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TEST AND EVALUATION OF A PASSIVELY COOLED THRUST CHAMBER FOR FLUORINATED PROPELLANTS

J.G. Campbell
THE MARQUARDT COMPANY
A Division of CCI Corporation
Van Nuys, California

TECHNICAL REPORT AFRPL-TR-69-232

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FOREWORD

(U) This report covers work performed by The Marquardt Company, Van Nuys, California under Contract F04611-68-C-0037 during the period 26 December 1967 to 1 September 1969. The work was sponsored by the Air Force Rocket Propulsion Laboratory, Directorate of Laboratories, Edwards, California, Air Force Systems Command, United States Air Force, as Air Force Systems Command Project No. 3058, Air Force Element Code 6.24.05.18F. This report was submitted during October 1969.

(U) The AFRPL Project Engineer was Lt. Don L. Riedl, RPRRE. The Marquardt Program Manager, Mr. J.G. Campbell, was responsible for overall program and technical supervision.

(U) This report contains no classified information extracted from other classified documents.

(U) The report number assigned to this document by The Marquardt Company is 6149.

(U) This technical report has been reviewed and is approved.

Don L. Riedl, 1 Lt., USAF

Project Engineer

CONFIDENTIAL ABSTRACT

(C) A 3,000-pound thrust composite graphitic thrust chamber was made by coating a Carbitex shell with pyrolytic graphite. Stress analysis was made to assist in the design of the optimum combination of pyrolytic graphite and Carbitex. The thrust chamber was test fired with ClF_3/BA1014 at a chamber pressure of 300 psia. The total firing duration was 300 seconds, including one single firing of 150 seconds and multiple hot starts. The overall performance of the thrust chamber was excellent. The measured throat erosion was 0.05 mil/sec. This composite graphitic structure appears capable of providing thrust chambers for even more severe chamber pressures and firing durations with negligible erosion.

CONTENTS

ILLUSTRATIONS

TABLES

SECTION I

INTRODUCTION

(C) Rocket thrust chambers for advanced propulsion systems using fluorinated propellants encounter a severe chemical and thermal environment. Numerous test firings in past years have shown that pyrolytic graphite (PG) is the material best suited to achieve long life with fluorinated propellants. However, utilization of pyrolytic graphite has been hampered by problems of residual stress and marginal ductility and strength. This report describes the design and test firing of a Pyrobond thrust chamber made of a new composite graphitic structure which combines the corrosion resistance and impervious surface of pyrolytic graphite with the added strength and ductility of Carbitex 713.

(C) A thrust chamber delivering 3000 pounds of thrust at a chamber pressure of 300 psia was delivered by Marquardt to the Air Force Rocket Propulsion Laboratory (AFRPL). Test firings were performed at the AFRPL with the propellant combination ClF_3/BA1014, using an Air Force injector. The test firings were very successful, leading to the conclusion that the Pyrobond structure is a significant advancement in the field of composite graphitic structures.

SECTION II

CHAMBER DESIGN

(U) The chamber configuration is shown in Figure 1, together with the insulation package surrounding the chamber and a water cooled adapter for attachment of the thrust chamber to the injector. The thrust chamber consisted of a Carbitex 713 shell coated on the inside surface with pyrolytic graphite.

(U) The chamber was designed for the following conditions:

Propellants:	ClF_5/N_2H_4, ClF_5/MMH, or ClF_5/BA1014
Chamber pressure:	300 psia
Mixture ratio:	2.8
Thrust:	3000 lbs at sea level (Exhaust to 13.2 psia)
Duty cycle:	400 seconds total firing duration, comprised of one long steady firing of at least 200 seconds duration, multiple hot restarts with off-times as short as 3 seconds between pulses, and at least one ambient restart of not less than 60 seconds
Insulation:	The temperature of the outside of the thrust chamber assembly must not exceed 400°F at any location at any time during the duty cycle.

A. Stress Analysis

(U) Stresses in the PG/Carbitex combustion chamber were calculated for a transient heating time of 60 seconds. Steady state temperatures and stresses were reached for most cases considered. The analysis was done with Marquardt's computer program for anisotropic stress analysis.

(U) The design variables were the thickness of the PG coating and the Carbitex. The assumed elastic properties of the PG and Carbitex are given in Table I. The Carbitex data were estimates for Carbitex 713 based on a very limited amount of data. Recent test data obtained at Marquardt indicate that the circumferential modulus of elasticity of Carbitex 713 in the a-b plane ranges from 2 x 10^6 to [illegible] x 10^6 psi, for wrap angles of 60° and 84°, respectively.

(U) The axial modulus of elasticity of Carbitex 713 varies from about 0.9 x 10^6 psi to 0.2 x 10^6 psi, for wrap angles of 60° and 84°, respectively. The wrap angle is the angle between the center line and the graphite filament in the Carbitex. The c-direction is normal to the chamber wall, whereas the a-b plane is parallel to the wall.

(U) The stresses were calculated for temperature gradients caused by a combustion temperature of 5410°F. The as-deposited residual stresses in the PG were assumed to be zero.

(U) The maximum stresses for four different combinations of PG and Carbitex wall thickness are given in Table II. It can be seen that the maximum stresses in the PG occur during heat up in the chamber at the interface between the PG and the Carbitex. This stress varied from 13,500 psi for Case 1 to 11,400 for Case 4. These stresses are all within the strength capabilities of PG, and would probably be reduced by residual stresses.

(U) The circumferential stresses in the Carbitex are far below the estimated circumferential strength of 10,000 psi. The axial strength of filament wound Carbitex has been measured at Marquardt since the design of the 3K chamber was completed. These axial strengths range from 500 psi to 2000 psi, for wrap angles varying from 84° to 72°.

(U) The wall thicknesses of Case 4 (0.120 in. PG on 0.480 in. Carbitex) were chosen for the chamber design. Some further reduction in axial stress in the Carbitex could have been shown analytically for thicker Carbitex, but the fabricability of such thicknesses of Carbitex 713 and the estimates of the elastic properties of this material were questionable.

B. Auxiliary Hardware

(U) Marquardt designed and fabricated auxiliary hardware for attachment of the thrust chamber to the thrust stand and insulation of the outer wall.

1. Insulation

(U) Graphite felt with a density of 5 lb/ft^3 was used as thermal insulation in the high temperature region adjoining the thrust chamber. The felt was cut in the form of rings from material having an average thickness of 0.85 inch. The rings were stacked around the chamber as shown in Figure 1. A 0.50-inch thick layer of "Dynaflex" insulation was placed between the outside of the felt and the stainless steel insulation case (T17244).

(U) Thermal analysis of the insulation package indicated that the outside wall temperature would be less than 400°F for any anticipated duty cycle.

(U) Six thermocouples were welded to the insulation case at locations as shown in Figure 1. Two W/5% - W/26% Re thermocouples were installed flush with the outside surface of the Carbitex. One was located at the throat and the other was located 4.75 inch upstream from the throat.

2. Water Cooled Adapter

(U) A water cooled adapter (T17242) was fabricated to attach the chamber to the Air Force injector. The portion of the adapter exposed to the combustion gas was made of Nickel 200. The wall thickness in the water cooled region was 0.100 inch. The seal between the adapter and the thrust chamber consisted of a Viton O-ring.

3. Retainer Ring

(U) The thrust chamber was held against the water cooled adapter by a retainer ring (T17243) attached by twelve 3/8-inch bolts. The attach bolts were spring loaded by stacks of Belleville springs (18 per bolt). The size of the retainer ring and the water cooled adapter were determined primarily by the location of existing bolt hole patterns in the Air Force injector. No attempt was made to minimize the weight of any of the attach hardware.

(U) A conical ring insert (T17248) made of stainless steel was placed between the retainer ring and the thrust chamber. The ring insert was required as a spacer to compensate for the fact that the final chamber wall thickness was 0.50 inch instead of the design value of 0.60.

4. Injector

(C) The injector used in the testing of this chamber was a concentric ring, like-doublet injector. These were 338 doublet elements consisting of 169 fuel elements and 169 oxidizer elements. The outer fuel ring was on a 0.1 inch larger radius than the outer oxidizer ring, and thus provided a mild degree of zone cooling to the chamber walls. The injector face was made of nickel and the flange was made of 347 stainless steel. The injector gave stable combustion and good performance (92 to 93% I_{sp}).

SECTION III

CHAMBER FABRICATION -- MATERIALS AND PROCESSES RESEARCH AND DEVELOPMENT REPORT

A. Carbitex

(U) The Carbitex 713 shell for the thrust chamber was fabricated by the Carborundum Company, Niagara Falls, New York. Carbitex 713 is a filament wound structure made of graphite yarn and finished by a proprietary Carborundum process into a graphitic composite structure.

(U) During the past several years, Marquardt has developed the Pyrobond structural concept of combining the properties of pyrolytic graphite with those of other forms of graphite. The process of depositing pyrolytic graphite on Carbitex 713 has been found to be particularly successful because of the compatibility of the thermal expansion coefficients of the two materials and because of the excellent bond between the Carbitex and the pyrolytic graphite.

(U) Previous fabrication of PG/Carbitex composites had been done with 100-pound thrust chambers and 2-inch diameter tubes. The fabrication of the 3K thrust chamber therefore involved considerable uncertainty in the fabrication techniques to be used in making the Carbitex.

(U) The original order placed with the Carborundum Company called for fabrication of three Carbitex 713 shells. The wall thickness was specified to be 0.480 inch. The wrap angle at the throat was specified to be 60° in order to increase the axial strength of the Carbitex.

(U) Two Carbitex shells were fabricated by the Carborundum Company within 16 weeks after the order. The order for the third shell was cancelled because it could not have been delivered in time for inclusion in the AFRPL test firing program.

(U) Final machining of the Carbitex revealed a rough surface in many places which was caused by loose and broken fibers. The Carbitex shells were then ground in an attempt to improve the quality of the surface. However, the final condition of the Carbitex was not good, and was not as free from flaws as were the Carbitex thrust chambers which were fabricated several years earlier. The finished thickness of the better of the two Carbitex shells was 0.360 inch and the throat diameter was 3.487 inches.

B. Pyrolytic Graphite Coating

(U) The pyrolytic graphite coating and final machining of the thrust chamber was done by the Super Temp Corp., Santa Fe Springs, California.

(U) A preliminary furnace deposition run was made with the second Carbitex shell to provide information on deposition time and furnace setup. A 0.020-inch pyrolytic graphite coating was applied to the inside and outside of the chamber. These coatings were free of cracks or other flaws.

The coatings were adherent, even in the regions of greatest surface flaws in the Carbitex.

(U) The better of the two Carbitex shells was then coated with pyrolytic graphite with a target thickness of 0.120 inch. PG was also deposited on the outside of the chamber in an attempt to compensate for the undersized Carbitex wall and to produce a total wall thickness close to the original design value of 0.600 inch.

(U) After removal of the chamber from the furnace, the coating thickness was found to be only about 0.070. The cause of the inaccuracy of extrapolating deposition time from the trial run is not known with certainty. Super Temp attributed the problem to the fact that the Carbitex shell was fit tightly into a 3-foot diameter furnace with only a few inches of extra length for the furnace supports and gas inlet. The 3-foot furnace was used because it allowed a large cost saving.

(U) The inside pyrolytic coating was of excellent quality with no cracks or delaminations.

(U) The inside of the combustion chamber is shown in Figure 2. The indentations visible on the right hand side are indications of a badly flawed area of the Carbitex. In spite of the flaws, the inside coating was everywhere adherent and free of cracks.

(U) The outside coating of PG was badly spalled and delaminated from the Carbitex, as shown in Figure 3. This conforms to previous experience in depositing pyrolytic graphite on male mandrels, which produces more cracking and delaminations than depositions on female mandrels.

(U) The exit of the chamber is shown in Figure 4. Again, the inside surface was of very good quality.

SECTION IV

TEST FIRING RESULTS

(U) The thrust chamber was test fired at the Air Force Rocket Propulsion Laboratory at Edwards, California. The assembly of the thrust chamber on the thrust stand is shown in Figure 5. The propellants were ClF_3/BA1014. The nominal chamber pressure was 300 psia. The nominal mixture ratio was 2.8. The firing test data are summarized in Table III.

A. Test Runs

1. Run 558

(C) The first test (Run 558) was a continuous firing of 150 seconds. After the test run, the chamber was removed for inspection and it was found to be in excellent condition except for localized injector streaks in the combustion chamber near the water cooled adapter. The rest of the chamber and throat showed little evidence of the firing.

2. Run 559

(C) The chamber was rotated for the second run (Run 559) to avoid repeating the erosion streaks on the same chamber locations. Run 559 consisted of a duty cycle as follows:

50 sec ON	
	5 sec OFF
5 sec ON	
	5 sec OFF
5 sec ON	
	5 sec OFF
5 sec ON	
	5 sec OFF
5 sec ON	
	5 sec OFF
10 sec ON	
	5 sec OFF
20 sec ON	

Total ON Time = 100 seconds

(U) At the completion of Run 559, the chamber was inspected while on the thrust stand and it was left there for the subsequent run, which was made on the following day.

3. Run 560

(C) Run 560 was to be a long firing of 150 seconds to further document the chamber life. The test was terminated after 40 seconds due to a local burn out of the chamber wall in the most severe localized erosion spot. The remainder of the chamber was found to be still in excellent condition.

B. Inspection after the Test Runs

(C) The thrust chamber was returned to Marquardt for inspection after the test firings. The inside of the combustion chamber is shown in Figure 6. The localized erosion spots just beyond the position of the water cooled adapter are particularly deep in two locations. The one erosion spot near the "A" index is the point of burn out.

(U) The outside of the chamber is shown in Figure 7. The burn out occurred just forward of the "A" index marker. Further spalling of the outer layer of PG was found, confirming the belief that the outside coating was not satisfactory.

(C) Careful measurement of the throat diameter showed some nonuniformity. The best estimate of nominal diameter after the test was 3.375 inches, compared to a pretest value of 3.345 inches.

(C) The total firing time, including a 5 second check out before each of the three runs, was about 300 seconds. Therefore, the throat erosion rate was about 0.05 mil/sec which is an extremely low erosion for this propellant combination, chamber pressure, and duration.

(C) Other characteristics of the Pyrobond thrust chamber observed in the post test evaluation were the absence of any cracks in the PG, and the tight adherence of the PG to the Carbitex on the inside surface.

(U) The injector used in the test firings had accumulated a total of over 1000 seconds of firing by the time Run 560 was commenced. Examination of the injector face had shown a gradual deterioration of the injector face over the 1000 seconds of firing. Bell mouthing of some of the orifices had begun to deflect some propellant jets.

(C) It is believed that further refinement of the injector design, together with the use of an injector with less wear, would eliminate the localized injector streaking. The ultimate life duration of an optimized injector with the Pyrobond chamber probably exceeds any anticipated requirements with this propellant combination.

C. Test Temperatures

(U) The temperature of the outer wall did not rise above ambient temperature during the longest test firing of 150 seconds. Twenty minutes after the run, the temperature at Thermocouple Location 3 (Figure 1), in line with the throat, had risen to 200°F.

(U) The temperature of the retainer ring at Thermocouple Location 7 (Figure 1) rose to 180°F during the 150 second firing. Four minutes after shutdown, it peaked at 220°F.

(U) The temperature of the Carbitex at the throat was not measured because of failure of the tungsten-rhenium thermocouple early in the firing. The temperature of the upstream tungsten-rhenium thermocouple rose to 3500°F during the 150 second firing.

SECTION V

CONCLUSIONS

(C) 1. A composite graphitic structure consisting of Carbitex 713 with a coating of pyrolytic graphite has demonstrated superior performance as a passively cooled thrust chamber for the propellant combination ClF_3/BA1014.

(C) 2. Steady state erosion rate of the throat of the 3000-pound thrust chamber at a chamber pressure of 300 psia was 0.05 mil/sec.

(C) 3. The PG/Carbitex thrust chamber concept has excellent prospects of providing superior performance at chamber pressures higher than 300 psia and durations longer than 300 seconds, provided that improvements in their fabrication can be made by the Carborundum Company to supply good quality Carbitex.

TABLE I

(U) SUMMARY OF ELASTIC PROPERTIES USED IN THE STRESS ANALYSIS

Material	Temperature (°F)	Modulus of Elasticity (psi)		Poisson's Ratio		Coefficient of Thermal Expansion (in./in.°F)	
		a-b Plane	c Plane	a-b Plane	c Plane	a-b Plane	c Plane
Pyrolytic Graphite	0	4.42×10^6	1.5×10^6	-0.17	0.95	-0.28×10^{-6}	13.1×10^{-6}
	4500	2.35×10^6	0.8×10^6	-0.17	0.95	1.31×10^{-6}	13.6×10^{-6}
Carbitex 713	0	1.0×10^6	0.5×10^6	0.17	0.17	1.2×10^{-6}	1.2×10^{-6}
	4500	0.5×10^6	0.3×10^6	0.17	0.17	1.8×10^{-6}	1.8×10^{-6}

TABLE II

(U) SUMMARY OF MAXIMUM TRANSIENT STRESSES IN THE
3K PYROBOND CARBITEX/PYROLYTIC GRAPHITE THRUST CHAMBER

ID = 6 in.; P_c = 300 psia; T_c = 5410°F

Case No.	Wall Thickness (in.)		Maximum Stress (psi)					
	PG	Carbitex	Pyrolytic Graphite				Carbitex	
			Inside		Interface			
			Axial	Circum.	Axial	Circum.	Axial	Circum.
1	0.08	0.24	-5800	-3800	6700	13,500	1680	2630
2	0.08	0.36	-5800	-4400	5700	12,000	1700	2500
3	0.12	0.36	-7300	-7800	6000	11,800	1560	2280
4	0.12	0.48	-7600	-8400	6400	11,400	1450	2050

TABLE III

(U) SUMMARY OF TEST FIRING DATA FOR THE 3K THRUST CHAMBER ASSEMBLY

Propellants: ClF_3/BA1014

Run Number	Duration (sec)	Mixture Ratio	Thrust (lbs)	Chamber Pressure (psia)	C*(1) Efficiency	Injector	Remarks
558	150	2.8	3579	307.8	98.3	31-1	Steady state firing
559	100(2)	2.82	3502	300.7	99.1	31-1	Duty cycle - 6 Hot starts
560	40	2.87	3417	296.	92.4	31-1	Localized burn through wall

(1) Uncorrected

(2) Duty Cycle: See Section IV

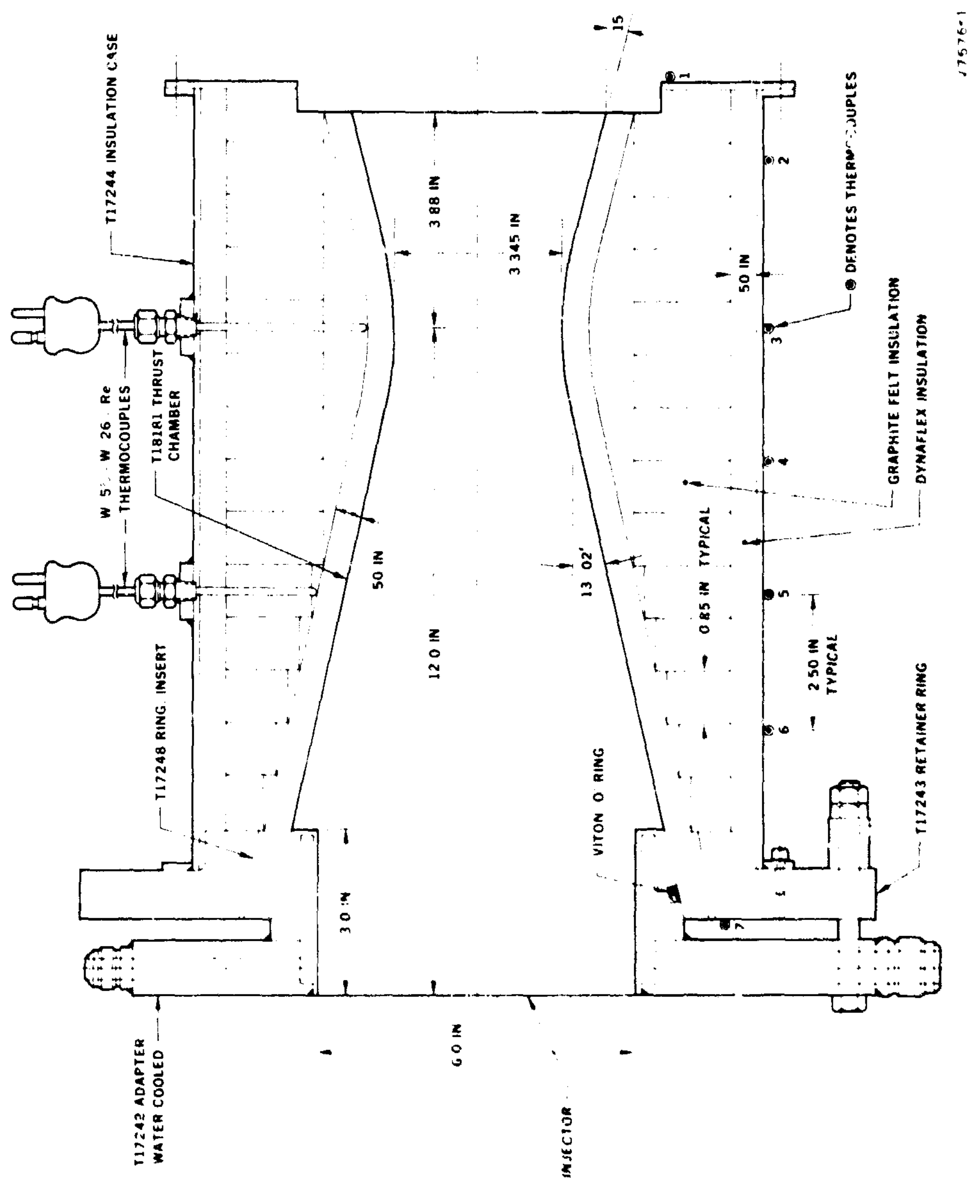
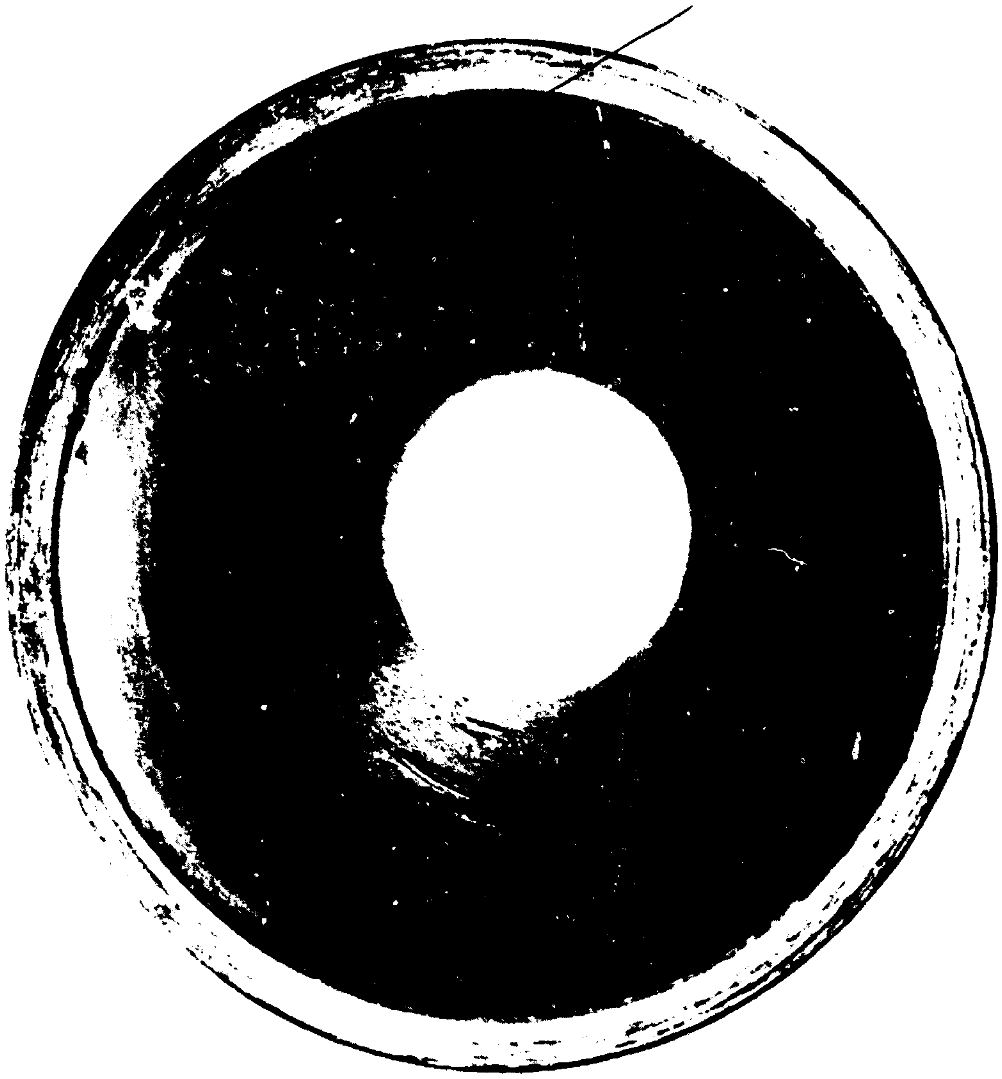


FIGURE 1. (U) 3K Thrust Chamber Assembly

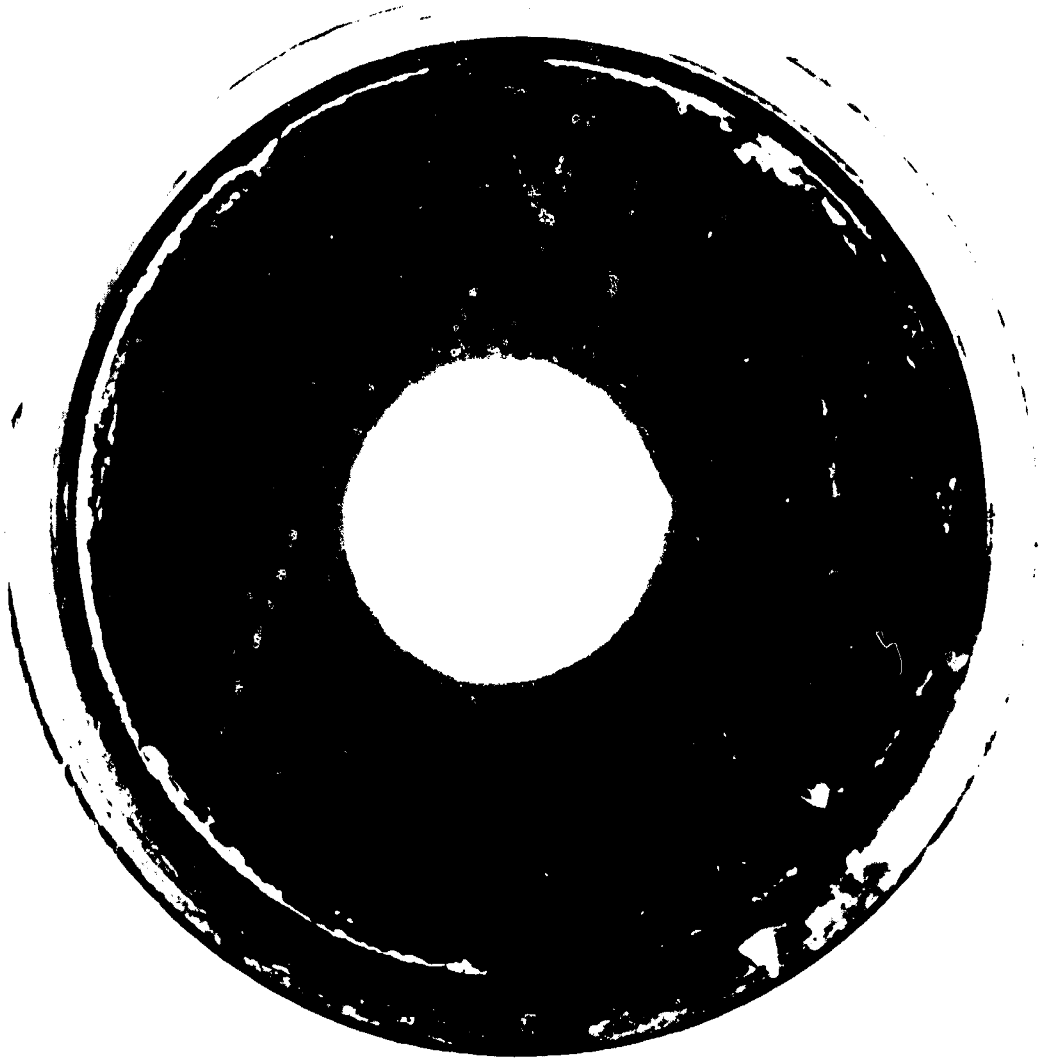


[illegible]

FIGURE [illegible]. (U) Exterior View of the 5K Pyrobond Carbitex/Pyrolytic Graphite Thrust Chamber Showing the Chamber Entrance

FIGURE [illegible]. (U) Exterior View of the 5K Pyrobond Carbitex/Pyrolytic Graphite Thrust Chamber Showing the Chamber Exit

FIGURE [illegible]. (U) Installation of the 3K Thrust Chamber Assembly on the AFRPL Thrust Stand



[illegible] chamber after [illegible] firing at AFRPL

[illegible] Nozzle After [illegible] at AFRPL

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14 KEY WORDS	LINK A ROLE	LINK A WT	LINK B ROLE	LINK B WT	LINK C ROLE	LINK C WT
Thrust Chambers						
Pyrolytic Graphite						
Composite Structures						

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