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H_2 Fueled Flightweight Ramjet Construction & Test

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HISTORICAL BACKGROUND

The "ACES" program began the investigation of regeneratively cooled ramjet engines for propelling aircraft at March 6 to 8 flight regimes while collecting and processing air for later use as oxidizer in rocket propulsion into an orbit flight mode. The Marquardt Company had as its prime task the design and demonstration of a ramjet capable of steady state operation using Hydrogen as regenerative coolant and with fuel flow limited to a $\Theta = 1$.

Marquardt progressed from shell type combustors to advanced tubular combustion chambers in direct connect test rigs. The first tests were made with water cooled center-bodies and plug nozzles using a pebble bed air heater to simulate flight air temperatures. Later tests were made on completely H_2 cooled flight weight V/G assemblies direct connected to a "SUE" burner heater.

Design studies were also conducted on integrated systems for take-off capability using offset turbojets connected to 2D or axisymmetric inlets. An 18" Hypersonic Ramjet evaluation scale model was designed based on the hot test results using fully V/G inlet and exit nozzle. This thruster would provide 25000 lbs. of thrust with an estimated weight of 250 lbs. A V/G inlet would also incorporate an inlet seal for possible take-off thrust by rocket operation.

HYPERSONIC RAMJET CONSTRUCTION FEATURES

Tubular combustion chambers were built based on thermal fatigue sub-element tests of a variety of hot wall configurations and candidate materials. The final selected tube shape was "D" configuration in Hastelloy X selected for its superior oxidation resistance and fabricability.

Combustion chamber pressure containing structure evolved from strap banding to a Rene 41 wire wrap to utilize the very high strength of the Rene at high temperatures. Several methods were evaluated to optimize the helical wrapping technique. A spacing coil of wire laced with alumina beads was used very successfully on several chambers built.

An inlet seal ring was evaluated in support of V/G inlet sealing evaluations. No further testing was made to improve this device because program directives precluded a test design of the 18" hypersonic ramjet.

THRUST CHAMBER DEVELOPMENT

The initial challenge to successful chamber design was the need to function under the high temperature conditions existing in both the coolant and the structure. This chamber had to be cooled by 1500° R supply H_2 while maintaining a 2000° R hot wall temperature. A heatflux of 3

Btu/in^2-sec. in the throat region was more difficult because the V/G nozzle shifted the throat location about 3" as operation ranged from Mach 3 to Mach 8.

Several different chambers were built and tested varying from cylindrical chambers with straight or corrugated hot wall tubes to contoured chambers of two lengths using smooth hot wall "D" tubes. A picture of the early test arrangement of a hybrid system using water cooled innerbody and centerbody with a cylindrical hydrogen cooled chamber as tested at the Marquardt Saugus Test Facility.

1961

Marquardt contracted with Rocketdyne to design and fabricate the first cylindrical thrust chamber. This subcontract was made to utilize their experience in regenerative cooled rocket engines and their proximity to Marquardt. This chamber was made of 1/8 diameter tubes furnace brazed with a strap banding to support pressure loads. This unit was needed for test system shake down operation and did not have a high temperature capability.

1963

Marquardt's initial chamber design was completed using straight corrugated "D " tubes brazed at 2100° F in Marquardt's cold wall vacuum furnace. The braze alloy was Ni-Au-Pd composition that exhibited base metal strength at high temperature. The tubes had a wall thickness of 0.010 and were shaped in a specially designed tool to form the buckles in the hot wall. The tube bundle was held by a closely wrapped wire coil. The tube material was either CRES 321 or Hast C (I can't be sure which). During hot testing analysis requested by WPAFB showed that hot wall bending stresses were excessive due to the outer wall fixity impact on section properties. The new chamber designs would not be subject to this condition because "D" tube with smooth wall and open wrap significantly reduced hot wall buckling and fatigue stresses by reducing the tube wall section dimensions.

1964

The first contoured thrust chamber was built for testing with the water cooled test hardware. It had a long cylindrical combustion section with contoured nozzle. The tubes were "D" shaped Hastelloy X with .010 wall thickness formed with rectangular ends for insertion into Rene 41 supply and discharge manifolds. The tubes were assembled to a Hastelloy X tool and brazed vertically at 2100°F. After the first braze, a Rene 41 Wire and spacing wire with threaded Alumina beads was wrapped together with braze alloy for a second braze at 1950°F using a Cr-Ni-Pd alloy. TIG welding the manifold closures and supply tubes completed the assembly.

1954

A second improved contoured thrust chamber was fabricated featuring a shortened combustion chamber length improved coolant tubes and an Alumina hot wall coating. This unit was destined for assembly into a newly designed V/G fully H_2 cooled ramjet to be tested at Marquardt's cell #2 altitude facility. Hybrid engine testing at sea level with finger injectors located forward of the centerbody showed that chamber length could be shortened and injection moved aft to the centerbody exit. This reduced the overall heat load to the engine without affecting performance.

Contoured chamber coolant tubes were formed by a propriety process developed by the Lefiell Company of Santa Fe Springs, CA. This process called "Roto-Draw" was SOTA for CRES tubing used in large rocket thruster of that period. This tube of Hastelloy X was LeFiell's first experience into superalloy tube forming. "Roto-Draw" changes the tube circumference without changing its wall thickness. A contoured D tube can be made from a varying round tube whose perimeters exactly match the dimensions needed for a contoured shape. The D shape is made in a split die under very high hydraulic internal pressure. Metallurgical examinations showed that the forming introduced large intergranular cracks and surface discontinuities. Intensive metal processing finally corrected the deficiencies to result in a tube wall with almost perfect intergranular structure and surface finish.

1967

Other elements of the V/G ramjet were four (4) strut assemblies made of brazed INCO 718 structure and machined rib type coolant walls made of Hastelloy X. After brazing, the tree subassemblies were welded together. These struts carried the plug nozzle pressure loads and provided the access for internal cooling, control and instrumentation for the plug nozzle actuation.

Several plug nozzles were designed and fabricated:

1. A shell type nozzle with machined ribs to support a brazed hot wall shell.

2. A transpiration cooled nozzle with sub-surface compartments to control the flow of coolant.

3. The final nozzle design consisted of 0.010 thick Hastelloy X formed "U" channels brazed into machined grooves of the conic plug structure. This assembly was also given an Alumina insulating coating.

1966-1968

The partially assembled thruster called a "Component Development Rig" shows the center body, the two concentric fuel injector rings, the plug nozzle and the instrumentation hookup needed for the actuator and the plug closure.

A test at the Saugus facility is shown with an uncoated chamber showing a high temperature ring where separation occurs at sea level operation.

The test installation in the cell #2 altitude chamber is shown with the torus H_2 supply manifold to control coolant and fuel flow independently for development reliability only.

The completed Ramjet development engine is shown after testing with improved contoured chamber installed. This assembly weighed 170 lbs. dry and featured a controlled plug nozzle to operate between Mach 3 to 8. Maximum chamber pressure was 250 psia. with hot wall temperatures limited to 2000°R. This assembly had over 3 hours of test time with many tests exceeding 10 minutes duration. The engine is stored in Marquardt's museum.

1965-1966

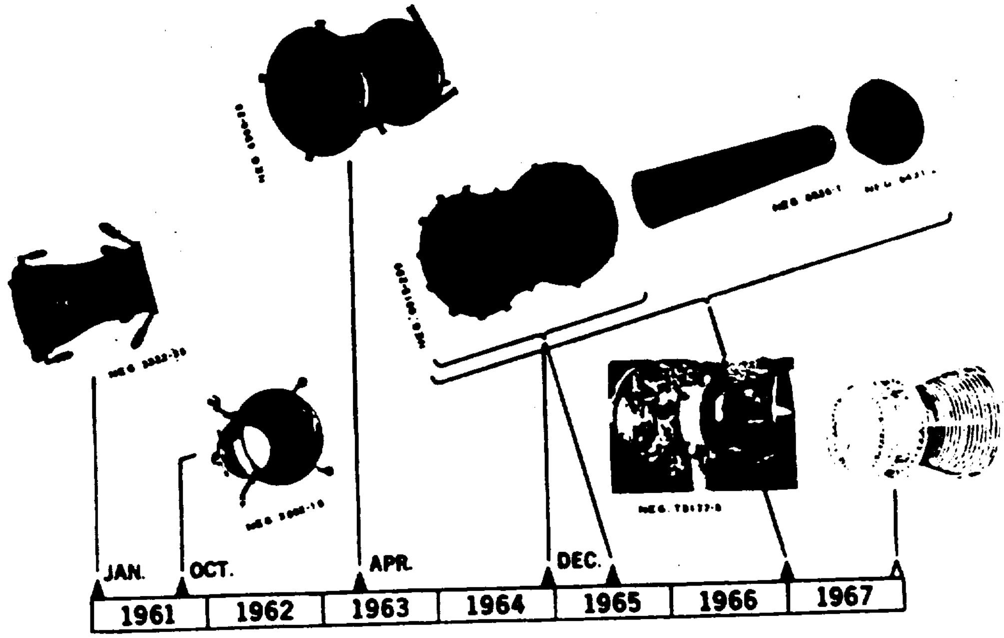
Interest in Scramjet technology funded the evaluation of a 2D Scramjet-Inlet/Combustor model. Marquardt designed and fabricated the Scramjet shown with using the tube forming and brazing background developed for the hypersonic ramjet as the basic design approach. The unique feature of this design was the use of a newly developed high temperature Hafnium-Tantalum Alloy by Ken Marnoch of Marquardt's material group that demonstrated stability when exposed to rocket discharges of temperatures over 5000°F. Samples of this material had just been tested, when the decision time for a leading edge was required. This material generates an oxide surface that prevents further degradation of the base material. Samples were successfully tested in a simulation of the actual Scramjet installation. The leading edge radius was 0.060" with a taper angle of 30°.

SUMMARY

Technologies developed and laid to rest include:

1. High temperature brazing methods and the importance of a cold wall vacuum furnace for temperature control.
2. Hastelloy X tube material processing & treatment.
3. The use of a Plasma sprayed metal-ceramic insulating hot wall coating to reduce the effects of localized overheating in nozzle throats.
4. High strength open helical wire wrap to reduce the thermal compressive stress on hot walls and thereby increase fatigue life.
5. "D" tube hot walls especially in high heat flux regions to reduce thermal stress and increase tube fatigue life.
6. Hot wall static pressure and thermocouple instrumentation techniques.
7. Very high temperature small radius leading edge potential.

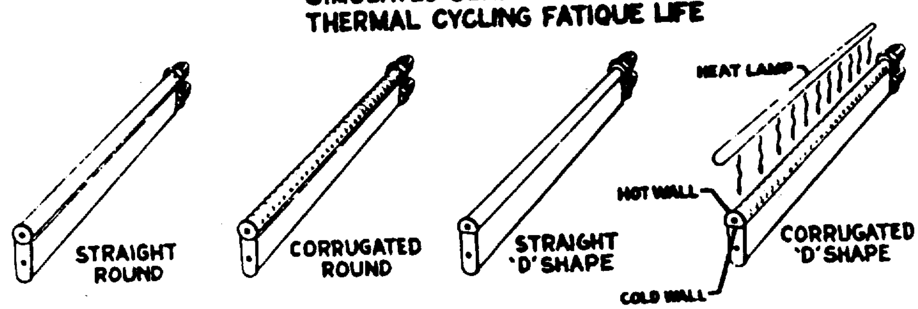
REGENERATIVELY COOLED COMPONENTS



HYPERSONIC RAMJET STRUCTURES

THE STRUCTURAL EVALUATION OF COOLANT TUBES WITH SIMULATED STRESS TO BUCKLING UNDER THERMAL FATIQUE LOADING IN THE PLASTIC RANGE.

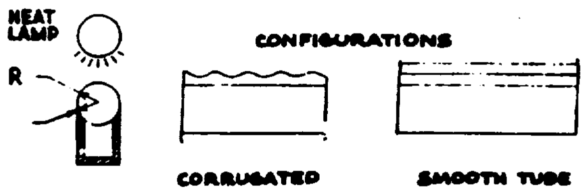
- EVALUATION OF-
  - CORRUGATED VS STRAIGHT TUBING
  - "D" SHAPES AND ROUND CONFIGS.
  - EFFECT OF R/t RATIOS (10-50)
  - COMPARISON OF HIGH TEMP. ALLOYS
- SIMULATION OF ENGINE ENVIRONMENT
  - MAX. HOT WALL TEMP.
  - Δ_T - HOT AND COLD TEMPS.
  - SIMULATED BENDING RESTRAINT/CLASSICAL BUCKLING
  - THERMAL CYCLING FATIQUE LIFE



HYPERSONIC RAMJET STRUCTURES

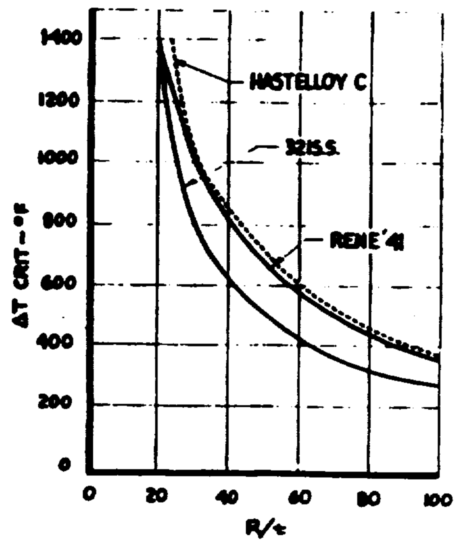
RESULTS OF STRUCTURAL THERMAL TEST OF COOLANT TUBES

TYPICAL TEST PRODUCTS (AVERAGE)



MAT'L	CONF	R/t	TEMP'E	ΔT	CYCLES	MADE
321SS	S/C	16.5	1200	1000	260	NONE
321SS	S	25	1200	1000	60	BUCK.-FAT.
HAST C	S/C	16.5	1200	1000	200	NONE
321SS	S	10	1700	1400	260	NONE
321SS	S	16	1700	1400	170	BUCK.-FAT.
321SS	S	25	1700	1400	14	BUCK.-FAT.
321SS	C	16.5	1700	1400	95	FATIGUE
HAST. C	S	16.5	1700	1400	125	FATIGUE
HAST. C	C	16.5	1700	1400	60	FATIGUE
RENE'41	S	16.5	1700	1400	60	FATIGUE

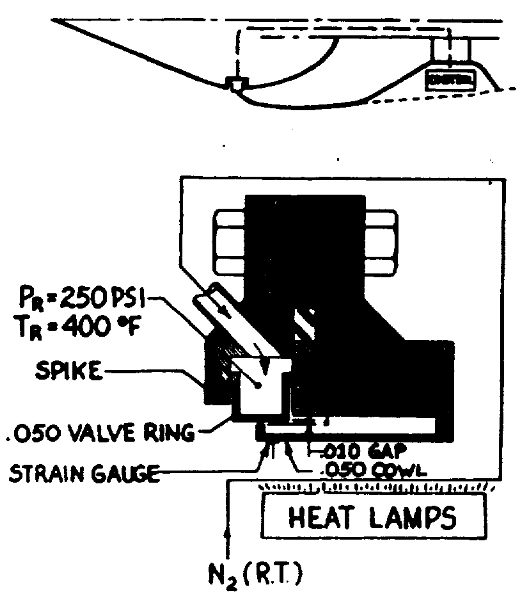
CRITICAL BUCKLING TEMPERATURE GRADIENT VS. COOLANT TUBE RADIUS THICKNESS RATIO



HYPERSONIC RAMJET STRUCTURES

THE DESIGN MFG & TEST OF A THERMALLY ACTUATED INLET VALVE SEAL FOR H/J TRANSITIONAL MODE CAPABILITY

- SEALING - THERMAL RESPONSE - PRESSURE FRICTION - LIGHT WT. - FLEXIBLE - OB ROUND & ECCENTRIC COWL
- CONTROL - STRAIN SENSING - COOLANT TEMP CONTROL



OBJECTIVES	RESULTS
DETERMINE μ	μ - .132
ΔR vs P_R	.002 PER 100 PSI
ΔR vs P_R + T	.008 PER 100 PSI + 100°
RING CENTERING CAPABILITY	ACCOMPLISHED FRICTION NOT RESTRAINT

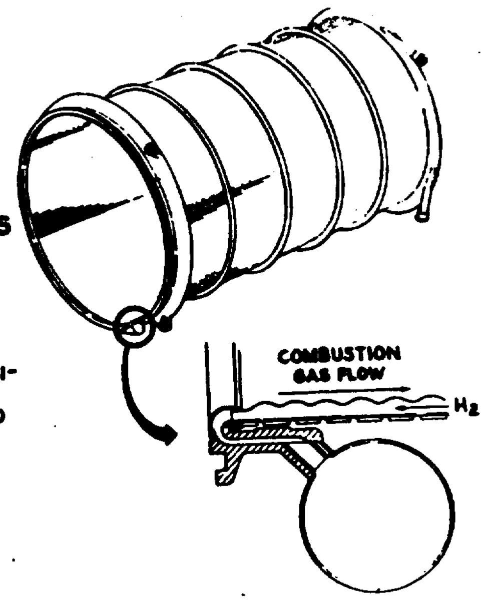
RECOMMENDATIONS

1. IMPROVED SURFACE MATL. & FINISH
2. HEATING TECHNOLOGY
3. CONTINUED DESIGN & EVALUATION

HYPERSONIC RAMJET STRUCTURES

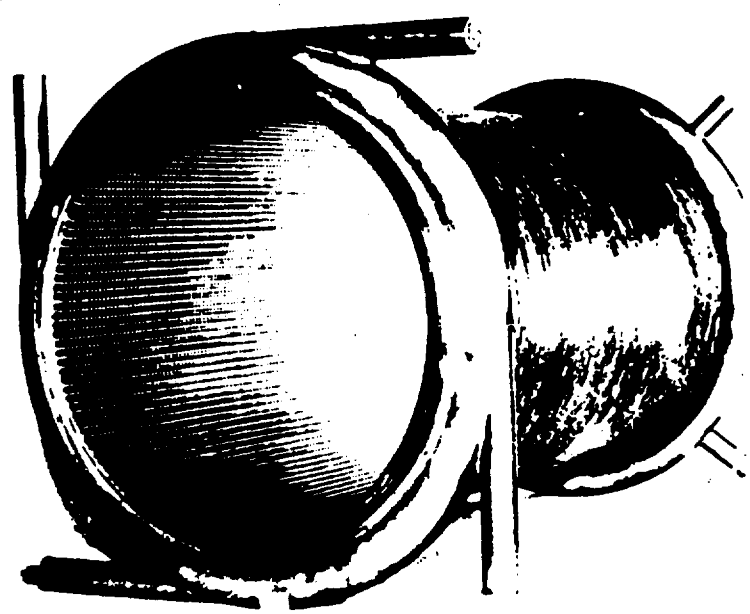
THE DESIGN & MFR. OF A FLIGHT WEIGHT, REGEN-COOLED, 18" DIA THRUST CHAMBER FOR COMBUSTION TESTING—WITH COOLANT TEMP. CYCLING CAPABILITY, USING RENE 41 PRIMARY STRUCTURE

- TEST CONDITIONS
  - GAS FLOW 40 PPS
  - CHAMBER PRESSURE 150 PSIA
  - GAS TEMP. 4,500°R
  - H_2 COOLANT FLOW 4 PPS
  - H_2 COOLANT PRESS. 500 PSIA
  - H_2 COOLANT TEMP. 570°R } THROAT
  - HEATFLUX 2 BTU/IN² SEC. } THROAT
  - MAX. HOT WALL 2,000°R } THROAT
- STRUCTURAL DESIGN LIMITATIONS
  - 250 P_c
  - 2000°R MAX. WALL TEMP.
  - 1500°R H_2
  - 600 PSI H_2
- ADVANCED TECHNOLOGY
  - TUBE DESIGN FOR INCREASED LIFE + MULTI-MODE FUNCTION
  - STEP BRAZING TECHNIQUES-ADVANCED ALLOYS
  - MFG. DEVELOP. —"D" TUBES/RENE 41 WRAP
  - LIGHT WEIGHT FLANGE + MANIFOLD CONCEPTS



HYPERSONIC RAMJET STRUCTURES

LT. WEIGHT 18" DIA. THRUST CHAMBER



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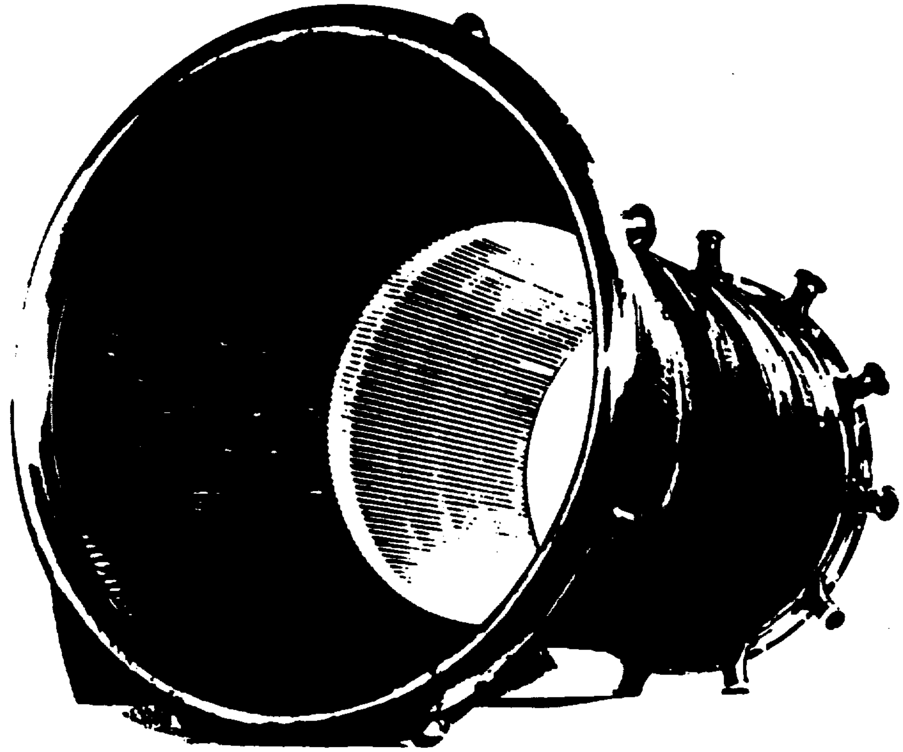
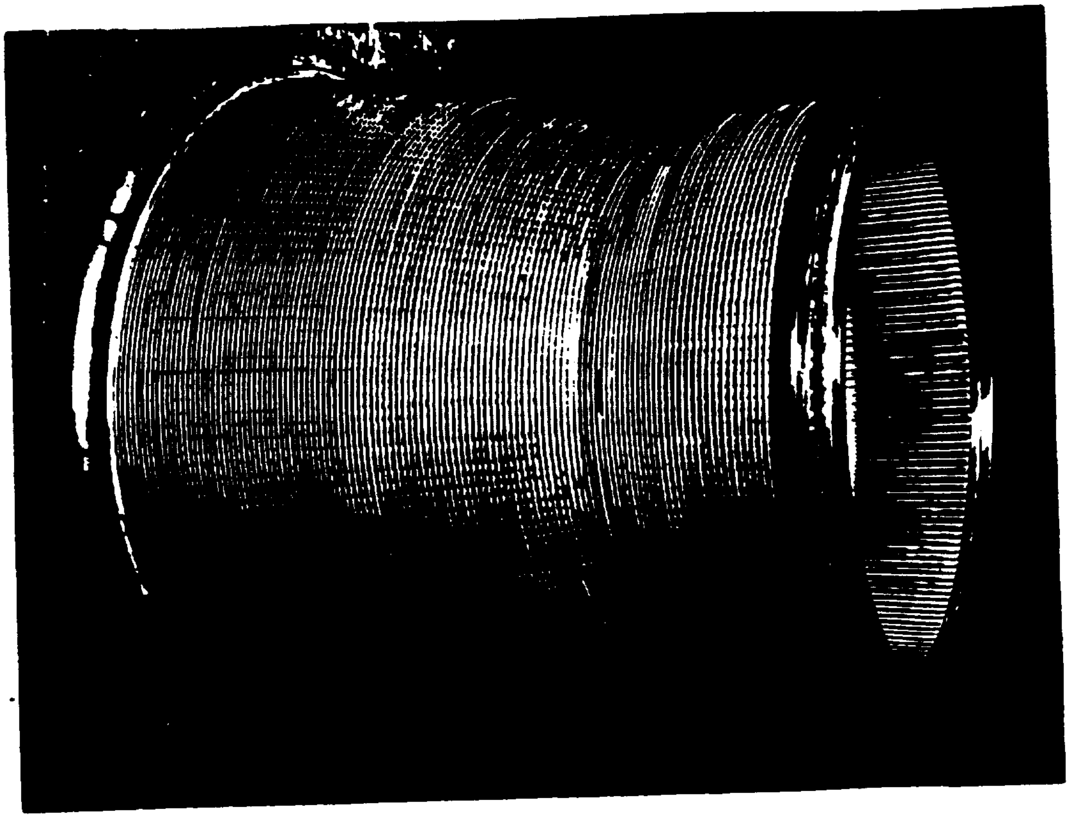
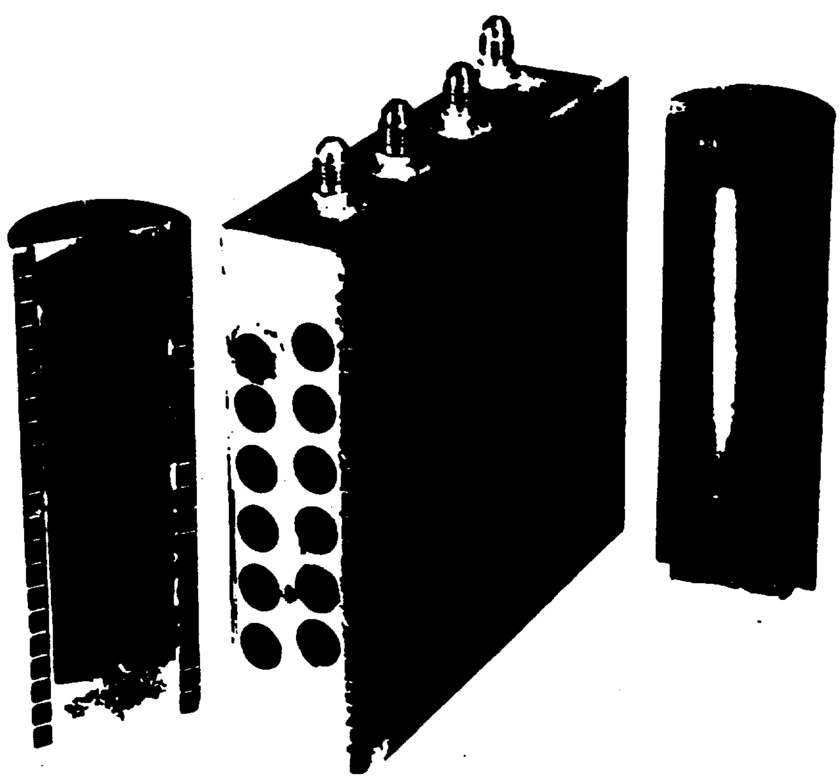


18" REGENERATIVELY COOLED THRUST CHAMBER
25 NOV 64 (U)

ROCKETDYNE 18" REGENERATIVELY COOLED THRUST CHAMBER
9-28-61



CONTOURED CHAMBER NO. 2 AFTER BRAZING RENE' 41 WIRE
31 MAR 65 (U)



CENTERBODY STRUT COMPONENTS AFTER BRAZING HOT WALL SKINS
20 JUL 67

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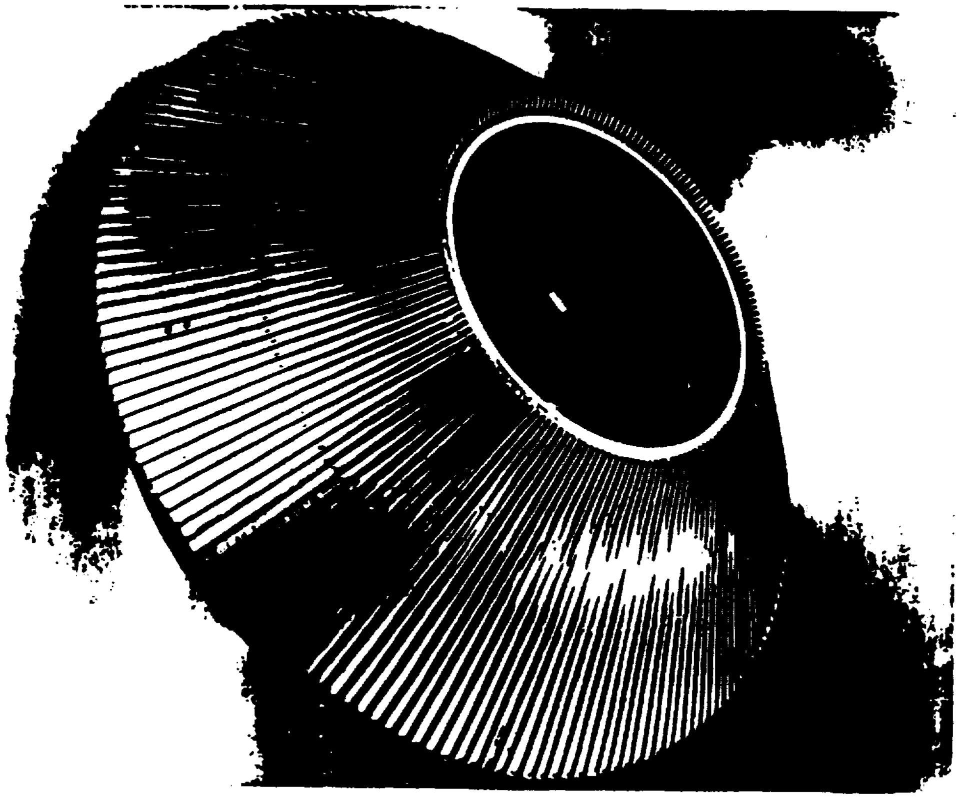

EXIT NOZZLE PLUG
RIB WALL BEFORE HOT WALL INSTALLATION

TRANSPIRATION COOLED EXIT NOZZLE PLUG--FRONT VIEW
24 NOV 64 (U)

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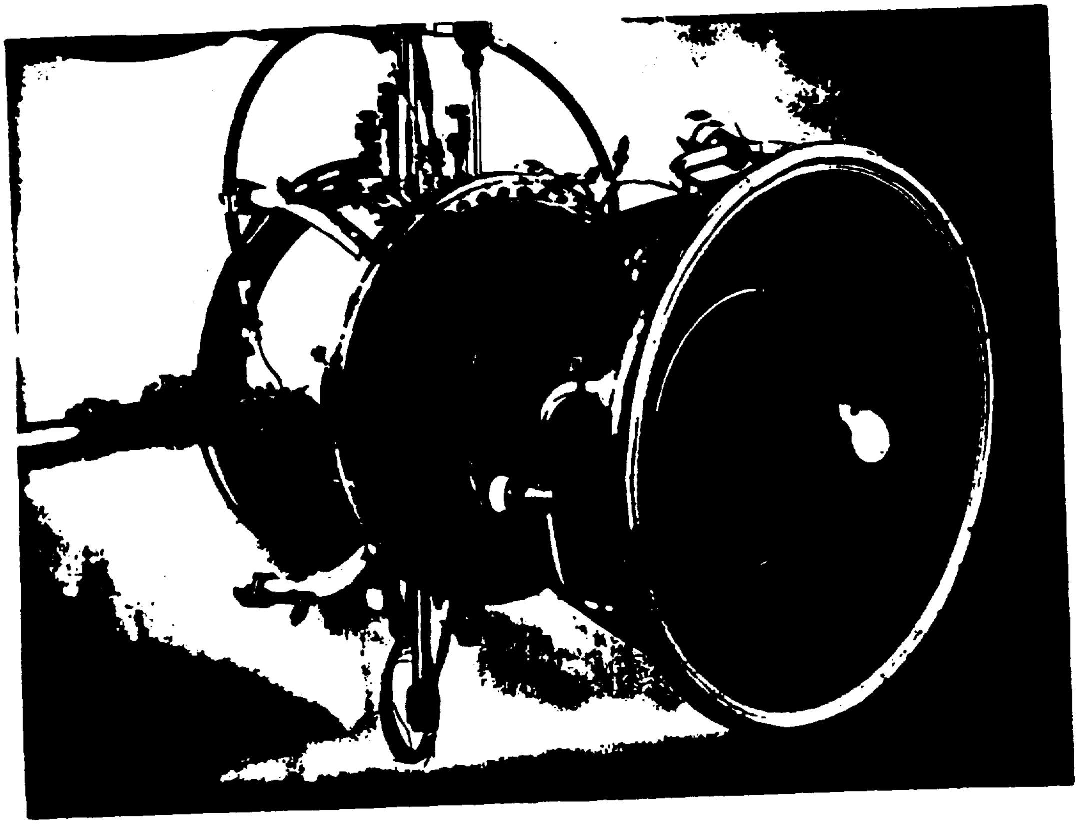

HYPERSONIC RAMJET DEVELOPMENT ENGINE
2 JUL 68