FEASIBILITY DEMONSTRATION OF PYROLYTIC GRAPHITE COATED NOZZLES

Contract No. AF 04(611)-9708
United States Air Force (AFSC)
Rocket Propulsion Laboratory
Edwards, California

First Quarterly Progress Report
Period Covered: 1 February through 30 April, 1964

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May 20, 1964

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Attention: RPMC (Lt. Russell Maxwell)

Subject: Contract AF 04(611)-9708

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FEASIBILITY DEMONSTRATION OF PYROLYTIC GRAPHITE COATED NOZZLES

Contract No. AF 04(611)-9708
Project No. 3059   Program Structure No. 750G

First Quarterly Progress Report

Period Covered: 1 February through 30 April, 1964

Submitted to: Air Force Rocket Propulsion Laboratory
Edwards Air Force Base, California

Prepared by: Atlantic Research Corporation
Alexandria, Virginia

Author: James D. Batchelor, Project Director

May 20, 1964

ABSTRACT

The objective of this program is to demonstrate the feasibility of pyrolytic graphite coatings for use in uncooled solid propellant rocket nozzles (in a size range of use for practical propulsion units) under very severe operating conditions. In prior work at Atlantic Research Corporation the excellent serviceability of pyrolytic graphite coatings in 1/2-inch diameter nozzles was demonstrated with propellants having flame temperatures from 5500° to 6500°F. In the current work nozzles of 1.1-inch and 2.3-inch diameter are to be tested with a 6500°F propellant. This report describes the work of the first quarter of this program.

Thermal analyses were completed on several nozzle systems typical of those to be used in motor firings. These analyses indicated the adequacy of the designs selected. Design of the 1.1-inch diameter test nozzle was completed. Several pyrolytic graphite coated throat inserts were prepared. Problems with delamination cracks occurred with those coatings. In the first motor firing test partial coating failure and subsequent edge spalling combined to cause erosion of the coating at a rate substantially above the predicted capability of the material.

LIST OF FIGURES

LIST OF TABLES

TABLE OF CONTENTS

1.0 INTRODUCTION

Pyrolytic graphite is a unique form of graphite which exhibits excellent erosion resistance in solid propellant rocket nozzles. The high density and absence of a binder phase are believed to explain its exceptional serviceability. Sub-scale rocket motor tests of 1/2-inch diameter pyrolytic graphite coated nozzles carried out at Atlantic Research Corporation have shown that consistently good performance can be achieved in nozzle service with propellants having flame temperatures from 5600°F to 6500°F. The higher the flame temperature and the motor operating pressure the higher the erosion rate observed for pyrolytic graphite. Specifically, 1/2-inch diameter nozzles with 6550°F propellant have shown average erosion rates of less than 0.5 mil/sec at 700 psi. Limited tests with 1-inch nozzles with a 6000°F propellant have shown low erosion rates, but the problems of coating retention have not been investigated sufficiently. The feasibility of scaling-up to 1-inch and 2.3-inch throats with 6550°F propellant is to be determined under this program.

The best erosion resistance can be achieved by using pyrolytic graphite as a coating so that the layer plane surfaces are exposed to the combustion gas environment. Depending on the heat sink capacity and the severity of the service conditions, it has been found that edge-oriented pyrolytic graphite erodes up to several times faster than a good coating. To achieve the higher erosion resistance of the coating, the difficulties in maintaining coating integrity must be accepted and suitable designs must be demonstrated by test firings nozzles of useful size. This feasibility demonstration is the principal objective of the current program.

To demonstrate the capabilities of pyrolytic graphite coated nozzles for solid propellant rocket motors operating under severe conditions, the present program consists of the design, fabrication and motor testing of a series of nozzles with an advanced propellant of 6550°F flame temperature. Four sub-scale nozzles (1100 pound thrust motor) and four full-scale nozzles (4600 pound thrust motor) are scheduled for test.

This report covers the first quarter of the program during which time a thermal analysis and design study were completed and the first sub-scale nozzle test was made.

2.0 SUMMARY AND CONCLUSIONS

During the first quarter of the program to investigate the feasibility of pyrolytic graphite coated nozzles for service under severe solid propellant motor conditons, the following work was accomplished:

(a) thermal analyses of typical nozzle systems

(b) design of sub-scale nozzle assembly

(c) preparation of coated throat inserts for the first two sub-scale firings

(d) fabrication and motor firing of the first sub-scale nozzle.

The thermal analysis work documented the capability of a pyrolytic graphite coated nozzle assembly constructed entirely of thermally stable materials to provide a suitable thermal history for firings up to 100 seconds with a propellant flame temperature typical of the most advanced solid propellants in current development. These analyses also confirmed the acceptability of the design dimensions selected for the experimental nozzles to be tested in the current program.

In the deposition of pyrolytic graphite coatings on graphite substrates for the sub-scale nozzles, delamination cracking was encountered. This problem was not solved by the initial changes in deposition process and machining procedures. Coated inserts with known cracks were selected for both the first and second sub-scale motor tests. The crack was at the exit end of the insert for the first motor test and at the inlet end of the insert for the second motor test.

The performance of the nozzle in the first sub-scale firing was adversely affected by the delamination crack. Post firing analysis indicated that partial coating loss occurred at the exit end of the throat insert within the first few seconds of firing. For the remainder of the firing erosion proceeded at a rate 2 to 3 times that anticipated for a good coating by the combined action of edge spalling and normal surface erosion. Following the second sub-scale firing, scheduled during May, work will be started on the first full scale nozzle and efforts will be continued to prepare crack free sub-scale throat inserts.

3.0 EXPERIMENTAL RESULTS

3.1 Thermal Analysis.

Pyrolytic graphite is an excellent thermal insulator in the direction normal to the deposition layer planes. When used as a coating this insulating property leads to a rapid rise in surface temperature, large gradients across the coating thickness, and a significant reduction in the heat leak to the nozzle body. To predict the temperature history of several points in selected nozzle designs, a series of thermal analyses was carried out. A series of cases was selected to provide a parametric study of the effect of coating thickness, substrate web thickness, and insulating back-up web thickness for both the sub-scale and full-scale nozzles. In line with our established experimental practice, ATJ graphite was selected as substrate material and baked carbon was selected as the insulation back-up material. In each case a standard thickness of 3/8-inch was selected for the steel nozzle structure. In both the sub-scale and full-scale cases calculations were made for both the nozzle throat location and an upstream position in the nozzle inlet region. At the throat location the composite construction consisted (from the gas side outward) of pyrolytic graphite coating, graphite substrate, carbon back-up, and steel structure. The material selected for the nozzle inlet cap (to protect the leading edge of the coated throat section) was an edge-oriented pyrolytic graphite plate. Thus, the thermal analyses in the inlet region were made for a composite consisting (from the gas side outward) of edge-oriented pyrolytic graphite, baked carbon insulator, and steel structure. The dimensions of each configuration selected for analysis are shown in Table 3-1.

Table 3-1 Dimensions of Nozzles Selected for Thermal Analysis

A. Throat location: 1.100" throat diameter; 4.750" outside diameter; steel thickness 3/8"

Case No.	Pyrolytic Graphite Coating Thickness (mil)	Graphite Thickness (inch)	Graphite/Carbon Interface Diameter (inch)	Carbon Thickness (inch)
A-1	0	0.700	2.500	0.75
A-2	0	0.950	3.000	0.50
A-3	30	0.670	2.500	0.75
A-4	30	0.920	3.000	0.50
A-5	60	0.640	2.500	0.75
A-6	60	0.890	3.000	0.50

B. Throat location: 2.300" throat diameter; 6.250" outside diameter; steel thickness 3/8"

Case No.	Pyrolytic Graphite Coating Thickness (mil)	Graphite Thickness (inch)	Graphite/Carbon Interface Diameter (inch)	Carbon Thickness (inch)
B-1	0	0.850	4.000	0.75
B-2	0	1.100	4.500	0.50
B-3	45	0.805	4.000	0.75
B-4	45	1.055	4.500	0.50
B-7	45	0.805	4.000	1.125*

C. Inlet location: 1.840" diameter (1.100" throat); steel thickness 3/8"

Case No.	Pyrolytic Graphite Plate Web Thickness (inch)	Carbon Thickness (inch)	Outside Diameter (inch)
C-1	0.830	0.50	5.250
C-2	0.830	0.875	6.000

D. Inlet Location: 3.540" diameter (2.300" throat); steel thickness 3/8"

Case No.	Pyrolytic Graphite Plate Web Thickness (inch)	Carbon Thickness (inch)	Outside Diameter (inch)
D-1	0.855	0.625	7.250
D-2	0.855	1.000	8.000

* Outside diameter for case B-7 = 7.000"

The thermal analyses were performed with existing programs on a Burroughs 220 and an IBM 7090 computer. These programs apply finite difference methods to the transient radial conduction in axisymmetric cylindrical geometry with the following features:

(1) Convective heat input at gas surface based on Bartz-correlation transfer coefficient and gas recovery temperature.

(2) Radiative heat transfer at gas surface based on particle cloud and surface emissivities and gas free stream temperature (no temperature lag in condensed phase).

(3) Temperature dependent thermal properties (as needed) for each material in composite structure.

(4) Adiabatic rear wall condition.

The results of the cases selected are shown in Figures 3-1 through 3-5. The dimensions used for these analyses do not correspond to specific designs previously selected for the firing program, but the cases selected do cover a range of the variables expected to cover the actual experimental designs. Several interesting facts may be noted by examining these predicted temperatures. First, the very strong effect of the insulating nature of the pyrolytic graphite coating is apparent from the rate at which heating of the nozzle occurs at the throat region compared to those cases without the pyrolytic graphite coating. (Figure 3-1) This insulating property of the coating leads to a very rapid rise in surface temperature, of course. Just how rapidly this occurs can be seen in Figure 3-2 in which the surface temperature of the sub-scale nozzle with only 30 mils of coating is shown with a greatly expanded time scale.

It can also be seen from these temperature plots that practical thicknesses of baked carbon in the range from 1/2-inch to 1-inch provide adequate insulation between the nozzle throat insert and the steel housing for all the firing conditions planned in this program. (Figures 3-1 and 3-4) In the inlet region substantial temperature rise can be expected from the heat sink edge-oriented pyrolytic graphite (Figures 3-3 and 3-5), but this need be no cause for concern for heavy weight nozzle test hardware. The plates of edge-oriented pyrolytic

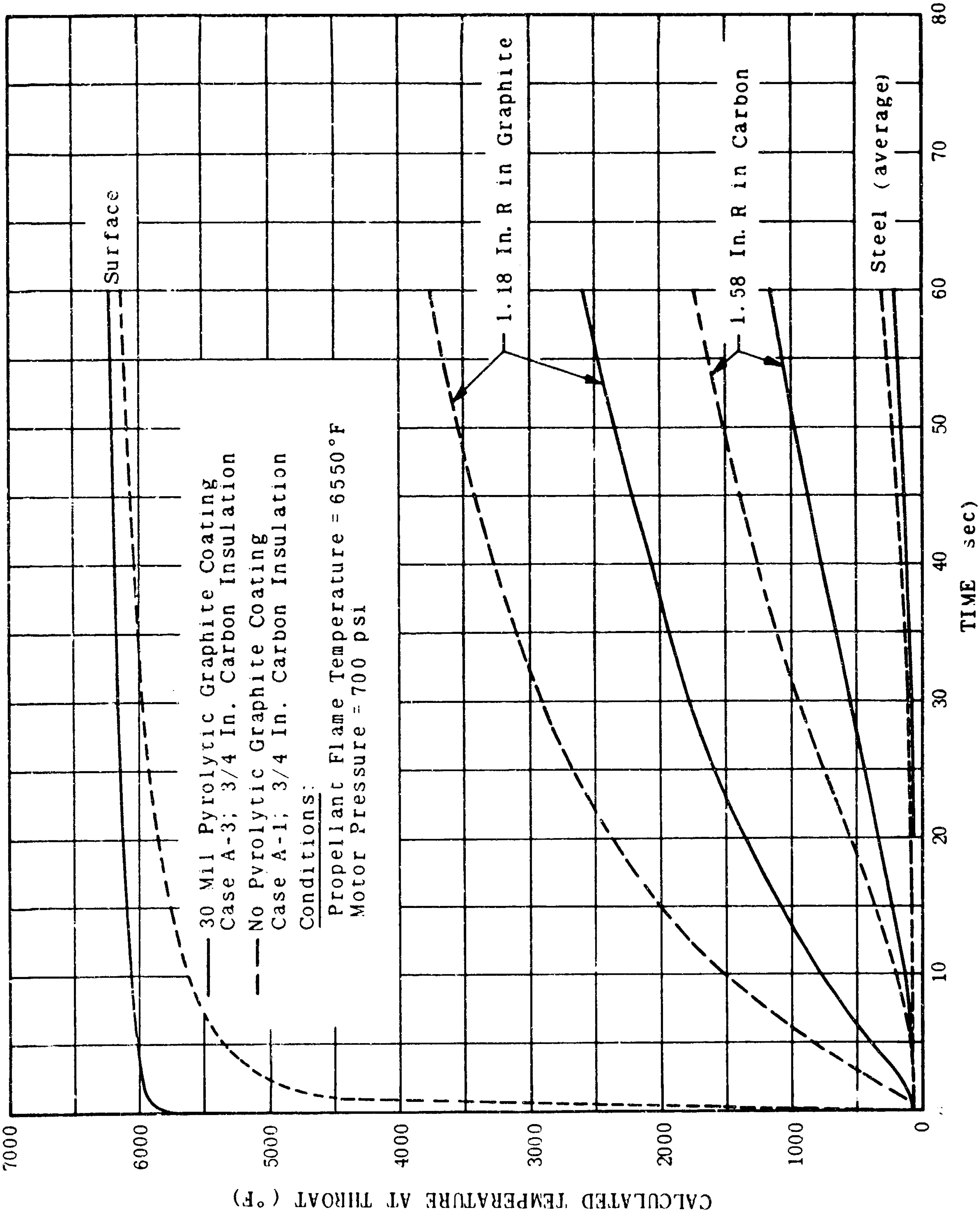

Figure 3-1. Effect of Pyrolytic Graphite Coating on Sub-scale Nozzle Temperatures.

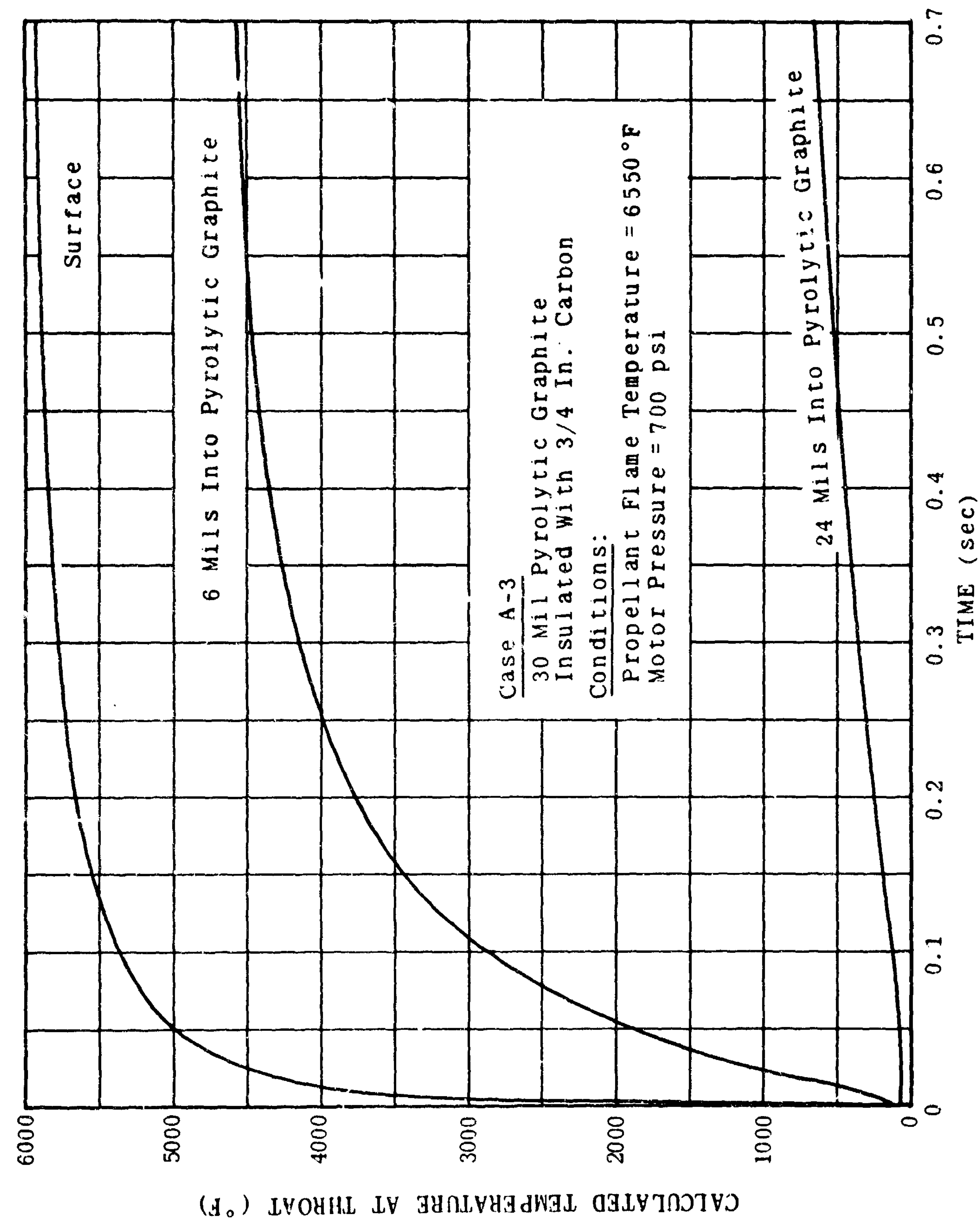

Figure 3-2. Initial Temperature Rise in Pyrolytic Graphite Coating on Sub-scale Nozzle.

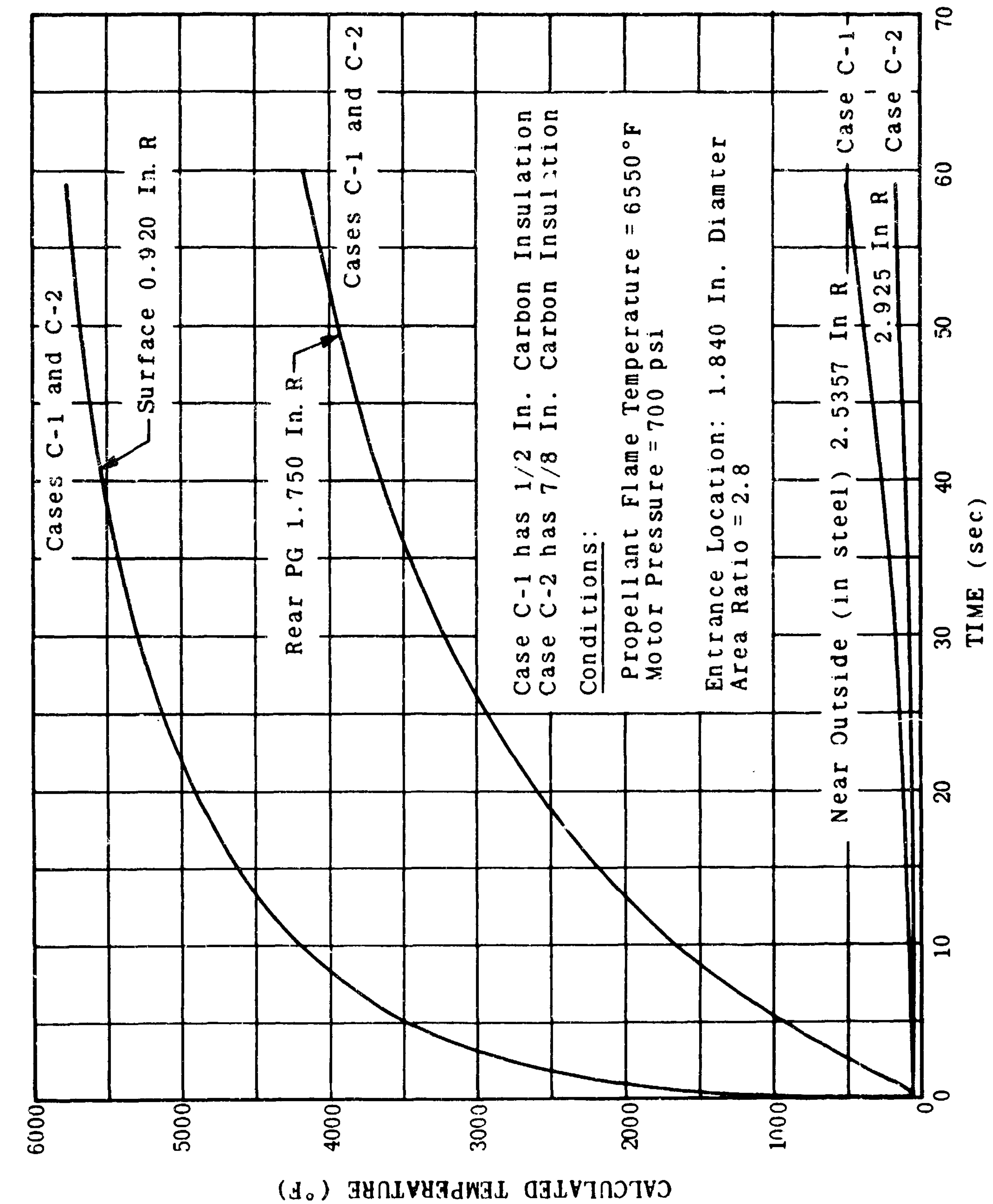

Figure 3-3. Temperature in Entrance Section of Sub-scale Nozzle.

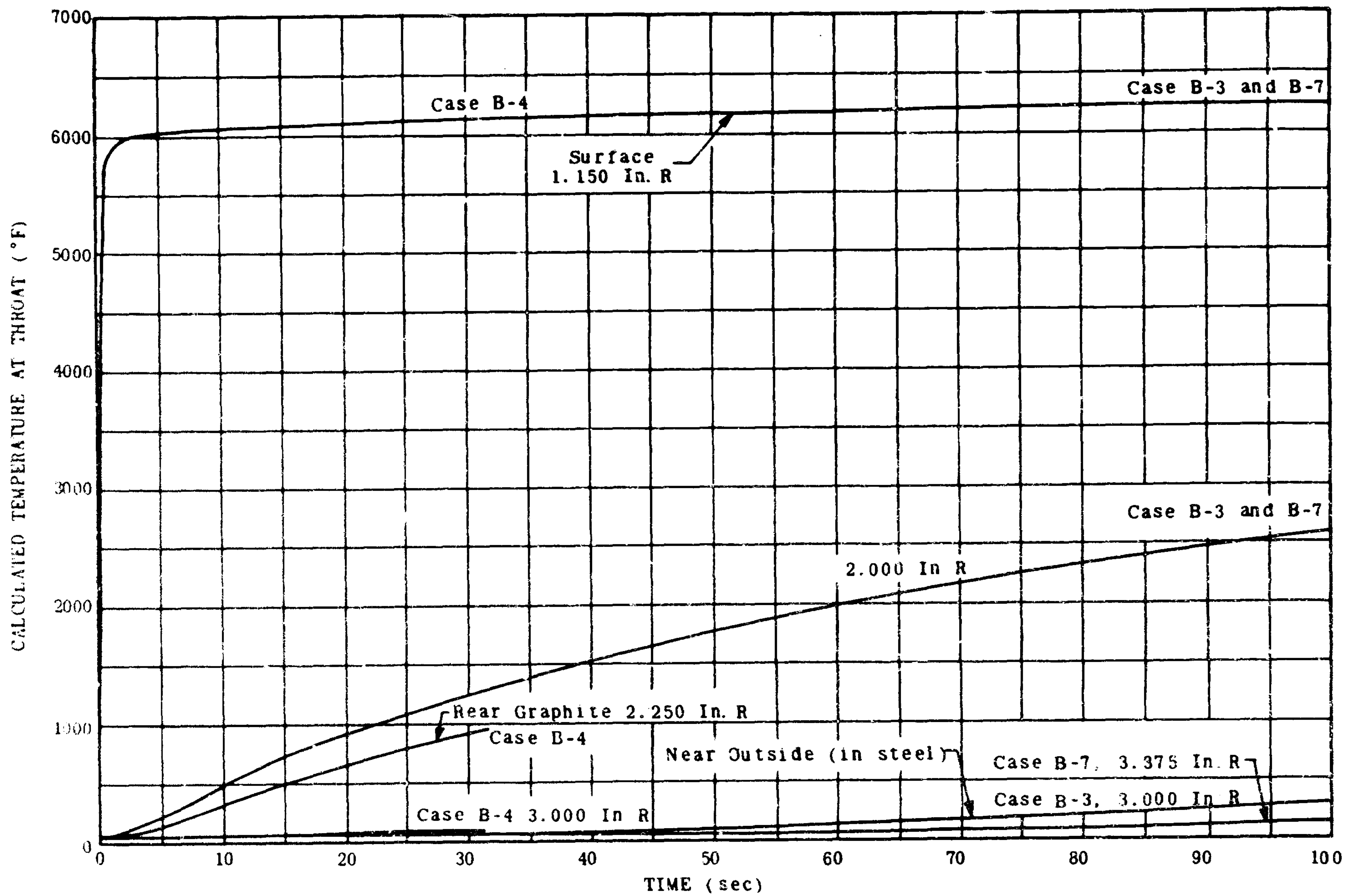

Figure 3-4. Temperatures at Throat of Full Scale Nozzle.

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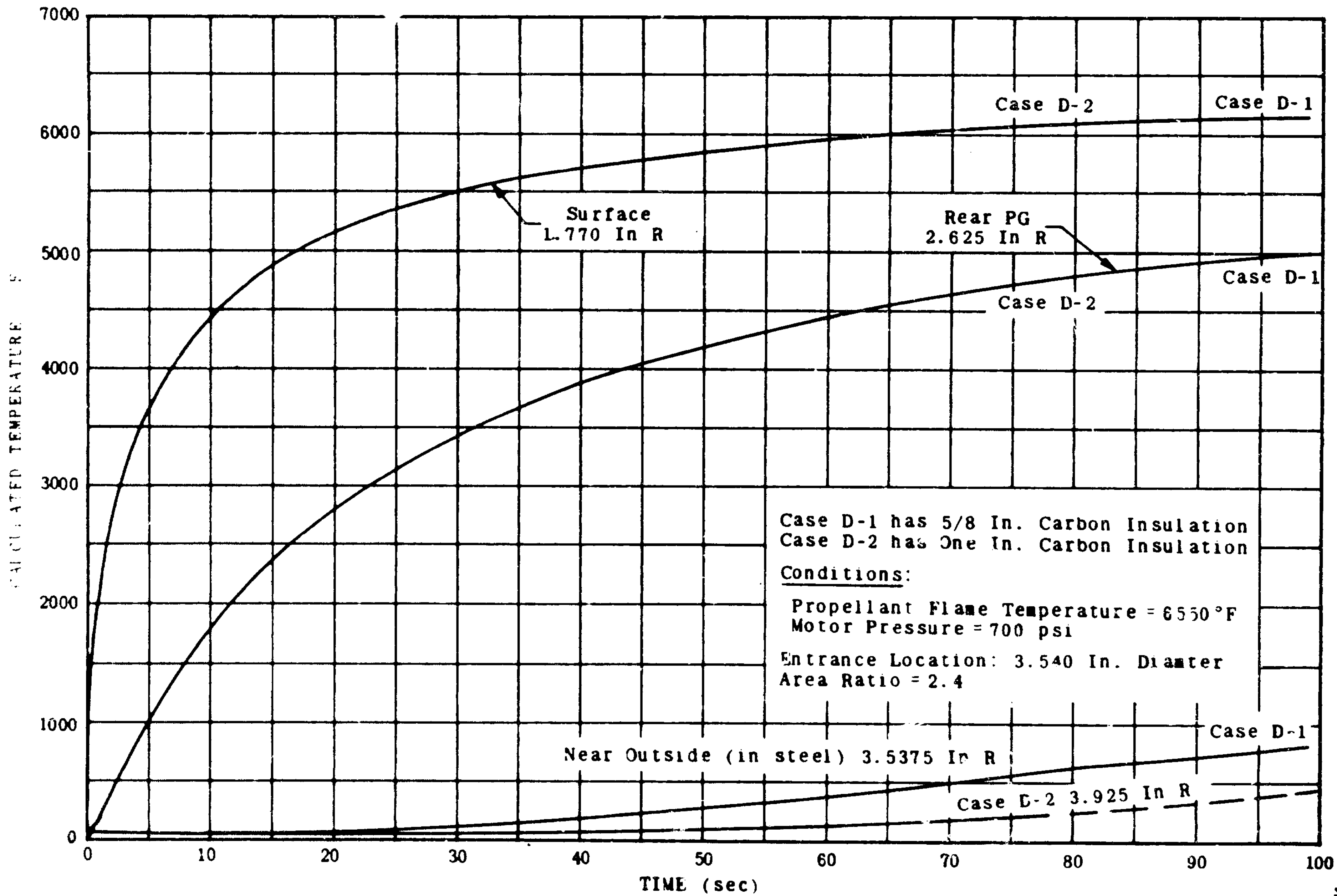


Figure 3-5. Temperatures in Entrance Section of Full Scale Nozzle.

graphite are included for the primary purpose of providing a low erosion condition at the leading edge of the coating and no greater weight of this material is desirable beyond that deemed suitable for this purpose. To minimize the amount of pyrolytic graphite plate and still maintain sufficiently low inside surface temperature for low erosion, a significant heat leak from the outside surface of the pyrolytic graphite plate is advantageous. In later sections of this report the design details and performance in the first test of this nozzle system are outlined in greater detail.

The data presented in graphical form were selected to illustrate certain behavior patterns typical of pyrolytic graphite nozzles. More complete tabular data for the fifteen cases selected for analysis are listed in the appendix so that the reader may make any further comparisons desired.

3.2 Nozzle Design and Fabrication.

The preparation of nozzles to demonstrate the feasibility of pyrolytic graphite coatings for nozzle service consists of the design of the nozzle assembly, deposition of the coating on the substrate, and fabrication and assembly of the remaining components of the nozzle system. The design philosophy utilizes a segmented concept in which the pyrolytic graphite coated throat insert is a segment only large enough to provide dimensional stability at the throat. The remaining segments form the total nozzle contour or support, back-up, or insulate the exposed segments. The basic design used in the first sub-scale test is shown in the assembly drawing, Figure 3-6. The actual segments of this nozzle prior to assembly are pictured in Figure 3-7. The individual components of the nozzle are numbered identically in these two figures. It is anticipated that many of the features of this basic assembly can be retained for each of the 1 1-inch diameter sub-scale nozzles. Changes in the curvature or length of the coated throat insert and re-location of the joint lines can be made without changing the basic features of the assembly

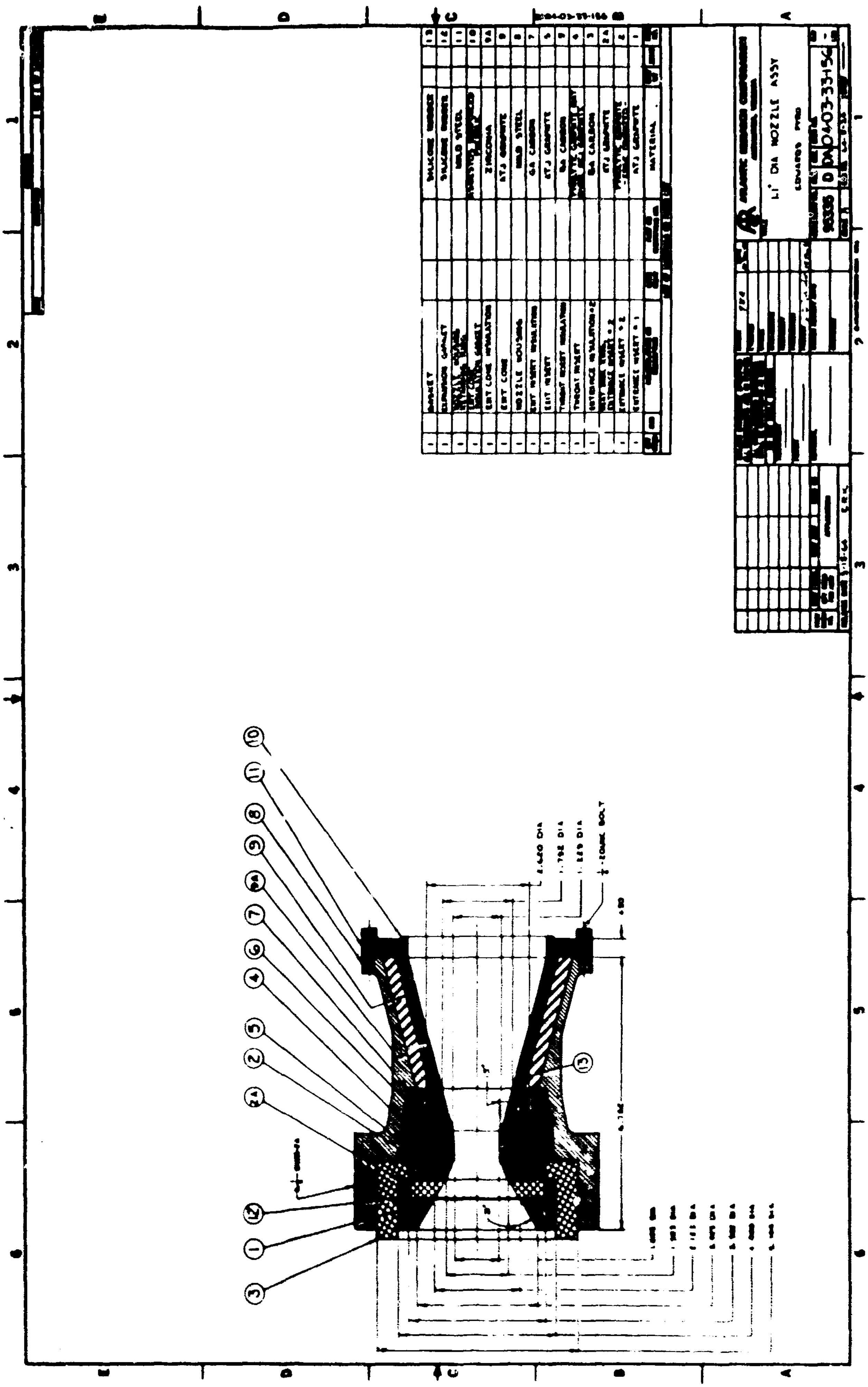


Figure 3-6. 1.1 Inch Diameter Nozzle Assembly.

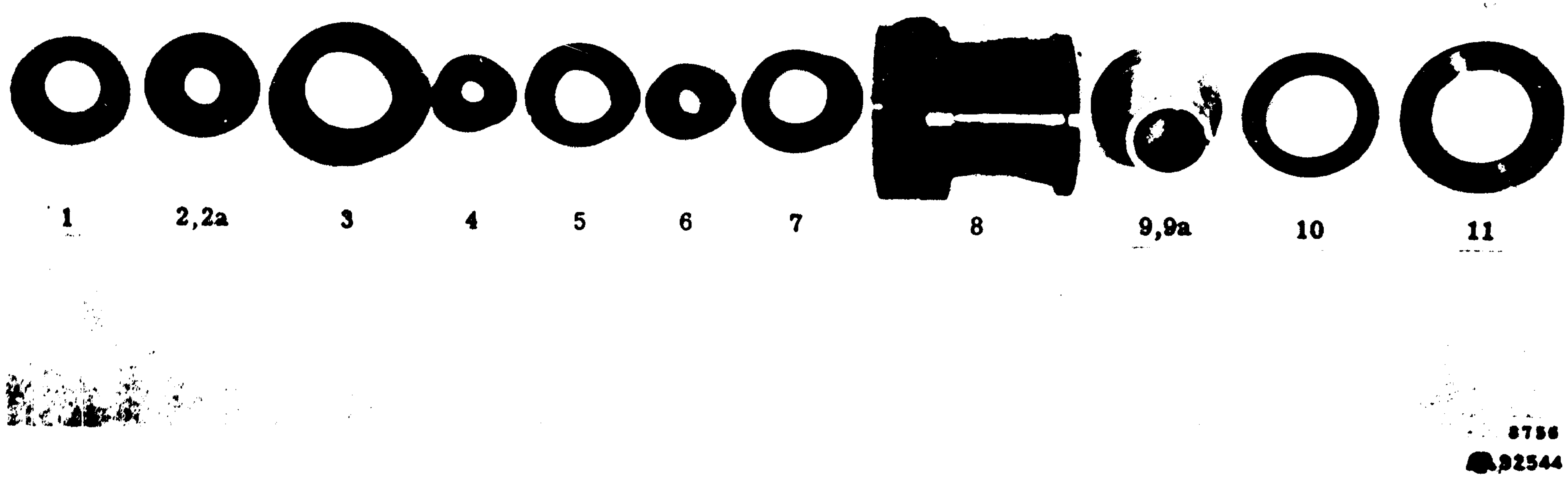
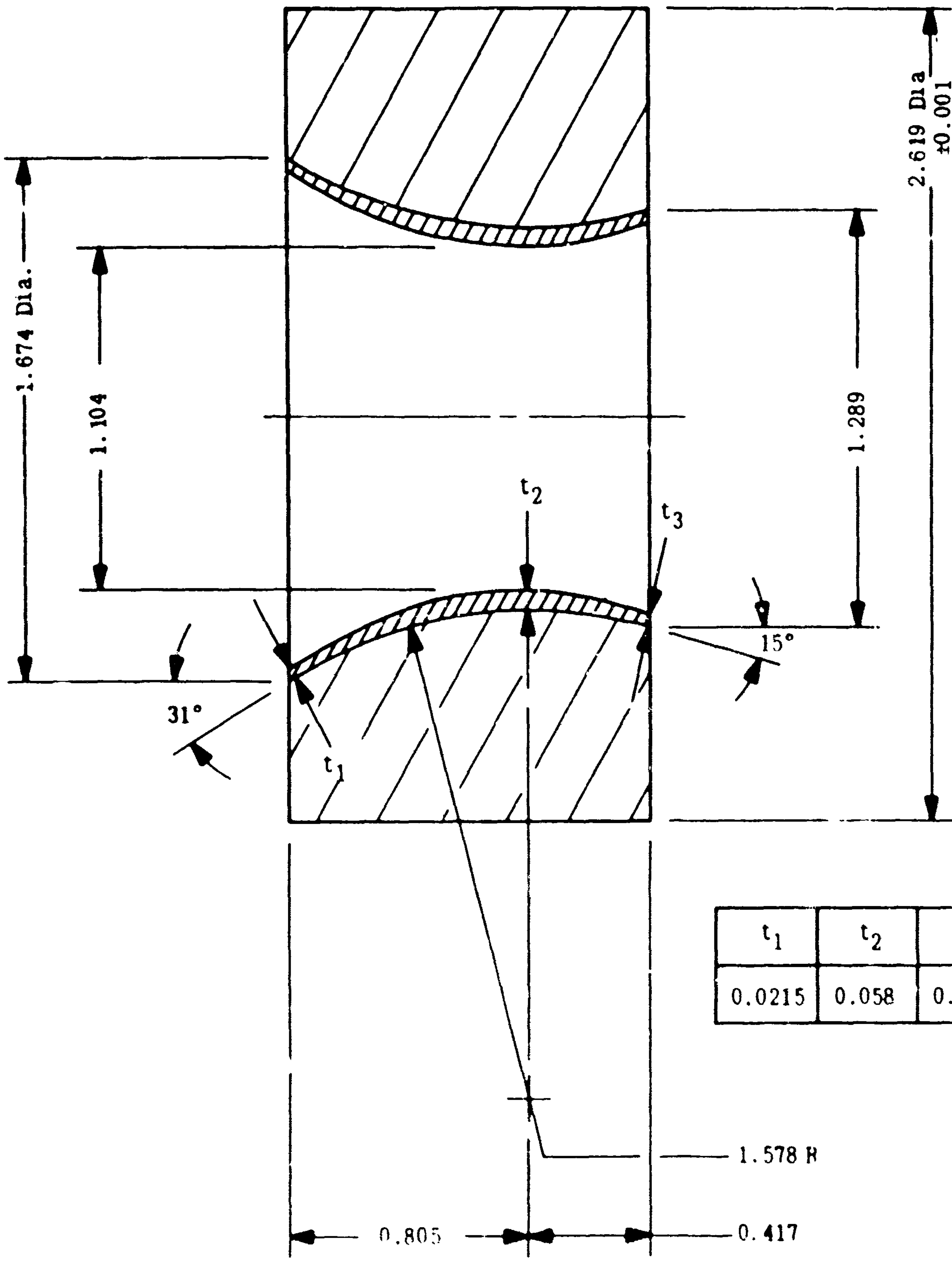


Figure 3-7. Components of Sub-scale Nozzle Prior to Assembly.

For the first sub-scale nozzle test a radius of curvature nominally three times the throat radius was chosen. The length of the coated insert was selected to place the inlet joint line at an area ratio of two relative to the throat and to carry the outlet end to the 15° tangent point to match the expansion cone half-angle. Several inserts were prepared with this basic configuration for the coated section prior to the first motor test. The pyrolytic graphite coated insert which was tested in firing EPb 1 is shown in Figure 3-8.

The pyrolytic graphite coated inserts were prepared by passing a gas mixture containing methane over a substrate heated to 2000°C in a resistance tube furnace. The substrate, which was pre-machined to the desired nozzle contour, was a part of a tube placed coaxially with the furnace tube. The methane-containing source gas was introduced into the region of the substrate by a water-cooled injector. Deposition conditions, such as the injector location, gas flow rates, and gas distribution, were adjusted to obtain the desired coating thickness and uniformity.

Six coated inserts were prepared prior to the first firing. In each insert significant delamination cracking at the exit end was noted during microscopic examination of the polished cross-section. The cracks were always in the coating, never at the substrate surface. These cracks, which result from the stresses built into the coating by its anisotropic behavior and by mismatch of expansion coefficients with the substrate, seemed to originate during the machining of the test piece from the coated substrate tube. Changes in machining practice did not eliminate the cracks, however. Moderate changes in the deposition conditions, including gas flow conditions, exit geometry, and substrate grain orientation, also failed to eliminate these cracks. It is clear that coatings as thick as 50 mils (nominal thickness selected for motor test) on a nozzle of the sub-scale size are above the optimum range and that residual stress cracking may remain a significant problem. Thus, it was decided that a typical insert containing a delamination crack at the exit end would be tested in the first firing to determine the capability of such a coated nozzle. The microstructure of both the inlet and exit end of the coated section selected



t_1	t_2	t_3
0.0215	0.058	0.0314

Figure 3-8. Detail of Coated Throat Insert for Firing EPb-1.

for firing EPb-1 is shown in Figure 3-9. The crack in the exit end averaged about 1 mil in width and was about 10 to 15 mil above the substrate.

One of the modifications used in the study to eliminate the cracks in the exit end of the coating was to use a design in which no machining was performed at the exit end of the coated section. In the piece selected for the second motor firing, EPb-2, a partial crack at the inlet end was noted. Since a crack-free piece had not been prepared this piece was chosen to determine the effect of the stress relief crack at the inlet as compared with the crack at the exit end. The firing test of this insert was scheduled for the week of May 11.

3.3 Motor Firing Tests.

A total of eight motor firing tests are scheduled for this program. Four of these tests are to be made with a sub-scale nozzle (1.1-inch throat diameter) in an 18-inch diameter motor. The remaining four tests are to be made with a full-scale nozzle (2.3-inch throat diameter) in a 36-inch diameter motor. The first six tests are scheduled for 60-second duration and the last two full-scale tests are to be of 100-second duration. All the firings are to be made with APG 112-b gel propellant (flame temperature, 6550°F) at a nominal motor pressure of 700 psi. These firing conditions are very severe and no known nozzle system of a weight comparable to that possible with a pyrolytic graphite coated nozzle can achieve the performance predicted for the pyrolytic graphite coating. Thus, if the feasibility of the coating system can be demonstrated a distinct advance in uncooled nozzle technology can be accomplished.

It was estimated from previous work that the inherent erosion rate of a pyrolytic graphite coating under the firing conditions to be used is of the order of 0.5 mil/sec. If any spalling or massive coating loss were to occur the average erosion rate would be higher. For a 60-second firing an absolute minimum of 30 mils of coating is indicated. For this program a nominal coating thickness of 50 mils was selected for the initial motor firings. In the first firing, EPb-1, a coating thickness of 58 mils was measured at the throat of the insert selected.

a. Inlet End b. Outlet End

Figure 3-9. Microstructure of Pyrolytic Graphite Coating Tested in Firing EPh-1.

The performance of the coating in the first motor test was less than optimum. The pressure-time curve for the firing is reproduced in Figure 3-10. The following data describe the firing conditions and nozzle behavior.

Firing No.	Motor Pressure, psi		Duration (sec)	Throat Diameter (inch)	
	Maximum	Average		Before	After
EPb-1	795	564	55.9	1.105	1.287/1.351

Two photographs of the nozzle assembly after test are shown in Figures 3-11 and 3-12. The temperature data, which corresponds satisfactorily with the predictions of our thermal analysis, consists of measurements made by thermocouples spot-welded to the steel nozzle body at three locations. To avoid unnecessary machining, the steel shell, especially at the region behind the throat, was significantly thicker than the standard 3/8-inch thickness used in the analyses. The temperatures noted indicate, however, that the heat leak from the approach section through the nozzle assembly was satisfactorily controlled. The data are as follows:

Location	Temperature at Tail-off, °F
1) Behind throat	155
2) Behind joint in exit cone	357
3) Near end of exit cone	225

Based on the overall change in throat dimension the total radial erosion at the throat ranged between a minimum of 91 mils and a maximum of 123 mils. Fortunately, considerably more can be determined from the firing test data than just these overall values. The axial profile of the erosion was prepared by carefully measuring the local minimum and maximum diameters at stations 0.1-inch apart axially along the fired insert. These profiles along with the original substrate and coating surfaces are shown in Figure 3-13. It can be seen from this figure that the effective throat of the nozzle after test is about 0.2-inch upstream of the initial location.

One more very useful calculation is possible from the test data. By using the ballistic equation for a motor of constant propellant burning surface the instantaneous throat diameter can be calculated from the initial throat diameter and the motor pressure curve.

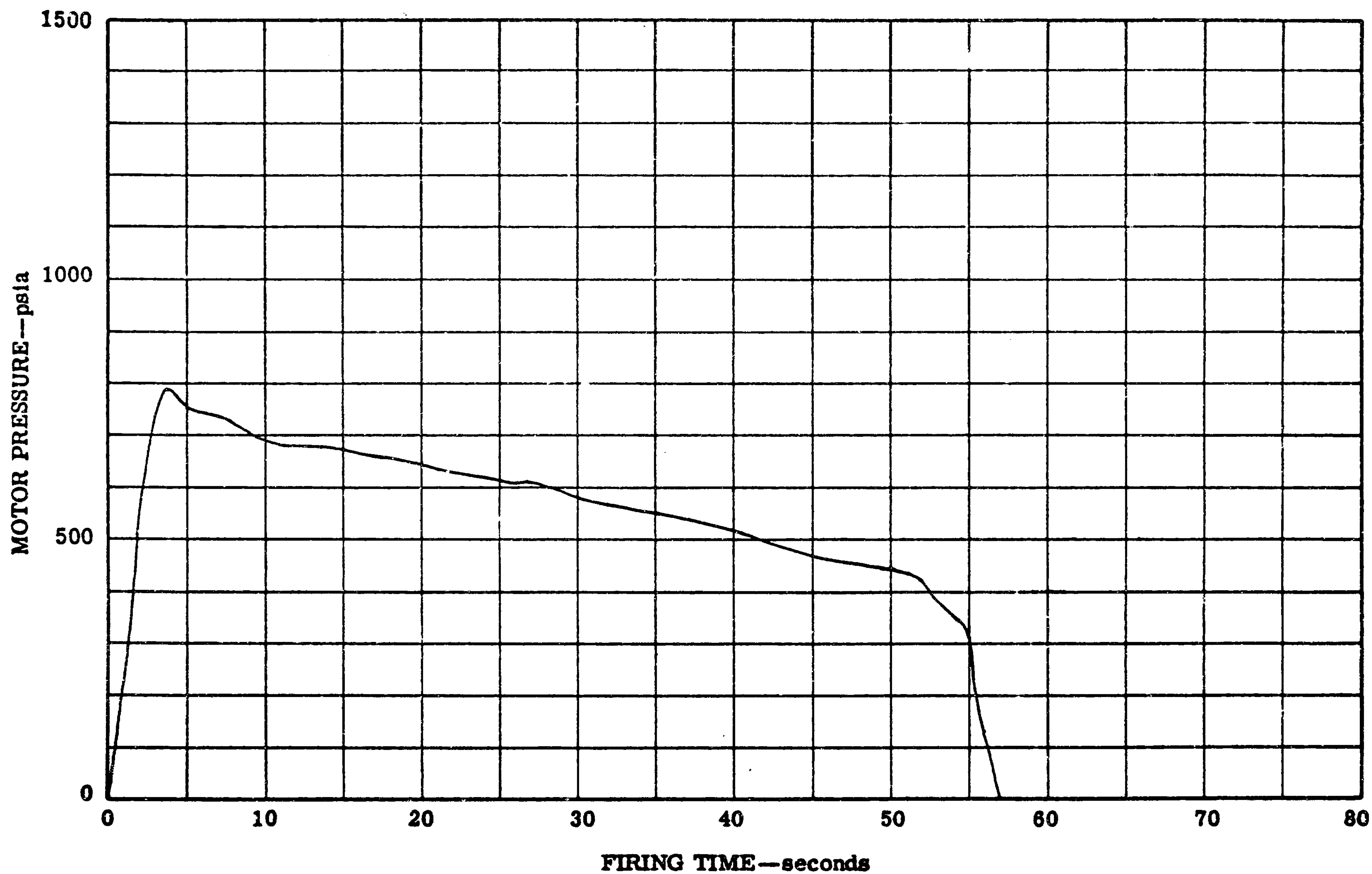


Figure 3-10 Motor Pressure Trace for Firing EP-b-1

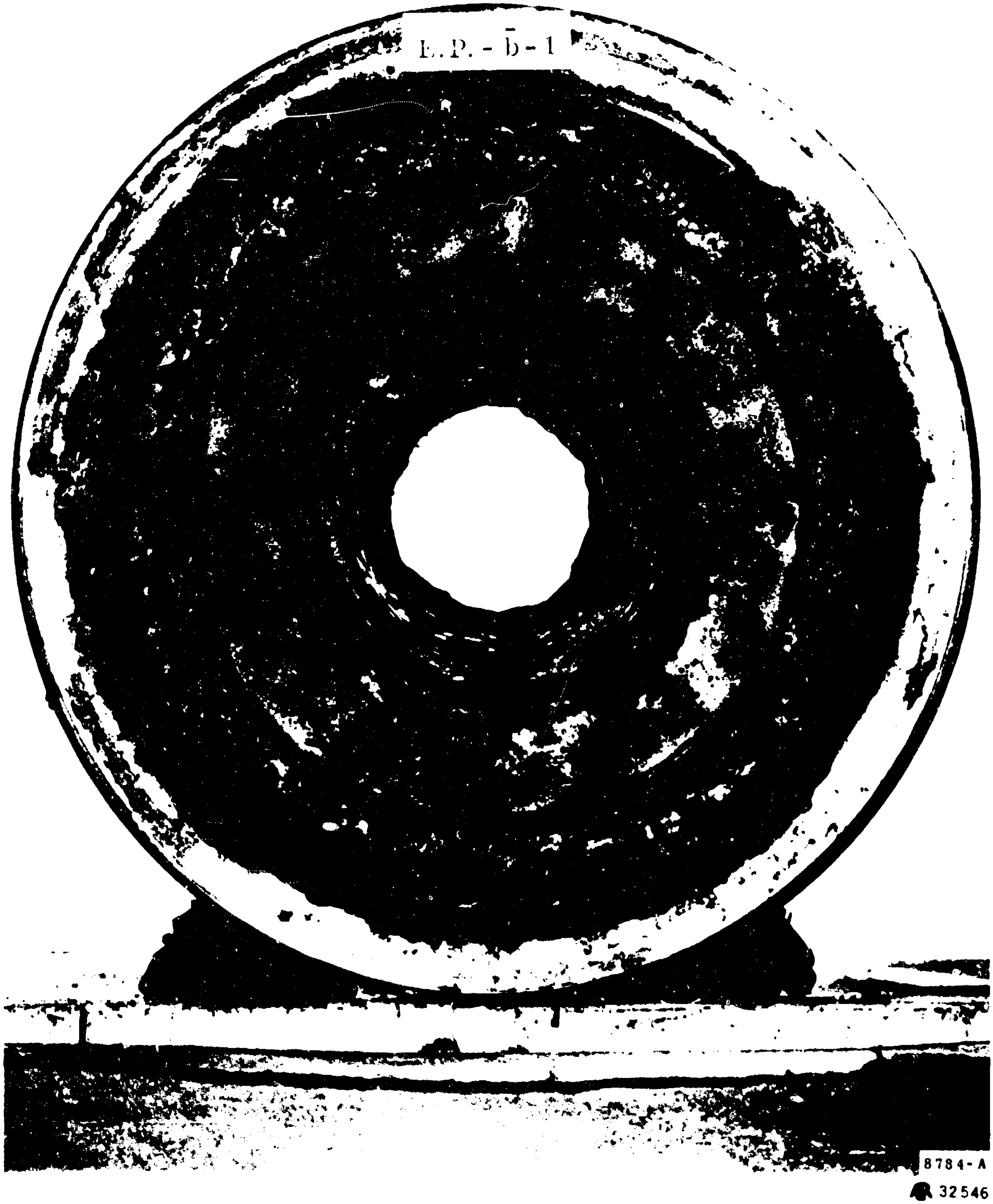


Figure 3-11. Axial View from Entrance End of Nozzle EPb-1 After Firing.

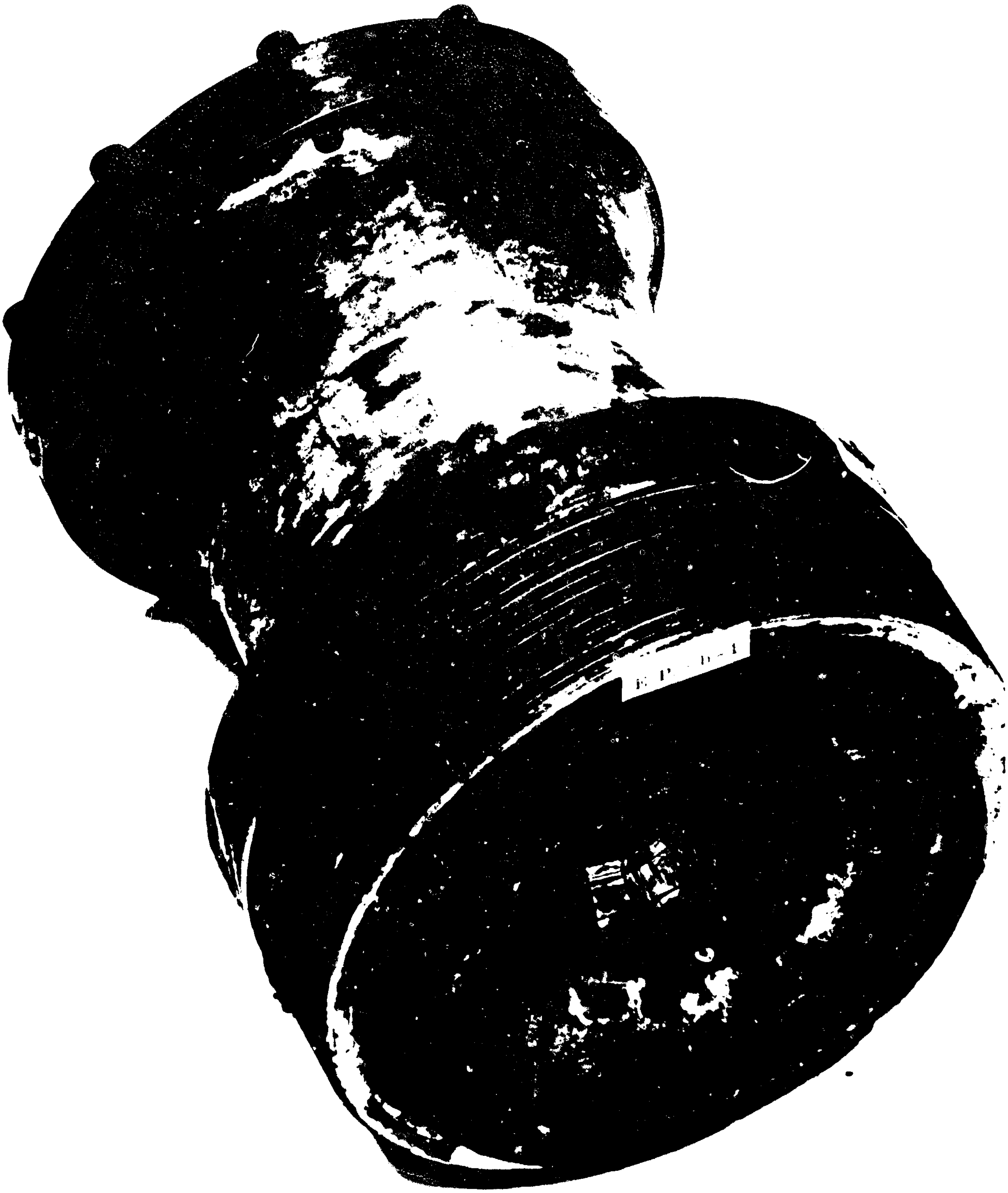


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Figure 3-12. Oblique View of Nozzle EPb-1 After Firing.

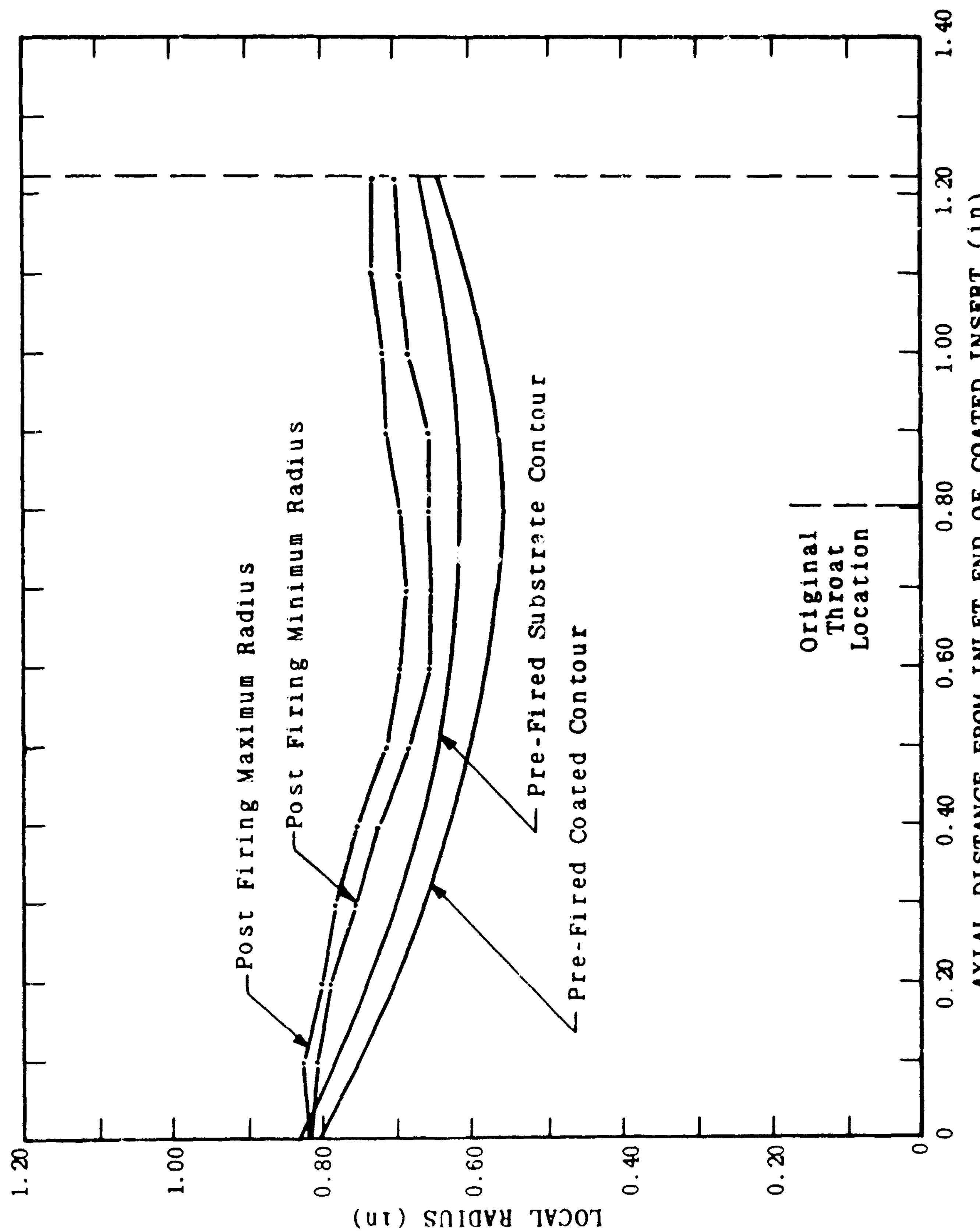

Figure 3-13. Throat Insert Profiles for Firing EPb-1.

Although such a calculation is not always highly precise because of the strongly pressure dependent properties, it was carried out for firing EPb-1 to indicate the nature of the erosion rate behavior. Assuming that at the instant of maximum motor pressure the throat diameter was still the original value, the final diameter consistent with the pressure just prior to tail-off was calculated using the propellant burning rate pressure exponent for the average motor pressure. The calculated final diameter was 1.333-inch which compares satisfactorily with the measured 1.319-inch value (the average of the measured maximum and minimum throat diameter). The instantaneous throat radii calculated in this manner throughout the firing duration are shown in Figure 3-14. Although some scatter exists in these data, several indications are clear. It is probable that early in the firing (within the first 5 seconds or so) a significant loss of coating occurred. This was likely at the exit end of the coated section where the delamination crack was known to exist. This behavior indicates that such a stress relief crack at the exit end is a source of failure initiation. For much of the remainder of the firing the trend of the throat radius indicates an average erosion rate of approximately 1.2 mil/sec. Since this throat erosion was smooth and steady up to about 50 seconds and because the actual throat location was moved upstream at the end of the firing, it is postulated that this total erosion rate represents the sum of the normal radial erosion of the coating plus an edge attack on the coating with loss by spalling. As the downstream edge was chipped away the throat radius was increased because of the nozzle radius of curvature. This explanation is consistent with the observation that the erosion rate was steady beyond the time when the total coating thickness at the original throat location had been removed. It is our belief that an upstream portion of the coating was serving as the nozzle throat until finally at the 50 to 52 second time when the rapid increase in erosion rate to an estimated 8.6 mil/sec indicates that the substrate ATJ graphite was fully exposed. It is our conclusion that the observed erosion of the pyrolytic graphite coating in firing EPb-1 was increased above the inherent value for this material by a partial coating loss followed by edge spalling.

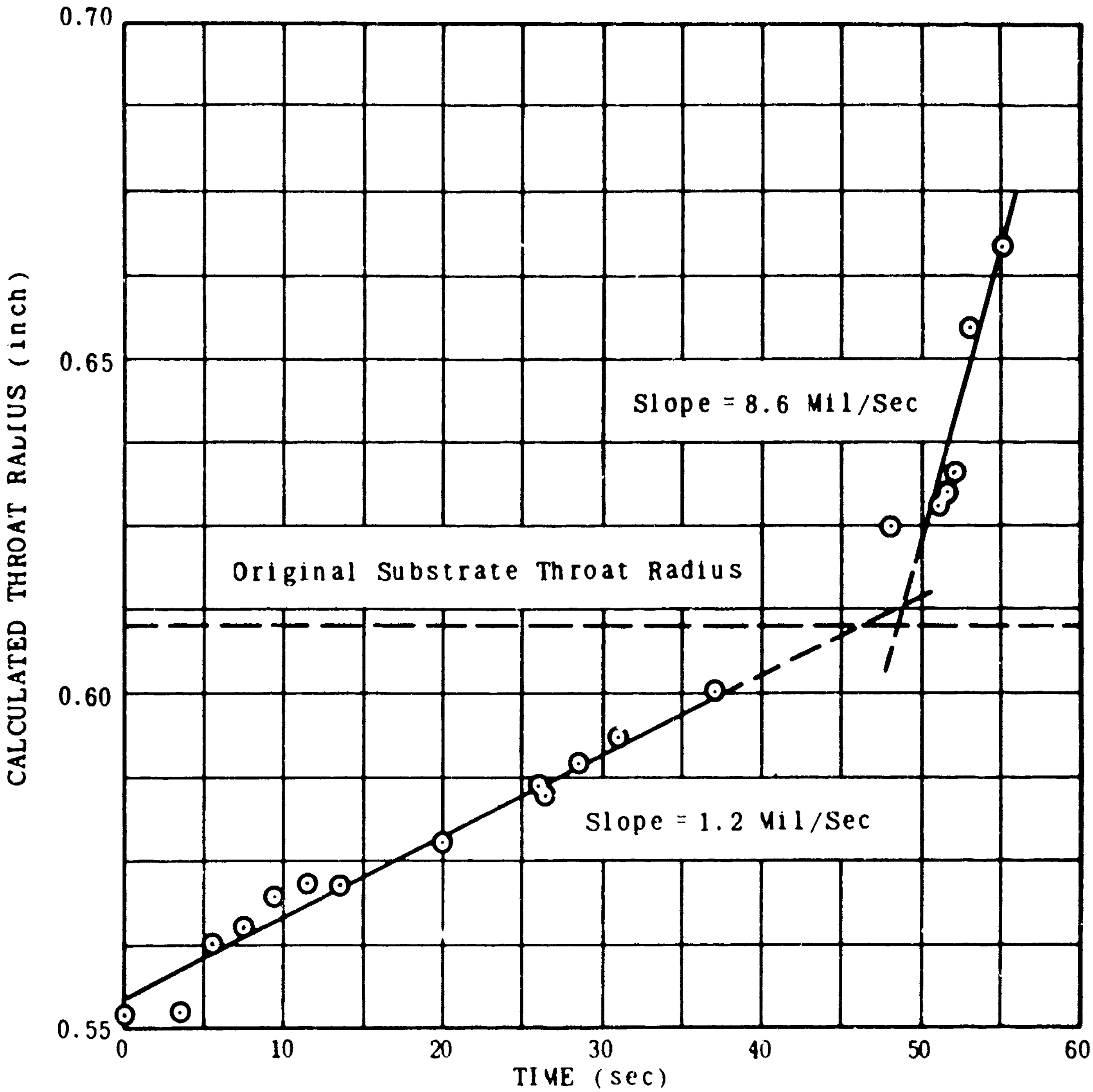

Figure 3-14. Calculated Instantaneous Throat Radii During Firing EPb-1.

4.0 FUTURE WORK

Preparation of a coated insert for the second sub-scale nozzle test was completed and this firing is scheduled for the week of May 11. Exit end cracking was prevented by a wrap around coating design, but an inlet end delamination crack was noted. Thus, the second firing will further investigate the tolerance of the nozzle system for delamination cracks. Following this test two main areas of work will be pursued. First, the preparation of a suitable coated insert for a full-scale nozzle will be undertaken. The third firing is scheduled to be a full-scale nozzle test. It is believed that amelioration of the delamination tendency will accompany this scale up. Second, further effort to produce acceptable, crack-free coated inserts of the sub-scale size will be continued.

APPENDIX

Tabular Data from Thermal Analyses

Case A-1

Throat Location: 1.100" diameter

Location	Surface	Rear Graphite	Midpoint Carbon	Steel Average
Radius	0.550	1.180	1.580	2.200
Node No.	1	11	14	17,18
Time (sec)		**Temperature °F**		
1	4470	140	70	70
2	4891	315	71	70
5	5330	645	92	70
10	5608	1513	20[illegible]	70
20	5848	2365	568	79
30	5964	28[illegible]9	[illegible]5	106
40	6035	3270	1250	154
50	6083	3543	1510	216
60	6117	3751	1725	288

Case A-2

Throat Location: 1.100" diameter

Location	Surface	Rear Graphite	Midpoint Carbon	Steel Average
Radius	0.550	1.440	1.730	2.200
Node No.	1	13	15	17,18
Time (sec)	Temperature °F			
1	4430	84	70	70
2	4850	164	75	70
5	5283	533	150	70
10	5550	1114	398	78
20	5798	2004	959	143
30	5932	2654	1443	263
40	6021	3156	1846	413
50	6085	3557	2185	565

Case A-3

Throat Location: 1.100" diameter

Location	Surface	Near Rear PG	Rear Graphite	Midpoint Carbon	Steel Average
Radius	0.550	0.574	1.180	1.580	2.200
Node No.	1	5	14	17	20,21
Time (sec)			Temperature, °F		
1	5925	804	85	70	70
2	5959	1119	152	70	70
5	6006	1643	405	78	70
10	6054	2184	780	133	70
20	6113	2866	1350	332	74
30	6151	3326	1772	560	89
40	6178	3620	2041	776	116
50	6199	3858	2365	970	154
60	6215	4046	2582	1142	201

Case A-4

Throat Location: 1.100" diameter

Location	Surface	Near Rear PG	Rear Graphite	Midpoint Carbon	Steel Average
Radius	0.550	0.574	1.440	1.720	2.200
Node No.	1	5	16	18	20,21
<u>Time (sec)</u>			<u>Temperature, °F</u>		
1	5925	801	72	70	70
2	5958	1117	94	71	70
5	6004	1611	232	89	70
10	6045	2076	484	174	72
20	6096	2662	910	401	91
30	6129	3057	1247	615	132
40.4	6156	3360	1481	810	192
50.4	6175	3585	1756	974	259
59.4	6190	3749	1929	1107	325

Case A-5

Throat Location: 1.100" diameter

Location	Surface	Rear PG	Rear Graphite	Rear Carbon	Near Outside (in steel)
Radius	0.550	0.610	1.250	2.000	2.220
Node No.	1	6	14	20	21
Time (sec)	Temperature, °F				
.05	4720	70	70	70	70
.1	5130	70	70	70	70
.2	5450	73	70	70	70
.5	5782	100	70	70	70
1.0	5955	175	71	70	70
2.2	6081	348	95	70	70
5.2	6134	624	228	70	70
10.2	6152	939	456	70	70
20.2	6176	1406	826	72	71
30.2	6193	1758	1121	79	75
40.2	6207	2038	1364	92	84
50.2	6218	2268	1570	112	100
59.2	6227	2445	1732	135	119

Case A-6

Throat Location: 1.100" diameter

Location	Surface	Rear PG	Rear Graphite	Rear Carbon	Near Outside (in steel)
Radius	0.550	0.610	1.500	2.000	2.220
Node No.	1	6	16	20	21
Time (sec)			Temperature, °F		
.05	4720	70	70	70	70
.10	5130	70	70	70	70
.20	5450	73	70	70	70
.50	5782	100	70	70	70
1.0	5965	175	70	70	70
2.2	6081	348	77	70	70
5.2	6133	603	146	70	70
10.2	6149	857	297	71	70
20.2	6168	1230	565	78	73
30.2	6182	1522	790	97	86
40.2	6194	1762	983	125	108
50.2	6204	1966	1151	160	138
59.2	6212	2124	1285	197	170

Case B-1

Throat Location: 2.300" diameter

Location	Surface	Near Rear Graphite	Near Rear Carbon	Near Outside (in steel)
Radius	1.150	1.950	2.685	3.0225
Node No.	1	13	19	21
Time (sec)	Temperature, °F			
.05	1880	70	70	70
.10	2410	70	70	70
.20	3000	70	70	70
.50	3778	72	70	70
1.0	4330	95	70	70
2.3	4901	247	70	70
5.3	5328	660	70	70
10.3	5602	1239	71	70
20.3	5839	2043	90	75
30.3	5957	2582	133	93
40.3	6029	2973	196	130
50.3	6079	3271	272	184
59.3	6112	3484	348	241

Case B-2

Throat Location: 2.300" diameter

Location	**Surface**	**Near Rear Graphite**	**Near Rear Carbon**	**Near Outside (in steel)**
Radius	1.150	2.185	2.685	3.0225
Node No.	1	15	19	21
Time (sec)		**Temperature, °F**		
.05	1880	70	70	70
.10	2410	70	70	70
.20	3000	70	70	70
.50	3778	70	70	70
1.0	4330	74	70	70
2.3	4900	132	70	70
5.3	5321	370	71	70
10.3	5579	774	82	71
20.3	5797	1413	143	91
30.3	5909	1881	235	142
40.3	5981	2240	343	216
50.3	6032	2524	456	304
59.3	6066	2732	559	389

Case B-3

Throat Location: 2.300" diameter

Location	**Surface**	**Rear PG**	**Rear Graphite**	**Rear Carbon**	**Near Outside (in steel)**
Radius	1.150	1.195	2.000	2.750	3.000
Node No.	1	6	12	20	21
Time (sec)			**Temperature, °F**		
.05	4550	70	70	70	70
.10	4980	71	70	70	70
.20	5330	81	70	70	70
.50	5692	155	70	70	70
1.0	5881	307	71	70	70
2.3	5995	592	96	70	70
5.3	6035	960	240	70	70
10.3	6065	1363	496	70	70
20.3	6105	1939	923	72	71
30.3	6135	2359	1266	80	76
40.5	6158	2690	1556	97	88
50.5	6175	2952	1797	122	108
60.5	6191	3169	2005	154	136
70.5	6203	3353	2187	193	170
80.5	6214	3511	2347	236	209
90.5	6224	3648	2489	282	252
100.5	6232	3767	2616	331	298
110.5	6239	3873	2730	383	346
120.5	6246	3967	2833	435	396
130.5	6252	4051	2927	487	447

Case B-4

Throat Location: 2.300" diameter

Location	**Surface**	**Rear PG**	**Rear Graphite**	**Rear Carbon**	**Near Outside (in steel)**
Radius	1.150	1.195	2.250	2.750	3.000
Node No.	1	6	14	20	21
Time (sec)			**Temperature, °F**		
.05	4550	70	70	70	70
.10	4980	71	70	70	70
.20	5330	80	70	70	70
.50	5692	155	70	70	70
1.0	5881	307	70	70	70
2.3	5995	591	78	70	70
5.3	6035	949	158	70	70
10.3	6061	1309	336	71	70
20.3	6097	1810	663	80	75
30.3	6123	2181	939	103	90
31.3	6125	2213	965	106	93

Case B-7

Throat Location: 2.300" diameter

Location	Surface	Rear PG	Rear Graphite	Rear Carbon	Near Outside (in steel)
Radius	1.150	1.195	2.000	3.125	3.375
Node No.	1	6	12	20	21
Time (sec)			Temperature, °F		
.05	4550	70	70	70	70
.10	4980	71	70	70	70
.20	5330	80	70	70	70
.50	5694	155	70	70	70
1.0	5882	307	71	70	70
2.2	5993	581	94	70	70
5.2	6035	954	237	70	70
10.2	6064	1359	493	70	70
20.2	6105	1937	921	70	70
30.2	6134	2357	1265	71	70
40.2	6157	2683	1550	73	72
50.2	6175	2947	1793	78	75
60.2	6190	3165	2002	85	81
70.2	6203	3350	2185	96	90
80.2	6214	3509	2348	111	102
90.2	6224	3647	2492	128	120
99.2	6231	3757	2610	147	135

Case C-1

Entrance Location: 1.840" diameter (1.100" throat)

Location	Surface	Rear PG	Rear Carbon	Near Outside (in steel)
Radius	0.920	1.750	2.250	2.5375
Node No.	1	5	9	11
<u>Time (sec)</u>		<u>Temperature, °F</u>		
.05	620	70	70	70
.10	850	70	70	70
.20	1150	71	70	70
.50	1650	92	70	70
1.0	2095	170	70	70
2.2	2692	417	70	70
5.2	3491	975	71	70
10.2	4207	1675	80	72
20.2	4925	2607	140	103
30.2	5299	3214	243	177
40.2	5528	3641	371	281
50.2	5683	3955	507	399
59.2	5783	4170	631	511

Case C-2

Entrance Location: 1.840" diameter (1.100" throat)

Location	**Surface**	**Rear PG**	**Rear Carbon**	**Near Outside (in steel)**
Radius	0.920	1.750	2.625	2.925
Node No.	1	5	10	12
Time (sec)		**Temperature, °F**		
.05	620	70	70	70
.10	850	70	70	70
.20	1150	71	70	70
.50	1650	92	70	70
1.0	2095	171	70	70
2.2	2692	418	70	70
5.2	3492	979	70	70
10.2	4210	1681	70	70
20.2	4928	2613	74	71
30.2	5301	3222	89	80
40.2	5532	3655	118	101
50.2	5689	3979	160	135
59.2	5791	4206	209	175

Case D-1

Entrance Location: 3.540" diameter (2.300" throat)

Location	**Surface**	**Rear PG**	**Rear Carbon**	**Near Outside (in steel)**
Radius	1.770	2.625	3.250	3.5375
Node No.	1	6	12	14
Time (sec)		Temperature, °F		
.05	670	70	70	70
.10	900	70	70	70
.20	1180	71	70	70
.50	1690	90	70	70
1.0	2181	175	70	70
2.2	2842	445	70	70
5.2	3703	1054	70	70
10.2	4442	1810	72	70
20.2	5148	2799	99	82
30.2	5500	3433	162	123
40.2	5712	3876	255	194
50.2	5852	4200	365	285
60.2	5950	4445	484	391
70.2	6022	4635	605	501
80.2	6077	4783	725	612
90.2	6118	4902	841	723
99.2	6148	4990	943	820

Case D-2

Entrance Location: 3.540" diameter (2.300" throat)

Location	Surface	Rear PG	Rear Carbon	Near Outside (in steel)
Radius	1.770	2.625	3.625	3.925
Node No.	1	6	13	15
Time (sec)		Temperature, °F		
.05	680	70	70	70
.10	900	70	70	70
.20	1180	71	70	70
.50	1690	90	70	70
1.0	2181	176	70	70
2.2	2842	446	70	70
5.2	3704	1059	70	70
10.2	4444	1817	70	70
20.3	5156	2815	71	70
30.3	5506	3446	78	74
40.3	5716	3880	95	85
50.3	[illegible]	4212	124	107
60.3	5954	4461	164	139
70.3	6027	4655	214	182
77.4	6067	4768	254	216