590 - 730	8.6 -12.1
205	630 - 780	9.2 -12.3
119	370 - 460	12.3 -19.0
114	380 - 480	12.6 -19.1
117	640 - 780	10.8 -16.7
241	720 - 870	11.2 -16.9
127	690 - 870	11.8 -18.0

TABLE VI

OVERALL RANGE OF SELECTED CALCULATED PARAMETERS IN TEFLON ABLATION STUDIES

Flight Conditions Simulated

altitudes	:	64,100 - 114,000 ft.
velocities	:	8,500 - 14,000 ft/sec
shock standoff	:	0.035 - 0.048 in.

Flow Conditions at the Arc Nozzle Exit

velocities	:	5400 - 7400 ft/sec
Mach numbers	:	1.87 - 1.93
Reynolds number/ft.	:	2.2×10^5 - 1.7×10^6
Compressibility factor	:	1.00 - 1.14

Local Conditions for the Model

	Stagnation Region	Non-Stagnation Region*
**heat flux ($Btu/ft^2 sec$)	500-950	370-870
surface temperature (°F)	1300-1400	1310-1400
effective heat of ablation (Btu/lb)	810-1870	
ablation velocity (in/sec)	.035-.073	.025-.067
mass loss rate (lbs/ft^2-sec)	.39 -.81	.28 -.74
time to steady state ablation (sec)	.03 -.12	.03 -.23
thermal thickness (in)	.002-.004	.002-.006
**shear stress (lbf/ft^2)	-----	5 - 19
**momentum thickness Reynolds no. (--)	-----	20 - 82
recombination rate parameter (--)	.0008-.09	-----
shock standoff (in)	0.113-0.153	

* positions evaluated were approximately at angles of 25° and 45°

** "calcrimetric" values

TABLE VI (cont'd.)

	Stagnation Region	Non-Stagnation Region*
velocities (ft/sec)	-----	1600-3700
compressibility factors (--)	1.01-1.19	
gas temperature (°F)	4800-7900	
gas pressure (psia)	12-101	

*positions evaluated were approximately at angles of 25° and 45°

injection) show factors of 2.5 - 4.0 are involved, depending on various considerations; this is being investigated further. The ("calorimetric") momentum thickness Reynolds numbers, Re_θ, indicate that laminar flow existed over the entire, or greater portion of, the model face. The thermal thickness (i.e., where the temperature drops by a factor of $\frac{1}{e}$) is very small and thus shows that the semi-infinite assumption is particularly good for the test models under these conditions. The compressibility factors indicate that essentially only oxygen dissociation occurred; for example, Z generally is ≤ 1.20 and thus, conditions of little to almost complete O_2 dissociation were present. The flight shock standoff gives an indication that departure from thermal equilibrium[15] was < 10 percent; considering that the actual (ground test) shock standoff is almost 3 times the flight value, no problems with thermal non-equilibrium occurred on these tests. The real gas "free stream" (arc nozzle exhaust) Mach numbers show, for example, that the results are on the lower edge of the validity of the modified Newtonian pressure distribution approximation[16]. Finally, the high Reynolds numbers per foot at the arc nozzle exit indicate free stream turbulence effects can noticeably influence the heat transfer to the model face.

SUMMARY AND CONCLUSIONS

Experimental data and the results of analyses have been presented on Teflon ablation runs carried out in the Re-Entry Studies Project Mach 2 arc-jet tunnel at the Applied Physics Laboratory Propulsion Research Laboratory. Data were obtained under the following arc chamber conditions: 25 to 140 psia and 1500 to 4000 Btu/lb. These simulate stagnation region re-entry heating environments of 8500 to 14,000 ft/sec at altitudes of 64,000 to 114,000 feet. Analysis of the data indicates:

(1) The experimental data has shown good agreement, both in respect to levels and trends, with the theory of S.M. Scala. This implies that Teflon is not as an efficient heat absorption material as is commonly supposed.

(2) Use of the theory of Georgiev, Hidalgo and Adams, without the consideration of any combustion effects (which is frequently done) can result in significant errors in regression and mass loss rates at the lower enthalpy levels.

(3) Wake analyses involving Teflon coated bodies, in either free flight or ballistic ranges, may be considerably in error in species and electron concentrations and enthalpy levels if incorrect Teflon ablation mechanisms are utilized in the analysis.

(4) The slight differences between the experimental results and the theory are believed to be due mainly to both inexactitudes in the determination of arc chamber conditions and in the analytical description of the actual physical situation. Some contributions may also be possible due to scouring by metallic particles and excessive free stream turbulence.

(5) To completely confirm the validity of the theory of Scala, it is suggested that more data be obtained in the enthalpy range of 3000-4500 Btu/lb.

REFERENCES

1. S. Georgiev, H. Hidalgo and M.C. Adams, "On Ablating Heat Shields for Satellite Recovery", AVCO-Everett Research Lab., Res. Rpt. 65, July 1959, (See also Res. Rpt. 47, Mar. 1959).

2. N.S. Diaconis, J.B. Fanucci and G.W. Sutton, "The Heat Protection Potential of Several Ablation Materials for Satellite and Ballistic Re-Entry Into the Earth's Atmosphere", General Electric Co. Rpt. R59SD43, Sept. 1959.

3. S.M. Scala, "A Study of Hypersonic Ablation", General Electric Co., Rpt. R59SD438, Sept. 1959 (Presented at 10th International Astro. Congress, 29 Aug.-5 Sept. 1959, London, England.)

4. S.M. Scala and N.S. Diaconis, "The Stagnation-Point Ablation of Teflon During Hypersonic Flight", Jour. Aero/Space Sci. Feb. 1960, pp. 140-141.

5. F. Falk, "An Arc-Jet Setup for Investigation of Re-Entry Phenomena", to be published.

6. N.G. Paul, F.Falk and L.O. Kauffman, "Results of Thermocouple-Probe Measurements of High-Temperature Gas Streams", to be published.

7. N.G. Paul, "A Discussion of the Analytical Results Obtained in Evaluating Current Teflon Ablation", to be published.

8. H.C. Kerr, "Mach Number Tables ($\gamma = 1.4$) with Correction Factors for Real Air", General Dynamics (Daingerfield, Texas), OAL Memo 147-1, CM1036-1, 9 April 1964.

9. C.F. Hansen, "Approximations for the Thermodynamic and Transport Properties of High-Temperature Air", NASA TR R-50, 1959, (See also: NACA TN 4150, 1958).

10. J.A. Fay and F.R. Riddell, "Theory of Stagnation Point Heat Transfer in Dissociated Air", Jour. Aero. Sci., Vol. 25, No. 2, Feb. 1958, pp. 73-86.

11. S.M. Scala and C.W. Baulknight, "Transport and Thermodynamic Properties in a Hypersonic Laminar Boundary Layer", ARS Jour. Vol. 30, No. 4, April 1960, pp. 329-336.

12. N.H. Kemp, P.H. Rose and R.W. Detra, "Laminar Heat Transfer Around Blunt Bodies in Dissociated Air", Jour. Aero/Space Sci., Vol. No.26, July 1959, pp. 421-430.

13. J. Kestin, P.F. Maeder, H.H. Sogin, "The Influence of Turbulence on the Transfer of Heat to Cylinders Near the Stagnation Point, Vol. 12, 1961, pp. 115-131.

14. R.W. Detra and H. Hidalgo, "Generalized Heat Transfer Formulae and Graphs", ARS Jour. Mar. 1961, pp. 318-321, (See also: AVCO Res. Rpt. 72, May 1960 and Res. Note 72, May 1958.)

15. S. Feldman, "On Trails of Axisymmetric Hypersonic Blunt Bodies Flying Through the Atmosphere", Jour. Aero/Space Sci., Vol. 28, No. 6, June 1961, pp. 433-448, 470 (See also AVCO Res. Rpt. 82, Dec. 1959).

16. L. Lees, "Hypersonic Flow". Proc. Fifth International Aeronautical Conference, Los Angeles, Calif., June 20-23, 1955, pp. 241-276.

17. A.M. Keuthe, W.W. Willmarth and G.H. Crocker, "Turbulence Field Near the Stagnation Point on Blunt Bodies of Revolution", Proc. 1961 Heat Transfer and Fluid Mechanics Institute, Univ. of So. Calif., Los Angeles, Calif., June 19-21, 1961, Stanford University Press, pp. 10-22.

18. W. Winovich, "On the Equilibrium Sonic-Flow Method for Evaluating Electric Arc Air-Heater Performance", NASA TN-D-2132, March 1964.

19. N.K. Hiester and C.F. Clark, "Feasibility of Standard Evaluation Procedures for Ablating Materials", NASA CR-379, Feb. 1966.

Appendix A

COMMENTS ON THE EXPERIMENTAL RUNS

As can be seen from the tabulated results, data were taken over a wide range of conditions. In general, the data were regarded as being quite satisfactory at the run conditions made; the scatter in the results appeared to be much less than is ordinarily encountered in ablation-type testing as can be seen by comparison with the results presented in Ref. 19. However, in order to have the complete record available for possible future use of the results, and also to indicate potential problem areas that could bear further examinations in the future, a discussion of the experimental conditions and the data are given in the following paragraphs. Four runs (#113, 162, 242 and 243) had to be disregarded completely due to irregularities in the flow conditions. Results from these are not included in this report. Run #148 also had suspected irregularities in the flow but as nothing definite could be shown*, the results were allowed to remain. This run provided the only point above Scala's prediction on Figure 4.

In respect to the data, it can be seen from Tables I and II** that slight paradoxes or anomolies are present ~ i.e., both in respect to measured ablation velocities and in respect to nose radii changes. For example, it is fairly well known that the ablation rate of Teflon is only weakly pressure dependent (see Fig. 5 for example) but is strongly and directly dependent on stagnation enthalpy (or enthalpy differences). At

---

* Unfortunately, the Fastax movie coverage, which has been a valuable tool in flow observations, was not available for this run.

** The data as shown are divided into 4 groups based on pressure level ~ and are further listed in these groups on the basis of increasing arc (total) enthalpy.

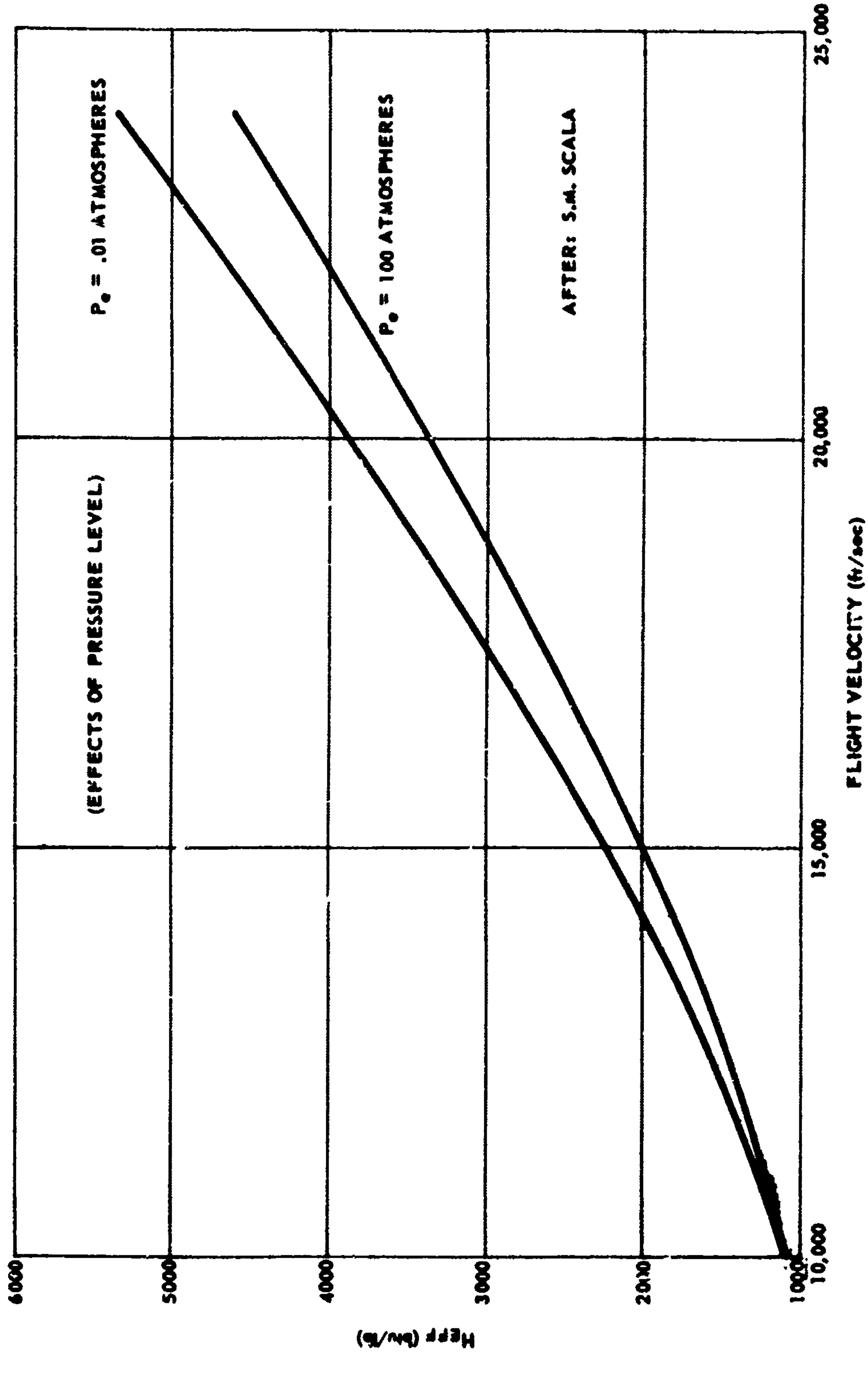

Fig. 5 EFFECTIVE HEAT OF ABLATION OF TEFLON

a given pressure level, an increase in the air enthalpy should result in an increase in ablation velocity. As can be seen, there are small inconsistencies in the measured results, particularly noticeable at the lower pressure conditions. The conclusion here is that even though considerable work has been done in the project on definition of the arc chamber environment, more effort will probably be needed.

The nose radii changes are also somewhat unusual considering the measurement techniques employed, the expected variation of local heat transfer over the face of the model, and the different heat inputs to the models. The results show some inconsistencies but in general imply that (from the sweeping generalization viewpoint) regardless of run condition or time the nose radius increases by approximately 10 percent.

In respect to the run conditions, the majority of the difficulties encountered were at the lower pressure (higher enthalpy) arc environments ~ with the main problem being flow definition. The problems were in respect to the nozzle either not starting ~ or in becoming unfilled during model injection ~ and in respect to accurate enthalpy determinations. The difficulties with the partially filled nozzle flows were noted from the Fastax movies and consideration of the change in shock standoff distance with relatively minor changes in the flow. The enthalpy determination problems were obvious considering the measured gross ablation rate data.

Some other general points applicable to the tests are: slightly asymmetrical model noses were observed after Runs 111, 127, 145, 147, 148 and 205 (indicating possible model misalignment before the run and/or an inadequate method of holding or pinning the models securely to the strut. With the latter, either the model inertia upon injection, or the effect of the air stream, or inertial effects when the strut "snaps home" into the middle of the stream could contribute). It was also noted that the center portion of the model face appeared to be slightly flattened on Runs 111 and 148 (possibly due to model movement in the holder in a circular fashion)*. Material was ablated from the body, or stem of the model in Runs #117, 119, 205 and 241 ~ and thus accurate determination of the nose total mass loss are problematical.** Difficulties were encountered initially in measurement techniques so that mean measured values had to be employed for Runs 111 and 112. Some indications of possible oscillatory flow were noted, from Fastax moving pictures, for Runs #111, 114 and 117. Arc body or electrode leaks were discovered after Runs #112 and 114 but these were believed to have occurred on shutdown and thus did not affect the arc effluent stream during the model portion of the run.

---

* Keuthe et al[18] have results where free stream turbulence (even under supersonic conditions) has resulted in movement of the stagnation point. This could be present in our tests where we get noticeable stagnation region blunting.

**Some of these runs were carried out for the primary purpose of obtaining spectrographic information and measurements on the contaminants in the flow behind the body ~ and thus no attempt was made to halt the runs before body ablation occurred.

UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1 ORIGINATING ACTIVITY (Corporate author) The Johns Hopkins Univ., Applied Physics Lab. 8621 Georgia Avenue Silver Spring, Maryland	2a REPORT SECURITY CLASSIFICATION Unclassified 2b GROUP

3 REPORT TITLE

High-Pressure Arc-Jet Ablation Characteristics of Teflon

4 DESCRIPTIVE NOTES (Type of report and inclusive dates)

Technical Memorandum

5 AUTHOR(S) (Last name, first name, initial)

Paul, N. G., Falk, F., and Kauffman, L. O.

6 REPORT DATE	7a TOTAL NO OF PAGES	7b NO OF REFS
December 1966	31	19

8a CONTRACT OR GRANT NO. NOw 62-0604-c b PROJECT NO. Task Assignment P 62 c d	9a ORIGINATOR'S REPORT NUMBER(S) TG-881 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10 AVAILABILITY/LIMITATION NOTICES

Distribution of this document is unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	Special Projects Department of the Navy

13 ABSTRACT

Experimental data and the results of analyses are presented for Teflon ablation runs carried out in the Re-Entry Studies Project Mach 2 arc-jet tunnel at the Applied Physics Laboratory Propulsion Research Laboratory. Data were obtained under the following arc chamber conditions: 25 to 140 psia and 1500 to 4000 Btu/lb. These simulate stagnation region re-entry heating environments of 8500 to 14,000 ft/sec at altitudes of 64,000 to 114,000 feet.

A comparison of the data with three major theories showed that the analytical treatment of S. M. Scala closely predicted the levels and trends of of the results. Teflon appears to be a considerably less efficient heat absorption material, by a factor of almost 2, than is conventionally anticipated.

DD FORM 1 JAN 64 1473 023558

UNCLASSIFIED

Security Classification

14. KEY WORDS
Ablation Teflon Arc-Jet Testing Heat of Ablation