THE Marquardt CORPORATION VAN NUYS, CALIFORNIA

FINAL REPORT

THE EVALUATION OF A TIN-ALUMINIDE OXIDATION RESISTANT COATING FOR REACTION CONTROL SYSTEM THRUST SYSTEMS APPLICATIONS

(Title - Unclassified)

1 August 1964 TMC Report No. S-430

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I. SUMMARY

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The objective of this program was to investigate the performance of a tin-aluminide coating on 90Ta-10W material for service in 100 pound thrust radiation cooled reaction control rocket thrust chambers. The coating used was R-505C, developed and applied by General Telephone and Electronics Laboratories, Bayside, Long Island, New York.

Rocket firing experiments were conducted with two (2) designs of propellant injectors and two (2) thrust chambers. The propellant injectors used included a design that resulted in nominal chamber wall temperatures in the 2800°F range and one which resulted in chamber wall temperatures in the 2300°F range. All tests were conducted under simulated altitude exhaust conditions of approximately 100,000 feet and propellants utilized were (50% UDMH/50% N_2H_4) and N_2O_4.

The scope of experimental study was of immediate technical interest to the Apollo Service Module reaction control system engine development program. As a result, additional experimental efforts were conducted by the Apollo Project Group under the Apollo Contract. The additional information so obtained is reported herein and includes test results with a disilicide-coated tantalum chamber.

The conclusion that may be reached, based on rocket firing experiments, is that tin-aluminide coated 90Ta-10W radiation cooled rocket engines have an upper temperature operating limit higher than 2360°F but below 2750°F.

AUTHOR

II. INTRODUCTION

An investigation of 90Ta-10W material, coated with an oxidation resistant tin-aluminide coating was conducted. The study was oriented toward the typical thrust chamber designs and operation conditions that prevail in the Apollo Service Module (S/M) Reaction Control System (RCS), which includes thrust chambers and propellant injection system (for purposes of this discussion). A photograph of this typical radiation cooled thrust chamber assembly, which includes propellant injection head and propellant valves is presented in Figure (1).

Two (2) 90Ta-10W chamber wall thickness designs having identical internal contours were test fired. The first chamber (designated by part number as X-18920) was designed with emphasis on structural integrity and light weight. The second chamber (P/N MD1141) was more "boiler plate" in design with emphasis on maximizing axial or longitudinal thermal conductivity and minimizing thermal gradients.

Advances in the design and performance of propellant injectors resulted in the use of two (2) injectors; an early Apollo S/M RCS design and a later prototype Apollo S/M RCS design whose performance results in greatly lowered chamber wall temperature. Propellants used in all experiments were 50% hydrazine - 50% UDMH and nitrogen tetroxide.

Pertinent details regarding the experimental hardware and test results are presented and discussed herein.

III. DESCRIPTION OF EXPERIMENTAL HARDWARE

The hardware experimentally studied has the same general appearance as shown in the photograph of Figure (1). The significant difference in the thrust chambers tested is the wall thickness. The wall thickness variation is shown in Figure (2) as a function of cross sectional area of metal for the chamber length. A basic reference used was the Apollo S/M RCS molybdenum chamber (P/N 225864) which had been experimentally operated with a wide range of propellant injector designs and which also represents a typical Apollo design. The full length of an Apollo chamber skirt is 6.984 inches (throat measured along the axial centerline to exit dimension), however, wall thickness is shown to only the 5 inch length in Figure (2) since this length fully covers the region of interest. A schematic of the basic molybdenum reference chamber (P/N 225864), the "thin wall" 90Ta-10W chamber (P/N X-18920), and the "thick wall" 90Ta-10W chamber (P/N MD1141) is presented in Figure (3) as a supplement to Figure (2).

The tantalum chambers were typically manufactured as a two-piece assembly from bar and sheet stock. The chamber section was machined from an electron-beam-melted recrystallized 90Ta-10W bar 2½" dia. x 4½" long. The skirt was first preformed by a hydroform operation, recrystallized at 2800°F for one (1) hour in 10^{-5}mm Hg vacuum and then floturned with an approximate 60% reduction in wall thickness. The chamber and skirt were butt-welded with no joint preparation by the gas tungsten-arc method. The welding was performed in a chamber containing an argon gas atmosphere. After welding, the weld was x-rayed.

A. 90Ta-10W Thrust Chamber (P/N X-18920) - Thin Wall Design

This chamber was designed with structural strength as a primary criteria. Reference to Figure (2) shows that this chamber, while structurally sound, has a significantly smaller cross sectional area of metal. A photograph of the chamber after tin-aluminide coating was applied by General Telephone & Electronics Laboratories is presented in Figure (4). The excess coating formed spheres on the chamber, both on the interior and the exterior surfaces as depicted in the photograph. These "balls" of excess tin and aluminum were formed when the chamber was furnace conditioned in air at ambient pressure for about 5 minutes at 2600°F. The spheres were measured and found to vary in size up to 0.010 inches in diameter.

B. Engine Assembly for 90Ta-10W Thrust Chamber (P/N X-18920)

The thrust chamber-injector assembly (similar to Figure 1) was designated configuration 20560-503. This configuration has been used with the reference molybdenum chamber design (P/N 225864) over a wide range of operating conditions. Chamber wall temperatures for this reference design were observed to be in the 2800 to 2900°F regime.

The propellant injector utilized in this assembly was designated P/N X205884 and has the following general characteristics:

1. Twelve doublets
2. Diameter of fuel injection orifice: 0.024 inches
3. Diameter of oxidizer injection orifice: 0.0314 inches
4. Impingement diameter: 1.25 inches
5. Fuel stream angle with engine axis: 35°
6. Oxidizer stream angle with engine axis: 35°
7. Momentum resultant angle: 0°
8. Based on O/F = 2.0 and total weight flow of propellant = 0.333 lb/second

The known history and performance of this injector configuration was considered to be a suitable frame of reference for the 90Ta-10W (P/N X18920) chamber tests.

C. Thrust Chamber (P/N MD1141)

The design motivation for a thicker walled chamber was based on the consideration of thermal conductivity along the wall of the chamber. Analytically, it was determined that a thicker wall could help distribute heat from regions subjected to high heat flux. The thickness of the chamber for a distance approximately 2.0 inches downstream of the throat was increased by the ratio of average heat conductivity (molybdenum/tantalum) with chamber P/N 225864 (molybdenum) serving as the reference from which to scale. A two dimensional heat transfer calculation was programmed on

The Marquardt Corporation 7040 computer for the three (3) thrust chambers discussed herein, and the results summarized in Figure (5). The local internal heat flux was established using the Bartz equation and a range of emissivity was selected for the chamber external surface. This simplified analytical model does not consider the effects on internal heat transfer coefficients caused by gas temperature stratification and wall film cooling by propellant droplets. The purpose of this analysis was to establish qualitative trends only and therefore the results do not closely represent actual temperature level or distribution as established by experimental tests. A throat temperature reduction of several hundred degrees is predicted by the analysis.

D. Engine Assembly for 90Ta-10W Thrust Chamber (P/N MD1141)

This chamber was test fired with an engine-injector configuration designated T-10060. This injector configuration represents an advanced prototype design that demonstrated reductions in chamber wall temperatures of more than 500°F over earlier prototypes. NASA, MSC participated in the technical decision to utilize this more advanced design for further coating evaluation since this injector is a configuration that more nearly represents a final Apollo design.

The propellant injector (P/N T-8240) utilized in this assembly has the following general characteristics:

1. Eight doublets
2. Diameter of fuel injection orifice: 0.0304"
3. Diameter of oxidizer injection orifice: 0.0354"
4. Impingement diameter: 0.700"
5. Fuel stream angle with engine axis: 35°
6. Oxidizer stream angle with engine axis: 43°
7. Momentum angle, approximately 22° from axial centerline
8. Nominal percent of fuel directed toward wall: 13%
9. Angle of impingement on wall, with respect to engine axis: 40°
10. Based on O/F = 2.0 and total weight flow of propellant = 0.333 lb/second

This injector design has been operated with several thrust chambers and its characteristics also represent a known datum of performance.

Two chambers of the MD1141 design were test fired with the T-10060 engine-injector configuration. P/N MD1141, S/N 1 was discilicide coated and tested by the Apollo Project. P/N MD1141, S/N 2 was tin-aluminide coated and test fired under the scope of the study herein.

IV. DISCUSSION

A. Chamber P/N X-18920

1. Experimental Results

Considerable engineering examination was directed at the results of the first rocket firing experiment in the series of tests recorded herein. This experiment was conducted with engine configuration P/N X20560-503, which is representative of early succesful prototype experiments conducted with molybdenum chambers protected with a disilicide coating.

The early failure of P/N X-18920 chamber (13 seconds of testing) by loss of the tin-aluminide coating in the throat section is illustrated in Figures (6) and (7). The exterior of the chamber showing the discolored throat region is shown in Figure (6) and the apparent "melting" and relatively uniform loss of coating in the interior region is depicted in Figure (7).

The tests were conducted with propellant at ambient temperature (approximately 75°F), a nominal O/F ratio of 2.0, and a total propellant flow rate of 0.337 lb/sec. The thrust level was approximately 99 pounds with an associated specific impulse of 297 seconds.

2. Discussion

The engineering considerations regarding possible mode of failure and the subsequent examination are summarized in the following table:

POSSIBLE MODE OF FAILURE	CONCLUSIONS AND OBSERVATIONS
1. Abnormal Engine Operation or Malfunction of Components	No evidence of abnormal engine performance or malfunction. Thrust chamber temperature rise was judged normal, appeared to rise to the 3000°F regime in approximately 5 seconds, hold at this level for about 5 additional seconds, and then rise rapidly in the throat region to the 3800°F level where the experiment was terminated.
2. Excessively Low Coating Emissivity on Chamber Exterior	Analytically, based on data obtained in the Marquardt M&P Laboratory, a comparison of coating emissivity with other coatings' emissivities does not substantiate this parameter as controlling. Color moving pictures of the chamber test show a typical temperature distribution and level for the experiment, with the exception of the continued rise of temperature in the throat region.
3. Thermal Conductivity of Coating	Does not appear to be of significant contribution after examination of this and other coatings analytically, and including a review of previous experiments.
4. Chemical Reaction of Coating & Propellants	If the coating has eroded the throat should become rougher, increasing the friction factor and the heat transfer coefficient. The throat material (90Ta-10W) will then be exposed to an oxidizing environment with the following exothermic reactions occuring. $2\ Ta + \frac{S}{2}\ O_2$ ---- $Ta_2O_5 + 499{,}000\ \frac{cal}{\text{gm-Mole of Products}}$ $2\ W + \frac{S}{2}\ O_2$ ----- $W_2O_5 + 337{,}900\ \frac{cal}{\text{gm-Mole of Products}}$ It appears that chemical reaction with propellants is possible, but not a primary cause of the failure.
5. Structural Failure of Coating	Examination of Chamber P/N X-18920 after the rocket firing test led to the following experiment and results: A test panel (approximately 3" x 5") of tin-aluminide coated 90-10 was heated to approximately 3100°F under atmospheric pressure using an oxy-acetylene torch. A ½ inch diameter copper tube was directed normal to the specimen and service air at a total pressure of 100 psig was applied to the sample from a distance of approximately ½ inch. The coating was observed to "blow away". This crude test illustrated a low resistance to dynamic pressure, or scrubbing.
6. Thermal Conductivity Along Chamber Wall Longitudinal Axis	The two dimensional heat transfer analysis showed that this consideration may be strongly influential. Recognition of the qualatative nature of the analysis and the dangers of a quantative application led to the engineering "scaling" of wall thickness, based on the conductivity of the materials. A basic molybdenum chamber that represents a design successfully rocket fired with many propellant injector designs was used as a basis for determining the wall thickness of the 90Ta-10W P/N MD1141 chambers.

3. Throat Erosion Analysis

Interpretation of the experimental data shows an erosion of the nozzle throat area. The change in throat area was computed from the following equation:

$$\frac{A_t}{A_{t_x}} = \frac{(M_o + M_f)_1}{(M_o + M_f)_x} \quad \frac{P_{cx}}{P_c}$$

where:

$\frac{A_t}{A_{t_x}}$ original throat area ratioed to the throat area at time "x".

M_o = oxidizer flow rate

M_f = fuel flow rate

P_c = chamber pressure

Subscripts:

1 = originally

x = at any time

The variation of throat area for the thirteen (13) second duration run is presented in Figure (8). The decrease in throat area is noted to occur about five (5) seconds after the start of the experiment and to progressively increase to the end of the test (13 seconds) where the rate of erosion again appears to stabilize. This pattern is consistent with the throat temperature data recorded in the respect that excessive temperatures were becoming apparent in the 8 - 10 second time range.

The throat inside the diameter measurements taken before coating and after rocket firing agree within 18%, showing that the test was stopped at a time very close to the loss of all the coating in the throat region.

4. Conclusions

a. The data indicates the nozzle throat eroded prior to the onset of the severe positive temperature gradient.

b. A preliminary heat transfer analysis does not account for the temperatures observed at the nozzle throat.

c. If the coating was eroded from the nozzle throat:

(1) An increase in heat transfer coefficient would occur due to roughness effects; and

(2) Two exothermic reactions are possible, which would add heat to the system.

d. A combination of the "blow test" and the calculated rate of erosion suggests that the failure may have occurred in two stages:

(1) The coating was literally blown from the throat area.

(2) The 90-10 and aluminum reacted with the combustion products to further increase temperature and throat erosion.

e. A rocket engine operating under the test environment provided apparently creates a combined throat heat flux and scrubbing environment that is beyond the capability of the R-505C coating applied to a 90% tantalum - 10% tungsten thrust chamber. The nominal maximum observed operating temperature level for similar molybdenum chambers has been approximately 3000°F, and it was in this temperature regime that the tin-aluminide coating had to perform.

B. Chamber P/N MD1141

1. Experimental Results, Chamber Serial #2, (Tin-Aluminide Coated)

The chamber was tin-aluminide coated by the General Telephone and Electronics Laboratories with their R-505C coating. The experimental technique used was consistent with that previously employed in the testing of the P/N X-18920 chamber. A total engine running time (including calibration runs, not tabulated) of 7972 seconds was recorded for the configuration.

The coating on the exterior of the chamber was observed to apparently fail near the end of the first test run of 3815 seconds, based on a review of motion picture coverage of the experiment. The coating on the throat interior appeared to withstand the temperature-scrubbing environment through a total of approximately 2 hours at chamber throat temperatures that did not exceed 2460°F. A change in O/F ratio and a subsequent increase in throat temperature to 2750°F resulted in a failure of the coating in 137 additional seconds of testing. Three (3) photographs of the chamber, taken after failure, are presented in Figures (9), (10), and (11) for respective views of the chamber exteriors, inlet end, and exit bell.

The loss of coating on the exterior of the chamber is noted in Figure (9). The relatively uniform failure of the coating in this internal throat area is depicted in the respective end views of the chamber in Figures (10) and (11). The variation, or erosion, of the throat area is shown in Figure (12). The analysis used to prepare Figure (12) is identical to that described for chamber P/N X-18920. The failure pattern appears to be quite similar to that observed in the P/N X-18920 chamber when compared to the rate of throat erosion in the final seconds of chamber operation.

A summary of test run duration and nominal parameters is given in the following table in the general sequence in which the tests were run.

Maximum Chamber Temperature (At Throat)	O/F Ratio	Run Time Seconds
2380°F	2.04	3815
1900°F	2.4	90
1900°F	2.3	90
1900°F	2.2	90
2460°F	1.8	90
2350°F	2.0	90
2450°F	1.95	1200
2750°F	1.77	137 (failed @ end of test run)

The foregoing data represents approximately 17 engine starts, including miscellaneous calibration runs.

2. Laboratory Tests of Effects of Tin-Aluminide Coating Thickness

Several specimens of 90Ta-10W alloy were coated with two different thicknesses of tin-aluminide coating, applied by the General Telephone and Electronics Laboratories, Bay-Side, Long Island, New York.

Metallographic examinations and weight change measurements showed negligible differences caused by the variation in coating thickness. The results of this study are presented in Appendix A.

3. Experimental Results, Chamber Serial #1, (Disilicide Coated)

The chamber was disilicide coated by the Chromizing Company's MGF coating. The specified coating thickness was 0.0015" - 0.0025". The experiments were conducted with the T-10060 engine assembly (T-8240 injector head) and are summarized and tabulated below. A range of O/F ratio was covered to increase the throat temperature above that normally encountered (2300°F). A test run @ 2600°F was initiated after a cumulative running time of greater than 2 hours. Failure of the coating occurred during the 2600°F test run after approximately 57 minutes of steady-state rocket operation at this throat temperature. Photographs of the chamber, showing the coating failure mode are presented in Figures (13), (14), and (15).

Maximum Chamber Temperature (At Throat)	O/F Ratio	Run Time Seconds
2300°F	2.02	3815
2300°F	1.88	60
2300°F	2.07	60
2400°F	1.73	60
2360°F	2.0	3600
2550°F	1.83	300
2000°F	1.6 to 2.4	(Approx. 15 runs of 5 seconds each plus miscellaneous calibration runs)
2600°F	1.82	3400

The foregoing data represents approximately 31 engine starts, including the miscellaneous calibration runs.

a. Visual Examination

The impingement pattern of the flame was graphically shown by the symmetrical oxidation patterns. There were eight (8) areas of yellow tungsten oxide, oval in shape, spaced equidistant around the internal circumference of the chamber. The oxidation pattern extended as streaks from these areas to the throat where the oxidation changed from a light oxidation, i.e., a color pattern, to a deep cutting, or erosion, acting in the form of grooves. The "tail out" of the throat oxidation extended into the "bell" and appeared as a feathered viscous glass. The glass is probably composed of oxides of tantalum, tungsten and silicon.

b. Metallographic Examination

The metallographic examination revealed that the failure occurred through deterioration or breakdown of the coating and subsequent oxidation of the base metal. A section through one of the yellow oxidized areas, half way down the length of the chamber, showed a break developing in the coating and samples taken in the throat show later stages of oxidation. Temperature effects were negligible in the flange region.

The coating in the flange measured 0.0015" which is the minimum specified. Further down the chamber where temperatures were at a maximum, the coating thickness was measured at 0.001".

The hardness of the flange was uniform across the section and of values normal for recrystallized 90Ta-10W alloy. The hardness surveys of the chamber and throat areas respectively, show the effects of oxidation. There is an increasing hardening with depth as the throat is approached due to the interstitial gas pickup when coating is no longer present.

The metallographic examination revealed that coating failure occurred by erosion and pitting, allowing the oxidizing atmosphere to reach the base metal. Oxidation of the base metal then progressed rapidly inwards and longitudinally under intact portions of the coating.

The coating loss in this chamber throat differs in comparison to the tin-aluminide in that coating failure appears to be local, rather than across a complete cross section. Minor differences in coating thickness could result in a more rapid local failure which may be indicated by the streaks observed on the chamber. The streaks appear to be a result of final coating breakdown, with resultant feathered viscous glass flow into the exit bell.

Observation of the test chamber during rocket firing operation and reviews of the continuous movie coverage taken during tests shows an apparent uniform thrust chamber temperature distribution. Temperature gradients (that undoubtedly exist) are of an order of magnitude that does not readily permit recognition and it is concluded that after several hours of rocket firing, the slight deviations in coating thickness and propellant injection perhaps combine to create the observed failure pattern.

A P P E N D I X A

EVALUATION OF TIN-ALUMINIDE

COATING THICKNESS ON 90Ta-10W ALLOY

I. INTRODUCTION

An investigation was made of the effect of coating thickness on the metallographic properties of 90Ta-10W, which had been coated with tin-aluminum alloy. The objectives were to heat specimens of various coating thickness to different temperatures and determine metallographically if any significant changes had occurred as a consequence of the different thicknesses.

II. EXPERIMENTAL

A. Materials

Nine (9) rectangular bars of 90Ta-10W whose approximate dimensions were 0.25 x 0.38 x 1.1 inches, were coated with R-505C by General Telephone and Electronic Laboratories at Bay Side, New York. Six (6) of the specimens were coated to a nominal thickness of 0.003 inches using a two-cycle coating process. Three (3) of the specimens were coated with a one-cycle process yielding a thickness of 0.001 inches.

B. Procedure

The "as coated" samples were weighed and the dimensions measured with a micrometer. A solution of 4N-HCl was used at ambient temperature for 15 minutes to remove all unreacted tin-aluminum alloy from three (3) of the six (6) specimens with the thicker coating. The alloy substrate was not exposed by the treatment. A dark gray to black coating of $Ta\text{-}Al_3$ plus oxides was observed after the chemical stripping treatment. The three (3) stripped samples were reweighed and redimensioned after the stripping operation. The weights and measurements of all nine (9) specimens are given in Table I.

The nine (9) samples were then divided into three (3) groups, which contained one (1) specimen with the 0.003 inch coating, one (1) specimen with the 0.001 inch coating, and one (1) of the stripped specimens. One group of specimens was heated to 1200°F and heat soaked for thirty (30) minutes. The second group was heated to 2500°F and soaked for five (5) minutes. The last group was heated to 2500°F and soaked for thirty (30) minutes. All heating was done in air at ambient pressures. After the heat treatment, the specimens were reweighed. Those speimens exhibiting a large weight change were remeasured to determine dimensional changes. The data are presented in Table I.

The specimens were then sectioned perpendicularly to the long axis, mounted in plastic, polished, etched, and examined metallographically. Pictures were taken and are shown in Figures (1) through (9). The coating thickness was determined and is given in Table II.

III. DISCUSSION

The specimens with 0.003 inch coating did not change significantly in weight and dimension with any of the heat treatments. The specimens with 0.001 inch coating gained less than 5-milligrams (one part in 5000) and that small a change can not be considered greatly significant.

The three (3) stripped specimens, however, did exhibit significant (one part in 500) weight gains on being heated to 2500°F. Dimensional changes were small but significant (one part in 500).

Metallographic examinations revealed that the coating thickness of the thick coated specimens (nominally 0.003 inches) had a coating thickness varying from 0.0041 to 0.0071 inches. The thin coated (nominally 0.001 inches) specimens had coatings varying in thickness from 0.00095 to 0.0023. The "stripped" specimens showed a coating thickness varying from 0.0019 to 0.0026 inches. The coating thickness as measured by metallographic techniques includes the amount of 90Ta-10W in which the aluminum has diffused. And with the specimens above, the oxides on the surface, produced by the heat treatments are also included in the thickness measurement. Since no dimension measurements were made prior to sending the specimens for coating and no weights were obtained for the specimens prior to coating, the coating thickness as applied (and excluding diffusion into the substrate) cannot be determined.

The photomicrographs of the specimens at x200 magnification show no differences attributable to the heat treatment the specimens have received. All of the figures show the substrate at the bottom of the picture. The narrow line just below the coating may be a non-stoichiometric tantalum aluminide observed by GT&E personnel. The broader, smooth-appearing layer is most likely Ta-Al_3. The rough layer above the smooth layer (most noticeable in Specimens 6-1, 6-2, and 6-3) is the excess tin-aluminum alloy with tin and aluminum oxides at the very top. The dark background is the plastic mounting material. The very dark line below the coating layer of Specimen 6-1 is evidence of coating separation. It is the only example of Sn-Al coating separation observed in these nine (9) specimens.

IV. CONCLUSIONS

A heat treatment of 1200°F for thirty (30) minutes causes insignificant oxidation of the Sn-Al coating whether the coating is thick, thin, or stripped.

A heat treatment of 2500°F for five (5) minutes and for thirty (30) minutes causes no significant oxidation of the Sn-Al coating if the coating is thick, but significant (although slight) weight gains are observed for stripped and for thinly coated specimens. The slight weight gains are accompanied by slight dimensional increases also, but photomicrographs at x200 magnification do not show significant amounts of oxide.

TABLE I

Weights and Dimensions of Sn-Al Coated 90Ta-10W Specimens

Specimen #	Heat Treatment	Weights (Grams)	Least Dimension Lt.End	Least Dimension Mid.	Least Dimension Rt.End	Middle Dimension Lt.End	Middle Dimension Mid.	Middle Dimension Rt.End	Length
	THICKLY COATED SPECIMENS								
6-1	As received.	28.8462	0.2606	0.2646	0.2643	0.3856	0.3853	0.3853	1.1238
	1200°F 30 Min.	28.8462		No change in weight					
6-2	As received.	28.0440	0.2617	0.2609	0.2608	0.3858	0.3863	0.3858	1.0965
	2500°F 5 Min.	28.0447		Slight change in weight (+0.0007 gms)					
6-3	As received.	28.5555	0.2603	0.2613	0.2610	0.3890	0.3877	0.3885	1.1132
	2500°F 30 Min.	28.5548		Slight change in weight (-0.0007 gms)					
	STRIPPED THICKLY COATED SPECIMENS								
6-4	As received.	27.0070	0.2616	0.2617	0.2611	0.3875	0.3867	0.3865	1.0536
	After stripping.	26.6546	0.2554	0.2553	0.2546	0.3806	0.3803	0.3800	1.0480
	1200°F 30 Min.	26.6550	0.2544	0.2551	0.2553	0.3800	0.3805	0.3805	
6-5	As received.	27.1937	0.2615	0.2618	0.2614	0.3855	0.3858	0.3865	1.0615
	After stripping.	26.8562	0.2555	0.2554	0.2554	0.3797	0.3801	0.3804	1.0563
	2500°F 5 Min.	26.8639	0.2557	0.2560	0.2562	0.3803	0.3807	0.3812	
6-6	As received.	28.3217	0.2584	0.2585	0.2586	0.3847	0.3847	0.3845	1.1114
	After stripping.	28.0520	0.2528	0.2530	0.2530	0.3808	0.3804	0.3802	1.1056
	2500°F 30 Min.	28.0639	0.2537	0.2538	0.2540	0.3814	0.3812	0.3809	
	THINLY COATED SPECIMENS								
7-1	As received.	26.2408	0.2527	0.2527	0.2526	0.3805	0.3802	0.3800	1.0322
	1200°F 30 Min.	26.2408		No change in weight					
7-2	As received.	28.5393	0.2533	0.2536	0.2538	0.3795	0.3798	0.3796	1.1177
	2500°F 5 Min.	28.5415		Slight change in weight (+ 0.0022 gms)					
7-3	As received.	27.9187	0.2530	0.2534	0.2535	0.3796	0.3800	0.3803	1.0937
	2500°F 30 Min.	27.9231		Slight change in weight (+ 0.0044 gms)					

TABLE II

Coating Thickness Measured by Microscopic Techniques

Specimen #	Heat Treatment	Side 1	Side 2	Side 3	Side 4
	THICKLY COATED SPECIMENS				
6-1	1200°F 30 Min.	0.0049	0.0046	0.0046	0.0046
6-2	2500°F 5 Min.	0.0045	0.0041	0.0050	0.0060
6-3	2500°F 30 Min.	0.0053	0.0071	0.0052	0.0054
	STRIPPED THICKLY COATED SPECIMENS				
6-4	0.0021	0.0021	0.0020	0.0020	-
6-5	0.0024	0.0019	0.0026	0.0025	-
6-6	0.0021	0.0024	0.0022	0.0023	-
	THINLY COATED SPECIMENS				
7-1	0.0016	0.0015	0.00095	0.0013	-
7-2	0.0013	0.0017	0.0023	0.0011	-
7-3	0.0021	0.0017	0.0018	0.0018	-

100 POUND THRUST RADIATION COOLED REACTION CONTROL ROCKET ENGINE ASSEMBLY

NEG. NO. CA4567-6A

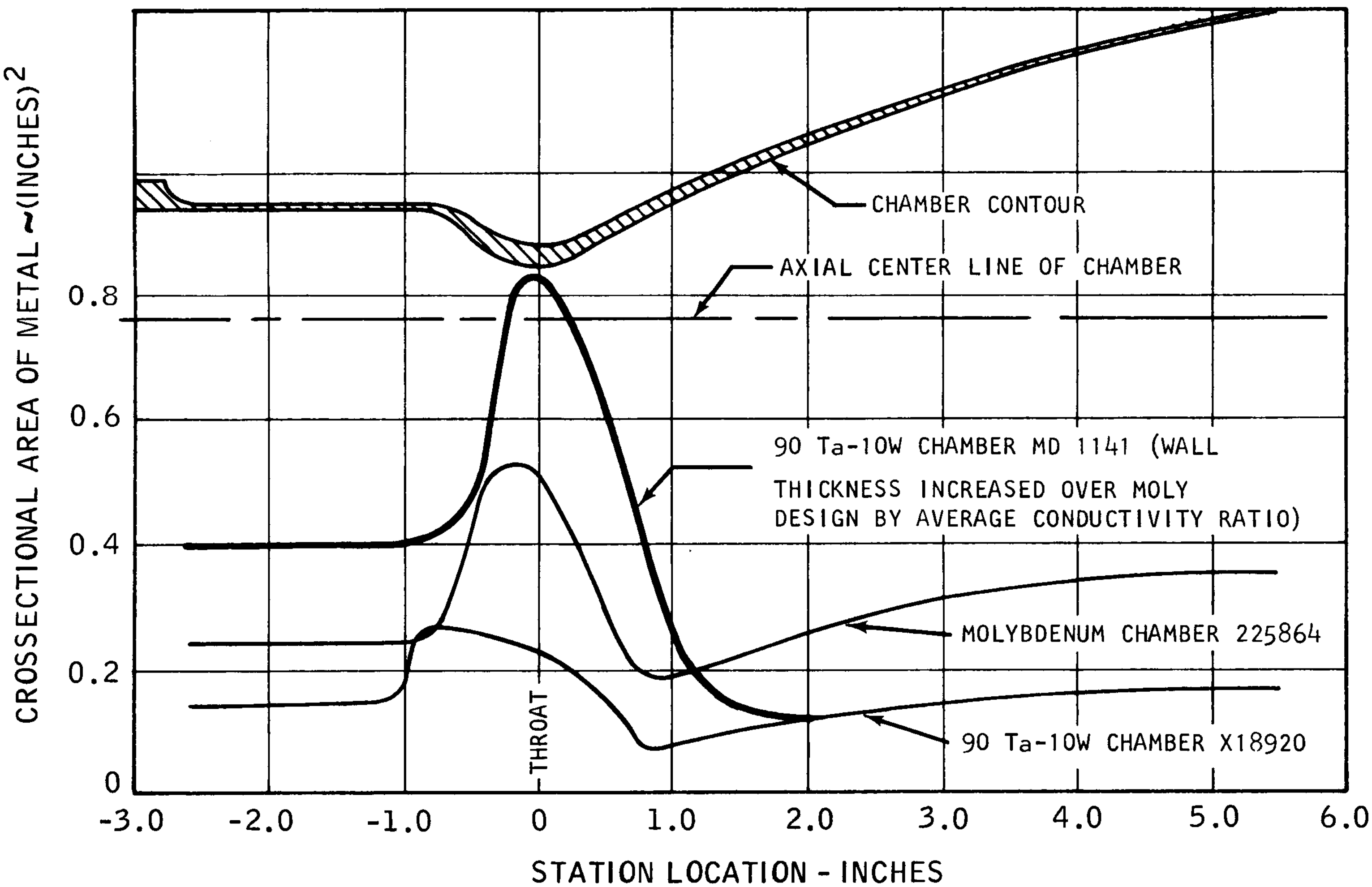
THE MARQUARDT CORPORATION

FIGURE 1

A1476-1
7-31-64

CROSS SECTIONAL AREA OF METAL SHOWN AS A FUNCTION OF CHAMBER LENGTH

THRUST CHAMBERS 225864 (MOLYBDENUM), X18920 (90Ta-10W), AND MD1141 (90Ta-10W)



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A1476-2
7-31-64

FIGURE 2

SCHEMATIC OF THRUST CHAMBERS

CHAMBER X18920, CHAMBER MD1141, AND MOLYLDENUM CHAMBER 225864

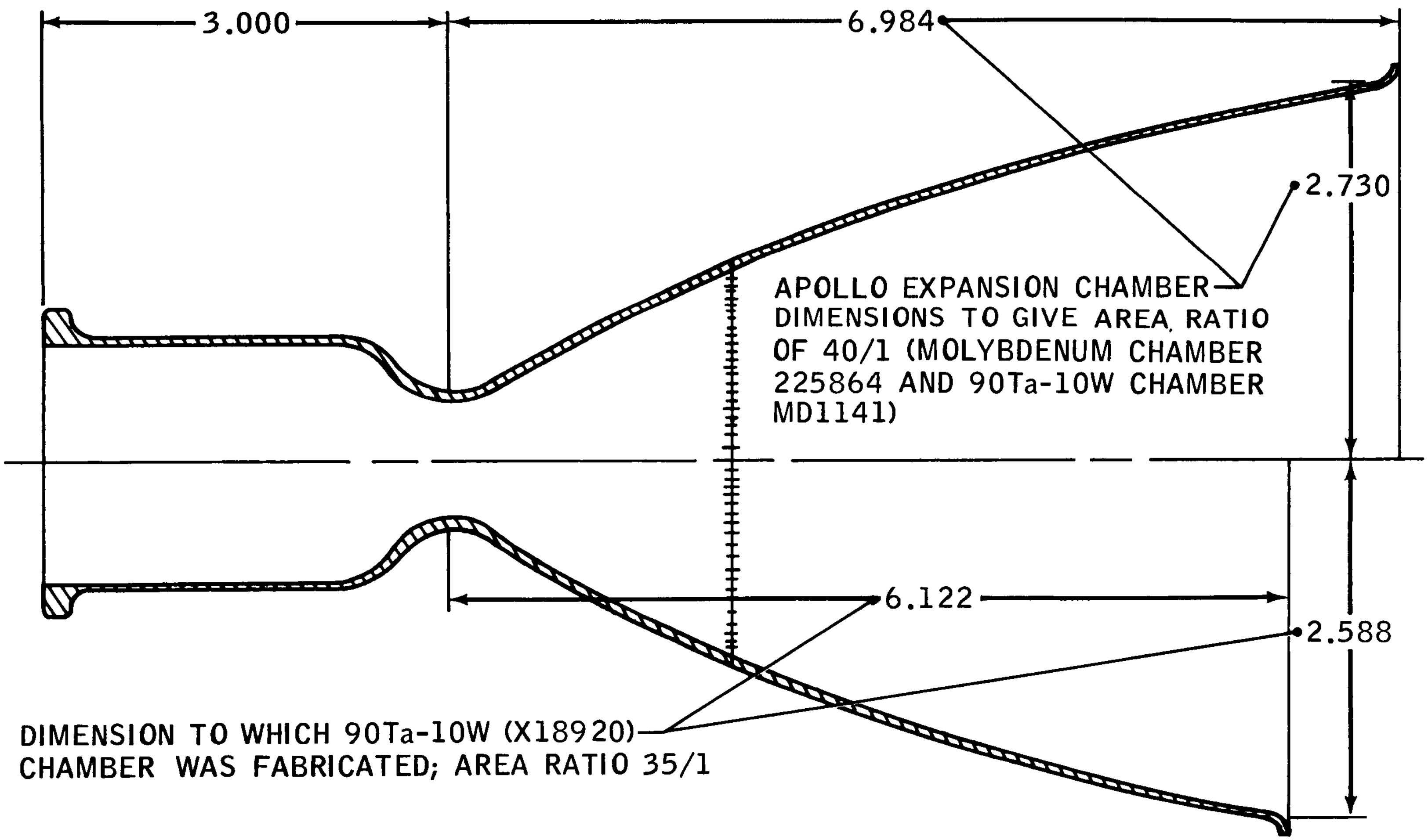

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FIGURE 3

THRUST CHAMBER X18920
90Ta-10W TIN ALUMINIDE COATED

BEFORE ROCKET FIRING

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FIGURE 4

THEORETICAL WALL TEMPERATURE ON LONGITUDINAL AXIS

100 LB. THRUST CHAMBER

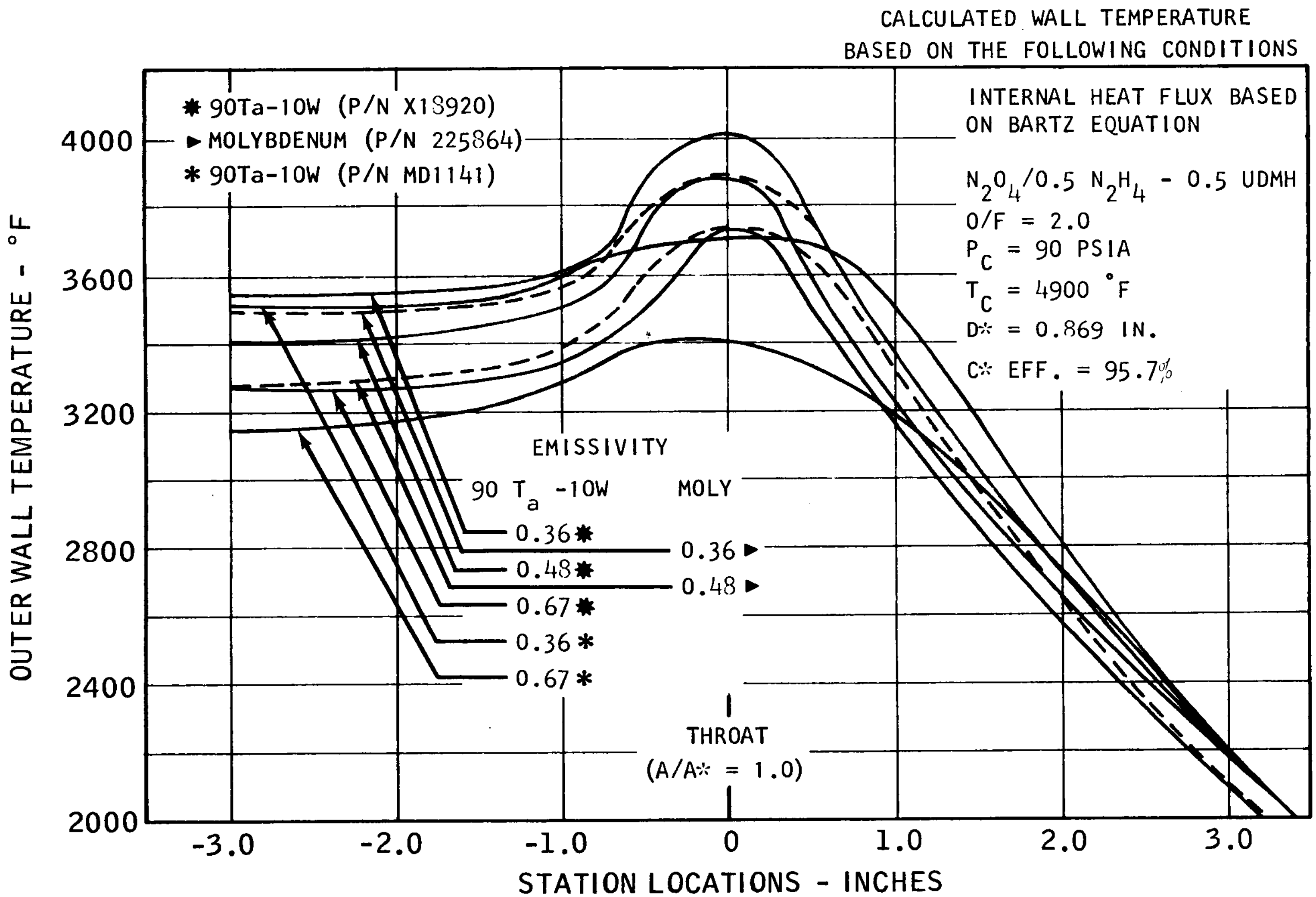

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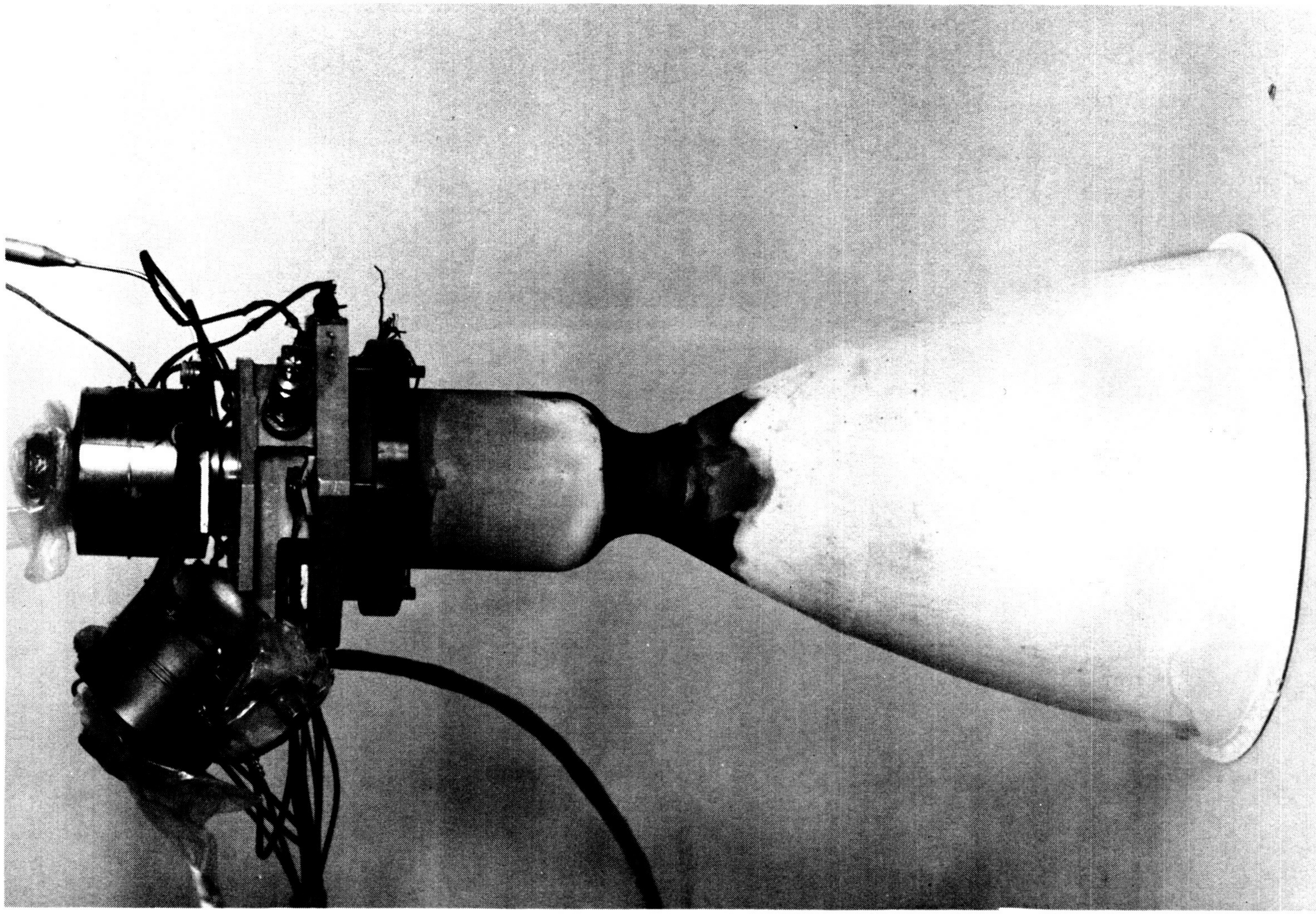
FIGURE 5

THRUST CHAMBER X18920
90Ta-10W TIN ALUMINIDE COATED

ENGINE ASSEMBLY X20560-503 SHOWN AFTER 13 SECONDS OPERATION



NEG. NO. T3106-78CN

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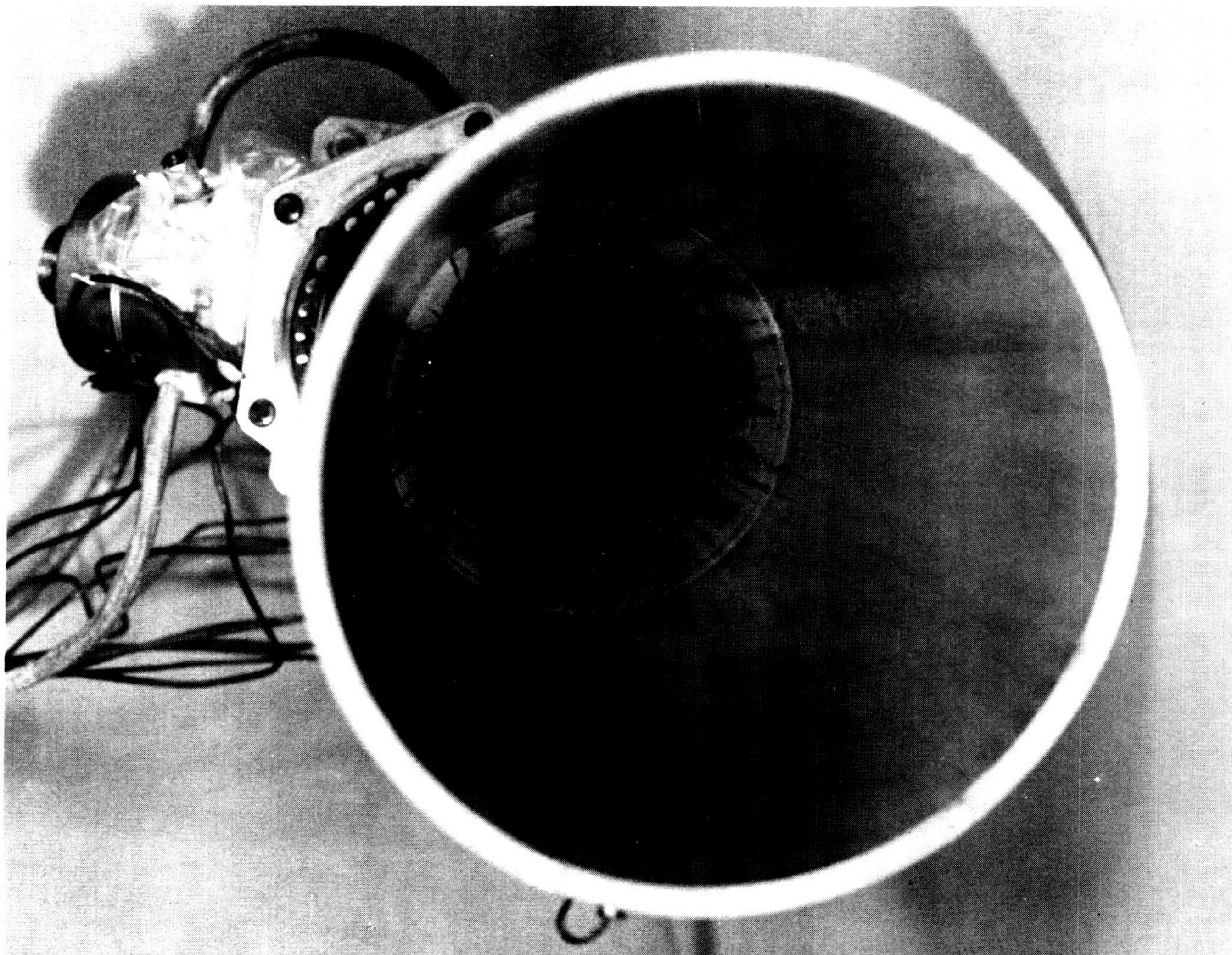
FIGURE 6

THRUST CHAMBER X18920
90Ta10W TIN ALUMINIDE COATED

ENGINE ASSEMBLY X20560-503 SHOWN AFTER 13 SECONDS OPERATION



NEG. NO. T3106-76CN

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FIGURE 7

THROAT AREA VARIATION WITH TIME

THRUST CHAMBER X18920 - 90Ta-10W ALUMINIDE COATED

ENGINE ASSEMBLY X20560-503

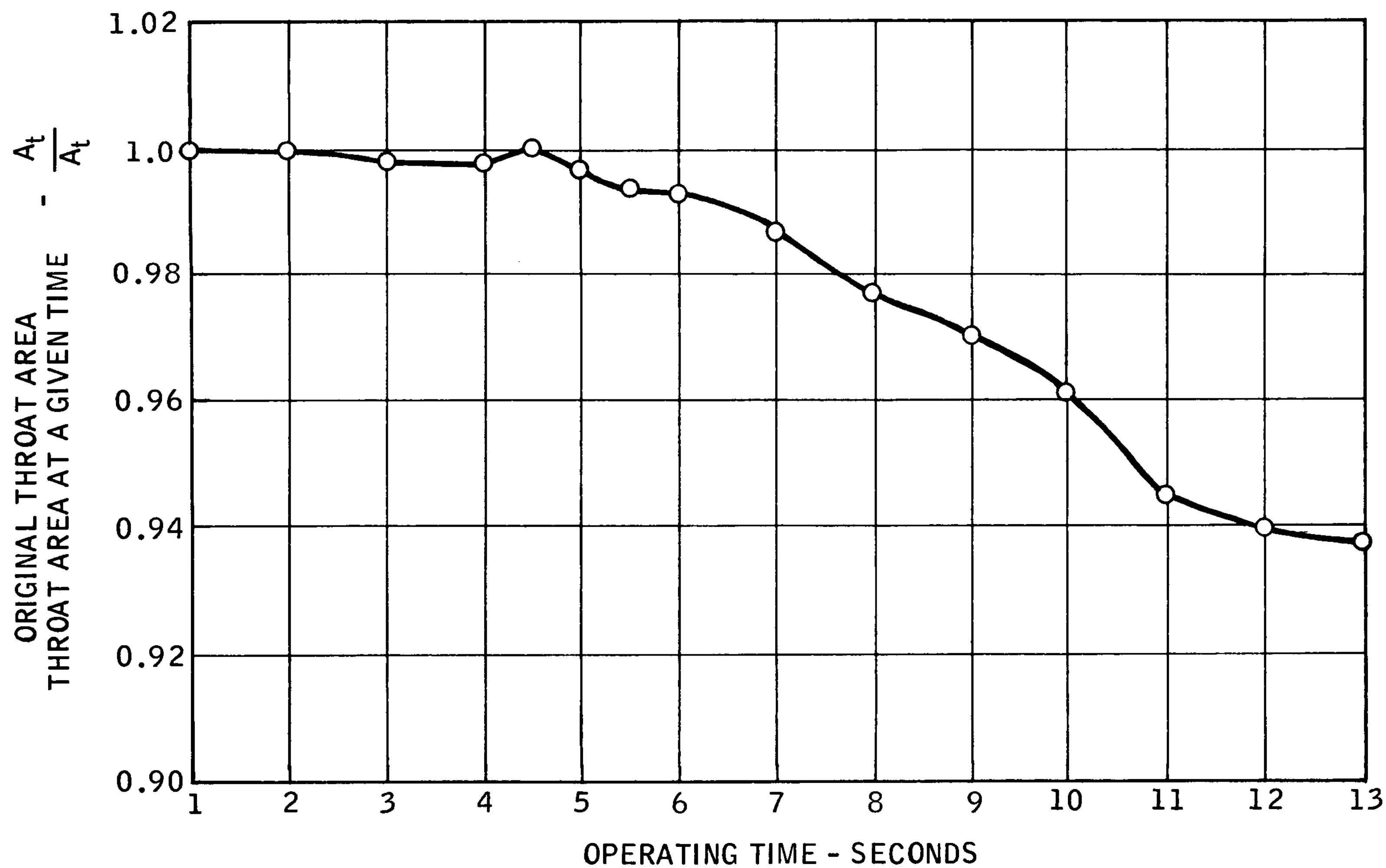

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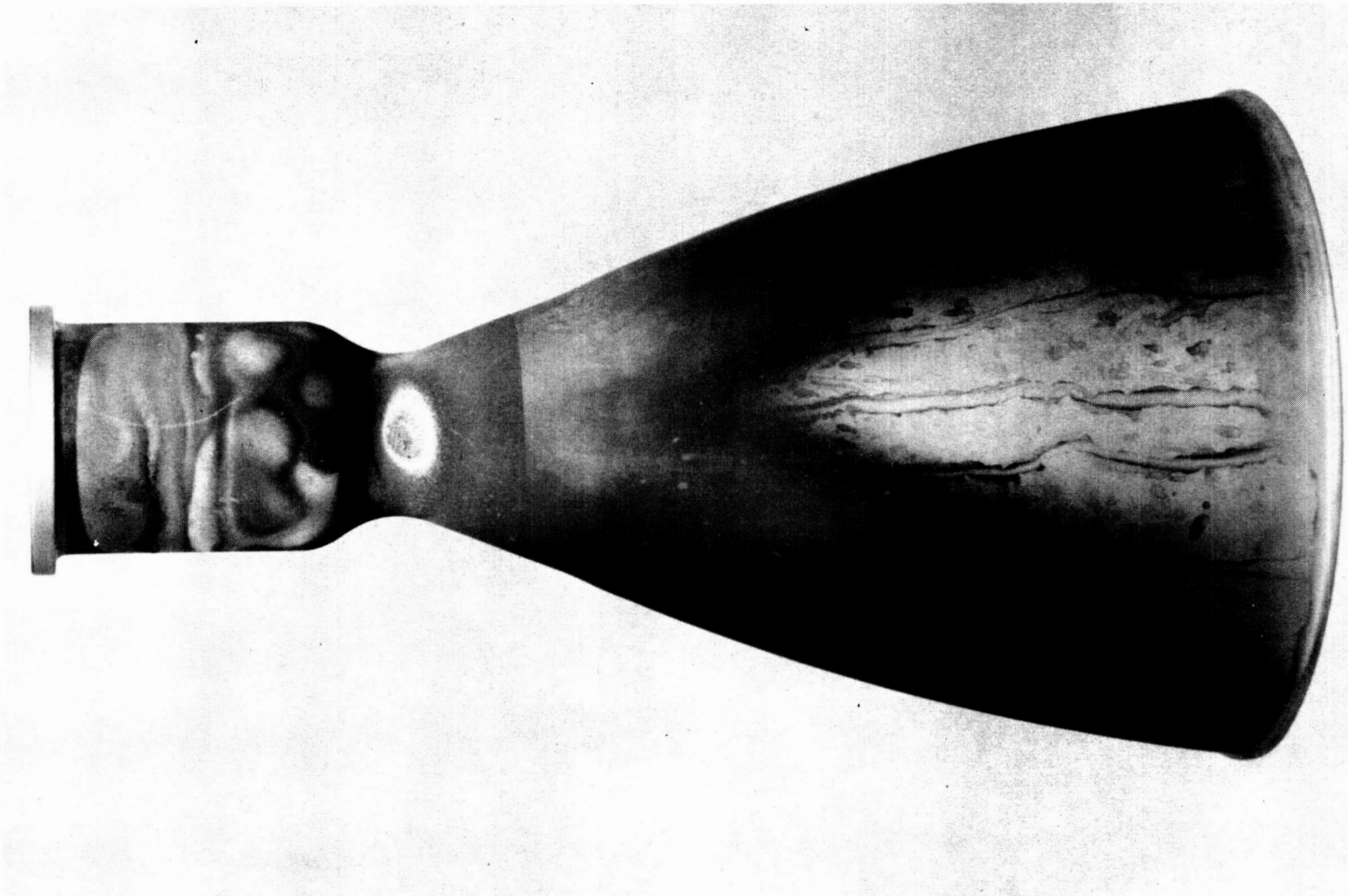
FIGURE 8

THRUST CHAMBER MD1141 S/N-1
90Ta-10W DISILICIDE COATED

ENGINE ASSEMBLY T10060 SHOWN AFTER 11553 SECONDS OPERATION



NEG. NO. 6162-1CN

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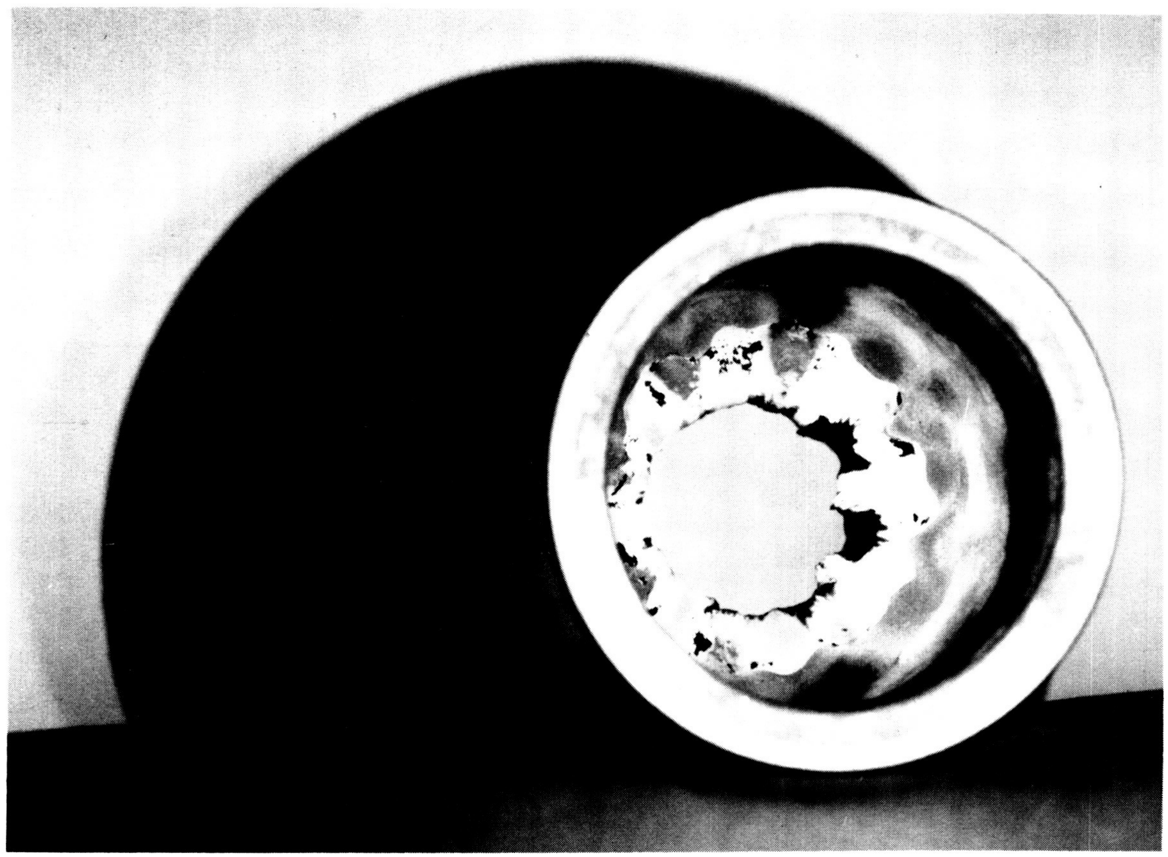
FIGURE 13

THRUST CHAMBER MD1141 S/N-2
90Ta-10W TIN ALUMINIDE COATED

ENGINE ASSEMBLY T10060 SHOWN AFTER 7972 SECONDS OPERATION



NEG. NO. NASA S-64-25143

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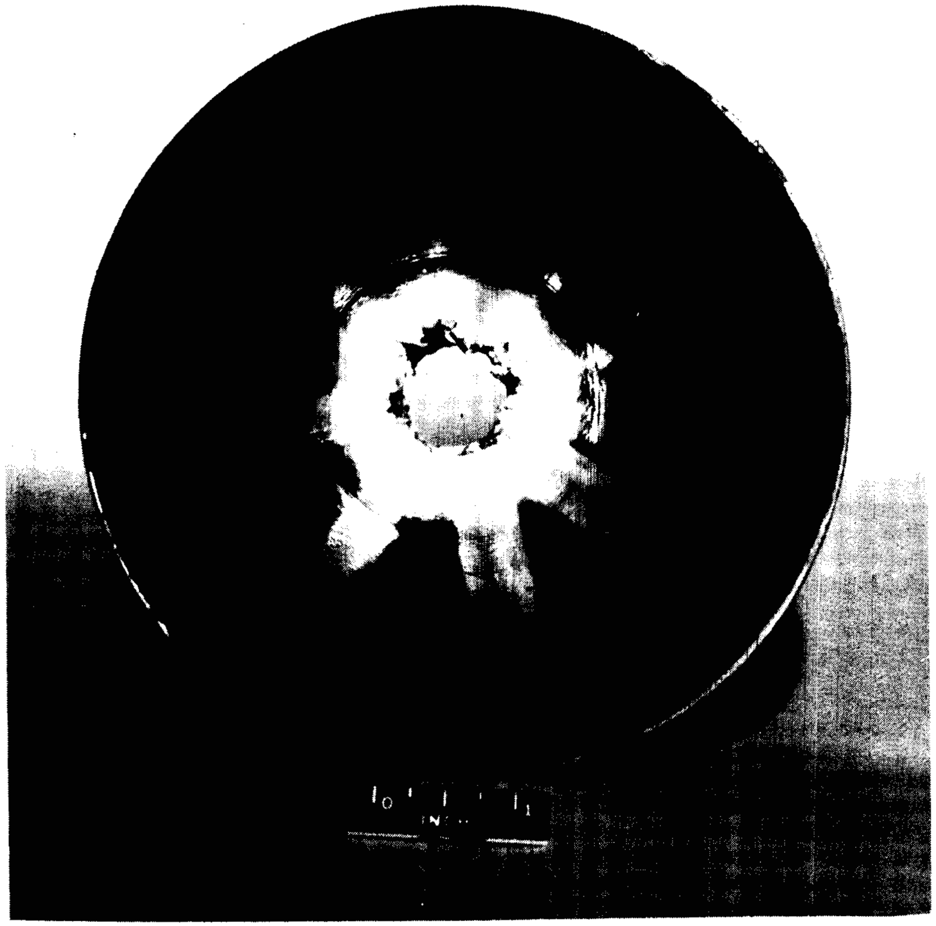
FIGURE 10

THRUST CHAMBER MD1141 S/N-2
90Ta-10W TIN ALUMINIDE COATED

ENGINE ASSEMBLY T10060 SHOWN AFTER 7972 SECONDS OPERATION



NEG. NO. NASA S-64-25142

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FIGURE 11

THROAT AREA VARIATION WITH TIME

ENGINE ASSEMBLY T10060

THRUST CHAMBER MD 1141 - S/N 2-90Ta-10W TIN ALUMINIDE COATED

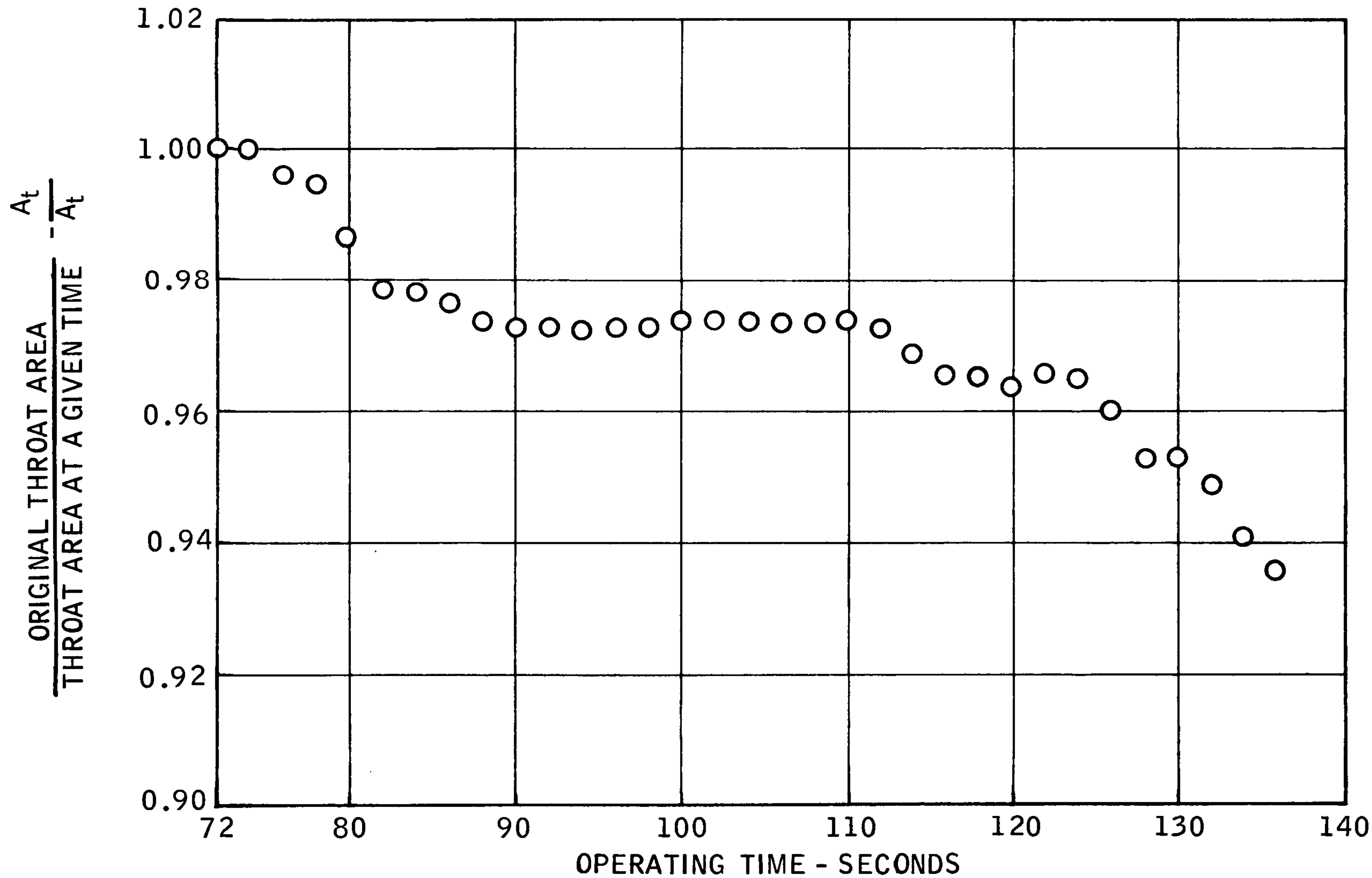

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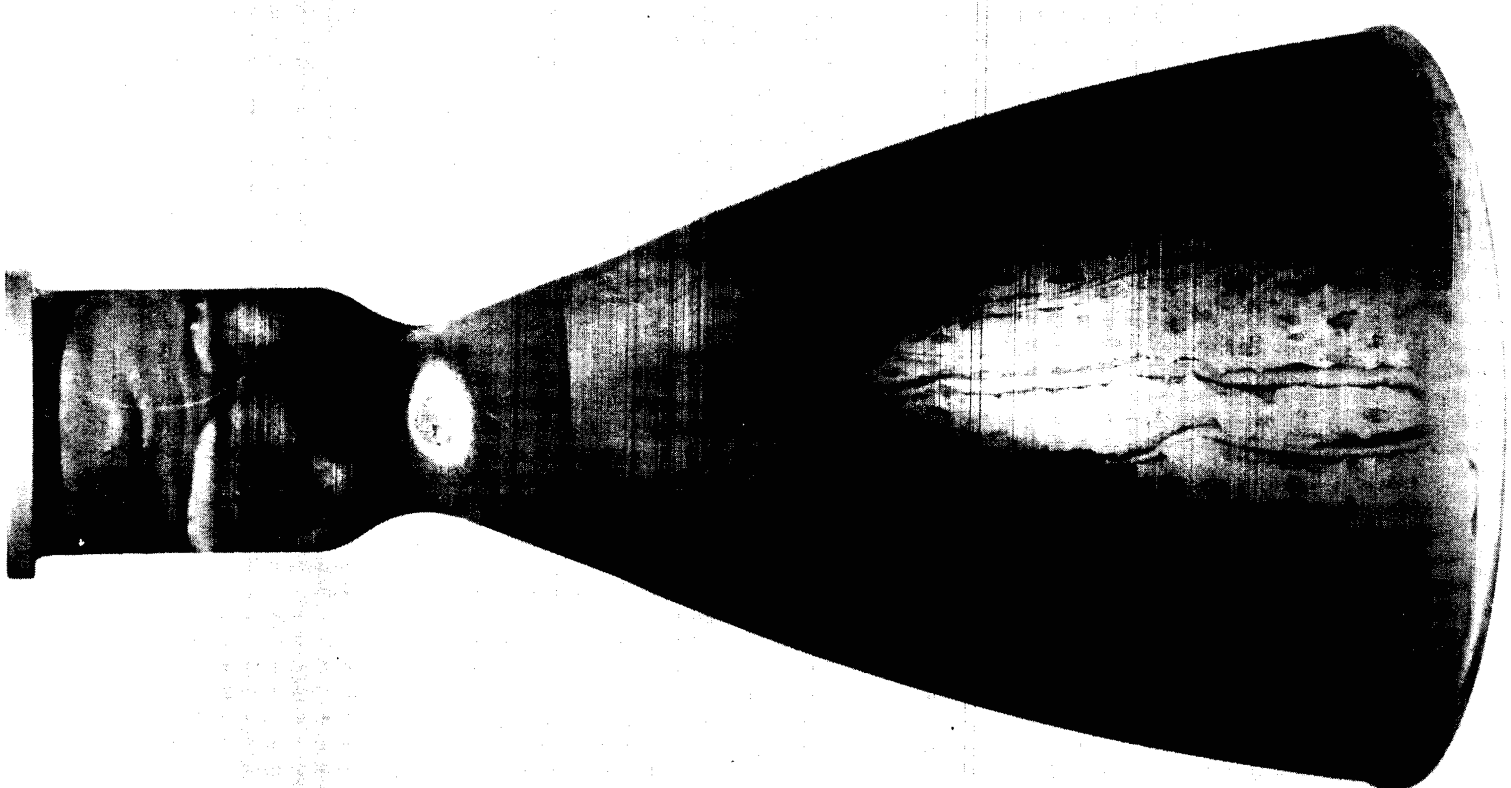
FIGURE 12

THRUST CHAMBER MD1141 S/N-1
90Ta-10W DISILICIDE COATED

ENGINE ASSEMBLY T10060 SHOWN AFTER 11553 SECONDS OPERATION



NEG. NO. 6162-1CN

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FIGURE 13

THRUST CHAMBER MD1141 S/N-1
90Ta-10W DISILICIDE COATED

ENGINE ASSEMBLY T10060 SHOWN, AFTER 11553 SECONDS OPERATION

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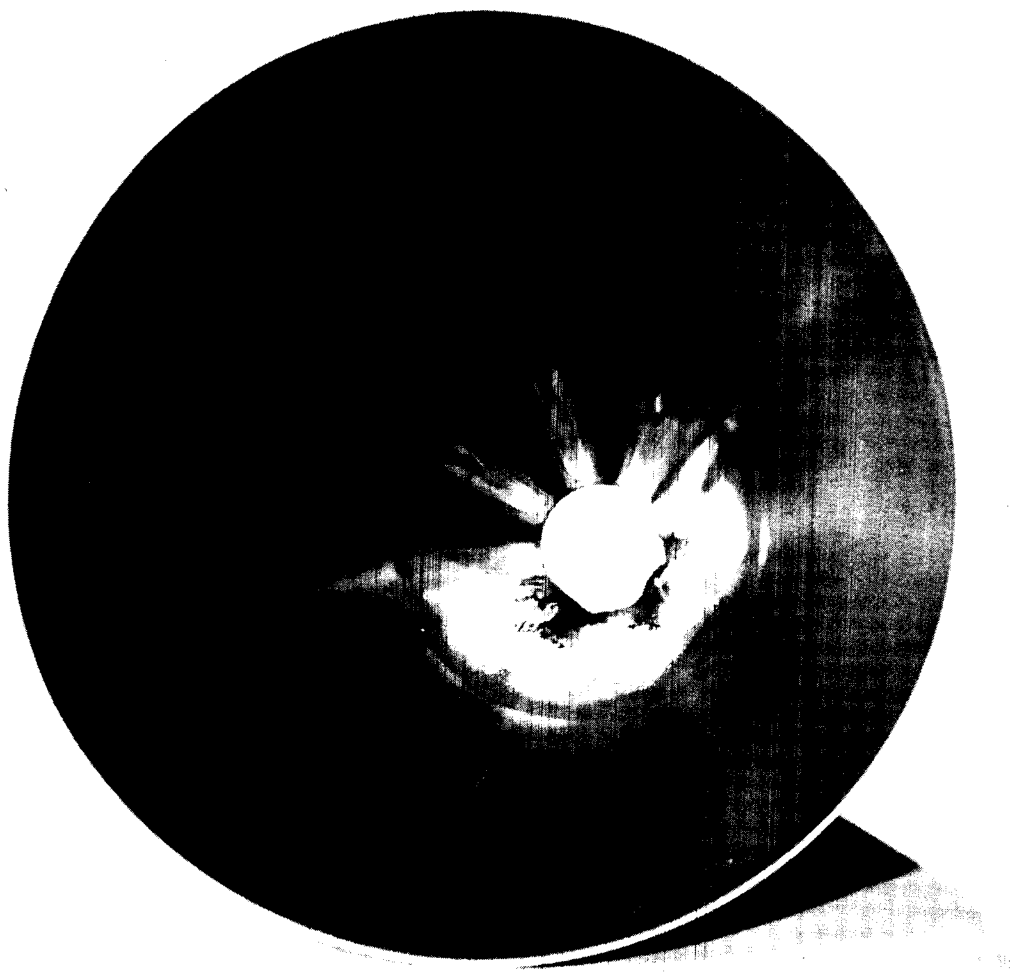
FIGURE 14

THRUST CHAMBER MD 1141 S/N-1
90Ta -10W DISILICIDE COATED

ENGINE ASSEMBLY T10060 SHOWN AFTER 11553 SECONDS OPERATION



NEG. NO. 6162-4CN

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FIGURE 15

Errata, TMC Report S-430

8 September 1964

Issued to correct typographical and editing errors.

Page 4, Paragraph B, Item 6

Revise item 6 to read as follows:

6. Oxidizer stream angle with engine axis: ~~33°~~ 23°

Page 9, Paragraph 3, Throat Erosion Analysis

Revise last sentence in Paragraph 3 to read as follows:

The throat inside ~~the~~ diameter measurements taken before coating and after rocket firing agree within ~~18%~~ 3.8% showing that the test was stopped at a time very close to the loss of all the coating in the throat region.

Page A-2, Paragraph II - Experimental; Sub-Paragraph B - Procedure

Revise last paragraph of B-Procedure to read as follows:

The specimens were then sectioned perpendicularly to the long axis, mounted in plastic, polished, etched, and examined metallographically. ~~Pictures were taken and are shown in Figures (1) through (9).~~ The coating thickness was determined and is given in Table II.