REGENERATIVE COOLING OF THE SPACE SHUTTLE ENGINE

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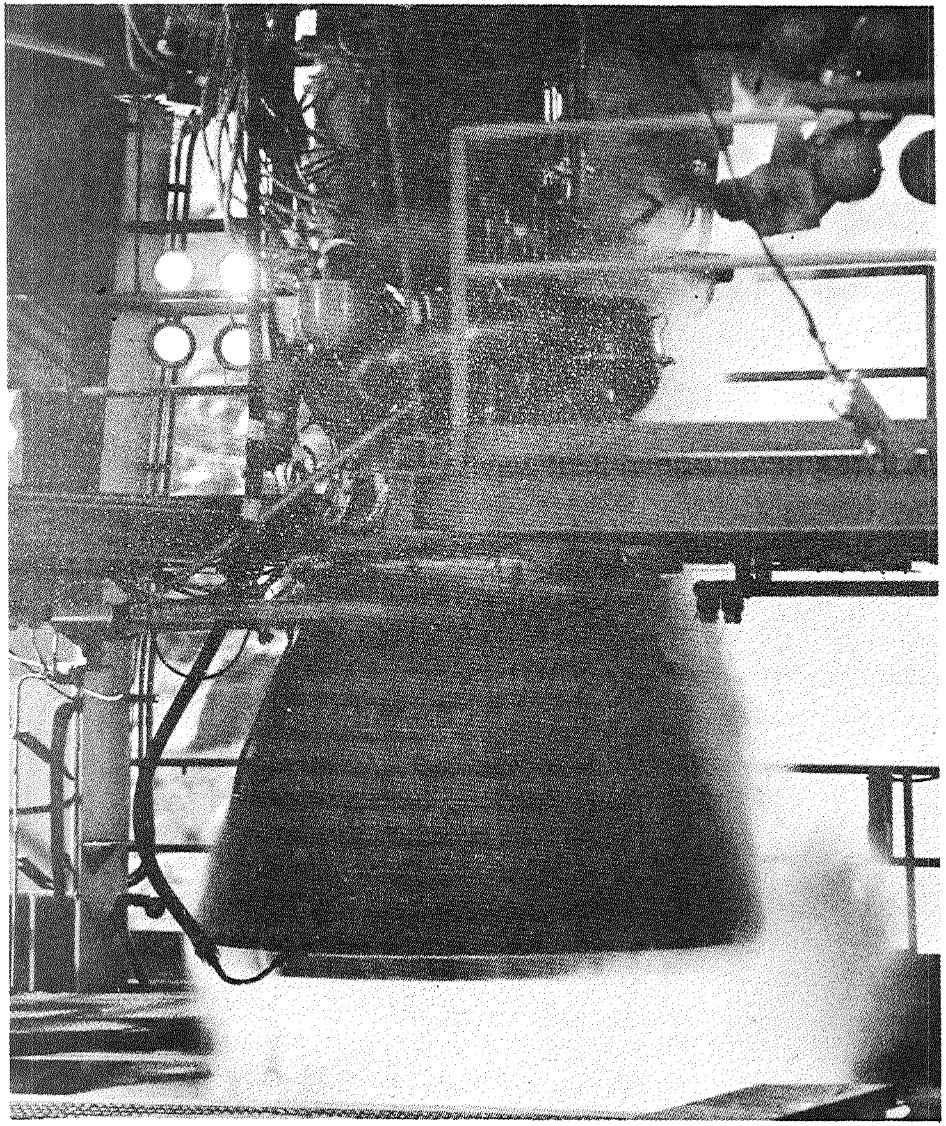
INTRODUCTION

The high temperature associated with the efficient combustion of rocket propellants necessitates the selection of a cooling technique which reliably maintains safe operating temperatures on all critical components. For all liquid booster propulsion units, such as the J-2 engine (Fig. 1), this task is accomplished by regenerative cooling. The prime assets of regenerative cooling are reliability, durability, and high performance.

The Space Shuttle Engine imposes requirements on regenerative cooling well beyond those associated with current engine systems. This presentation will compare those requirements to capabilities and available technology of regenerative cooling.



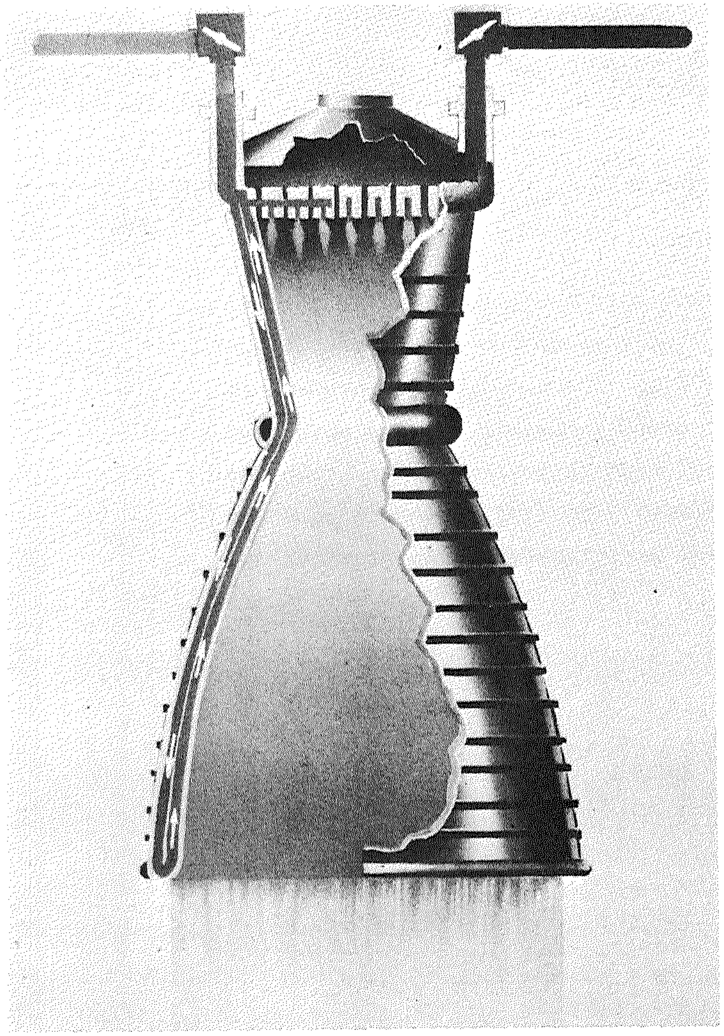
J-2 ENGINE FIRING

REGENERATIVELY COOLED THRUST CHAMBER

The principal of regenerative cooling is to maintain a cool wall by utilizing one of the propellants within the rocket engine to absorb heat that is transmitted to the thrust chamber from the combustion products. The selected coolant absorbs heat as it travels through the coolant passages and then returns this heat (regenerates) to the combustion process when it is injected into the combustion chamber.

Many types of coolants have been utilized in regeneratively cooled thrust chambers. Both oxidizers and fuels have been applied; cryogenics and storable propellants have each demonstrated the capability to cool regeneratively.

The techniques for constructing the coolant passages have also varied. The thrust chambers used for the early V-2 and Redstone rockets utilized a simple double wall construction. Later chambers utilized tubular construction. Current engines rely on both tubes and channel wall constructions. The latter is a modification of the earlier double wall technique.



REGENERATIVELY COOLED
THRUST CHAMBER

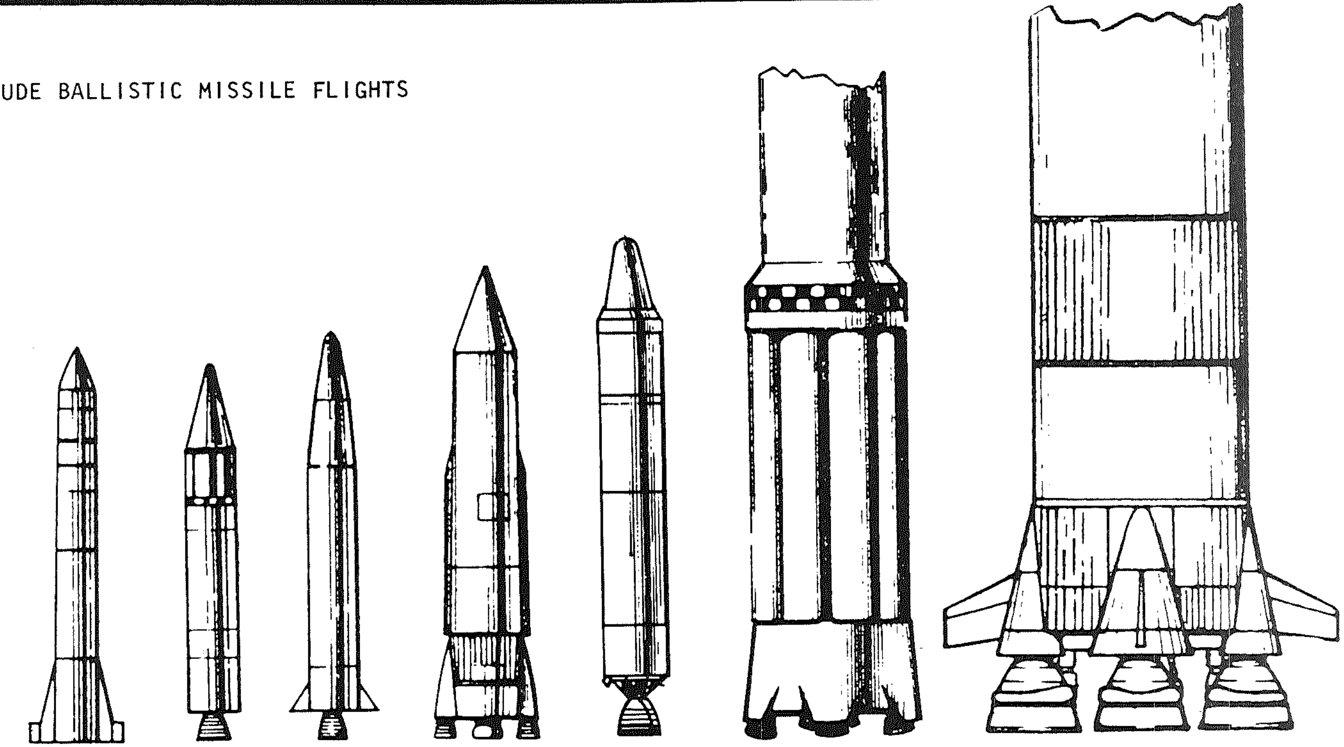
ENGINE LAUNCHES

The reliability of regenerative cooling is impressive. Figure 3 indicates space boosters and ballistic missiles which utilize regeneratively cooled engines. The number of flights for each of the propulsion systems is indicated and the number of regeneratively cooled engines associated with each vehicle is also shown. This chart represents over 4000 applications of regeneratively cooled engines. On all of these flights, regenerative cooling has had a failure-free operation.

ENGINE LAUNCHES

NUMBER OF REGENERATIVELY COOLED ENGINES	1	1	3	5-7	3	9-14	11
NUMBER OF FLIGHTS	75	46	404	386	54 *	15	8

* DOES NOT INCLUDE BALLISTIC MISSILE FLIGHTS

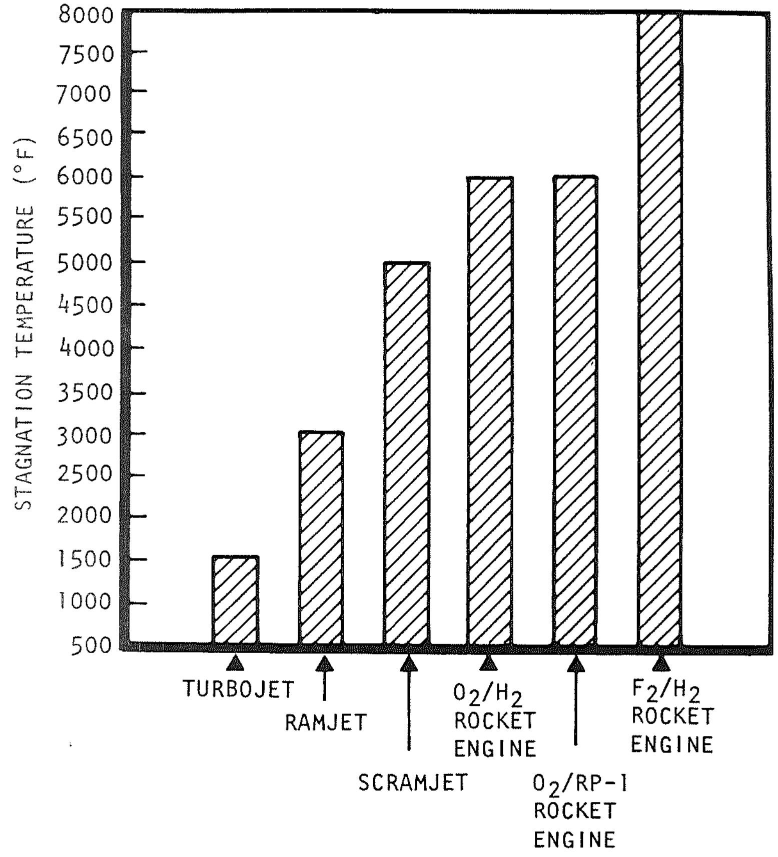


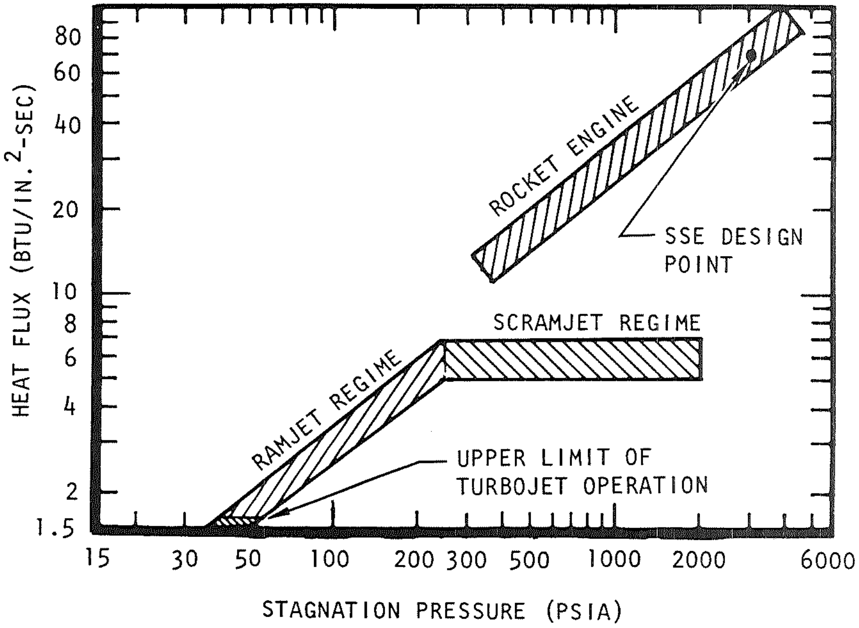
THERMAL CHARACTERISTICS OF PROPULSION SYSTEMS

The thermal environment within a rocket engine is substantially more severe than those experienced within other propulsion systems. Figure 4 indicates relative temperatures and heat fluxes that are experienced in rocket engines and air breathing propulsion systems. The severity of the thermal conditions is directly related to the stagnation temperature, the properties of the combustion gases, and the Mach number.

For air breathing systems combustion temperatures frequently exceed the allowable temperatures of most metals; but rarely approach the stagnation temperatures of from 6,000 to 8,000 degrees that are obtained within rocket engines. The heat fluxes experienced within oxygen-hydrogen rocket engines are substantially more severe than those encountered in air breathing propulsion. In the rocket engine the high stagnation temperature is combined with sonic hot gas conditions at the throat of the thrust chamber. Current oxygen-hdyrogen rocket engines, such as the J-2, J-2S, and M-1, experience heat fluxes ranging from 17 to 35 Btu/in^2-sec. At the Space Shuttle Engine design point the maximum heat flux is 72 Btu/in^2-sec. Regenerative cooling provides the only means for handling these severe heat fluxes without encountering appreciable performance losses.

THERMAL CHARACTERISTICS OF PROPULSION SYSTEMS





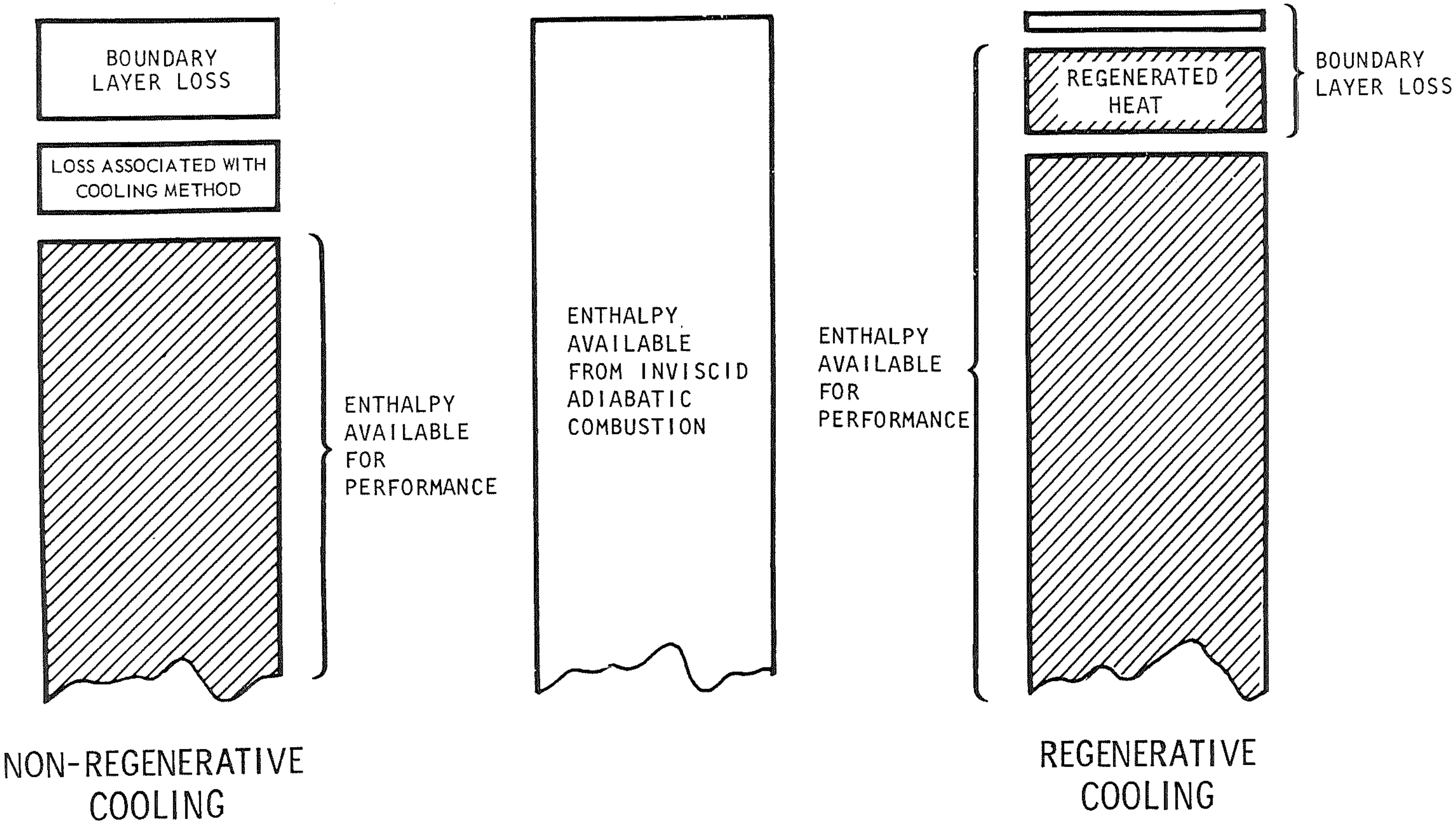
PERFORMANCE OF REGENERATIVE COOLING

The performance advantage of a regenerative cooling can be illustrated by comparing regenerative and non-regenerative cooling to an ideal combustion process. For a given set of propellant inlet conditions an ideal (adiabatic and nonviscous) combustion and expansion process is illustrated by the center bar; mixing is uniform, combustion is perfect and there are boundary layer losses. However, in a real thrust chamber potential performance detriments must be evaluated. For non-regenerative cooling, the boundary layer loss, which is largely a function of a wall temperature, is substantially unrecoverable. In addition, non-regenerative cooling methods may require mixture ratio maldistribution, injector bias and/or mass addition downstream of the throat. These factors incur additional performance losses. This loss generally ranges from a few seconds to several percent and is a function of the cooling technique. The extent of this loss is minimized by careful design and extensive testing.

Regeneratively cooled chambers are normally designed for low wall temperatures, thus the energy lost in the boundary layer is usually larger than that associated with non-regenerative methods. However, the majority of the enthalpy is recovered by the coolant and returned to the combustion process. This recovery of enthalpy provides a regenerative cooling performance gain.

The performance gain associated with regenerative cooling, plus the losses associated with non-regenerative cooling techniques form the difference between regenerative and non-regenerative cooling methods.

PERFORMANCE OF REGENERATIVE COOLING



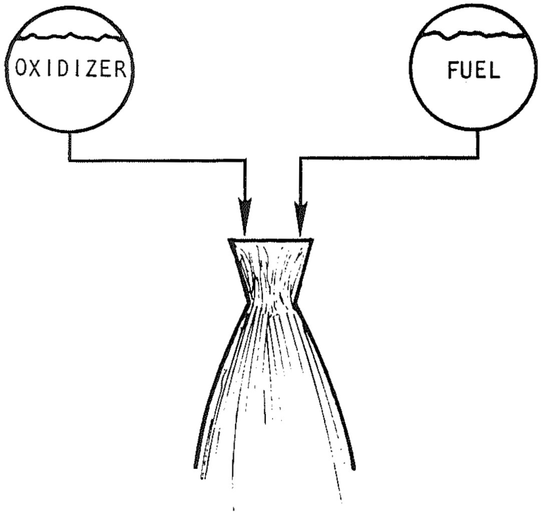
PERFORMANCE GAIN FROM REGENERATION

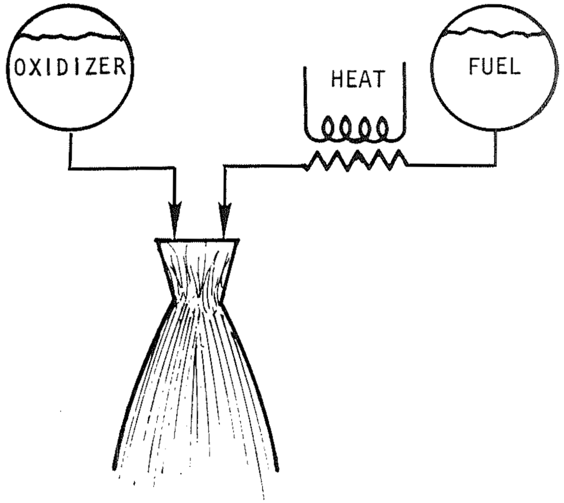
The performance gain of regenerative cooling can also be illustrated by using an enthalpy-entropy diagram for the equilibrium exhaust products of a reaction (neglecting divergency and kinetics). Pressure lines diverge on an h-s plot with increasing enthalpy or entropy; thus when heat is added to the propellants prior to combustion the enthalpy available from the expansion process is increased significantly.

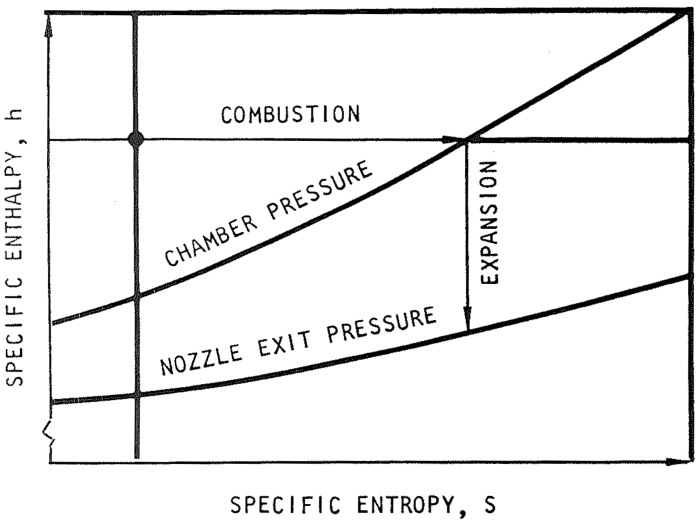
Figure 6 illustrates the favorable effect of preheating propellants. In a regeneratively cooled chamber this heat is removed from the combusted propellants. If the heat is all removed at chamber pressure no gain is noted.

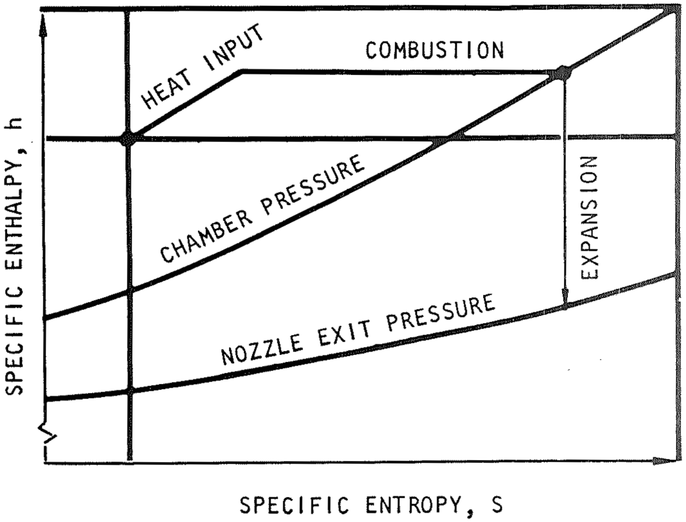
The maximum performance occurs when all the heat is removed at the nozzle exit. In a real engine, the heat is removed continuously so that the performance gain falls between these two extremes. For the Space Shuttle Engine the gain associated with the regenerative cycle is nearly one percent.

PERFORMANCE GAIN FROM REGENERATION



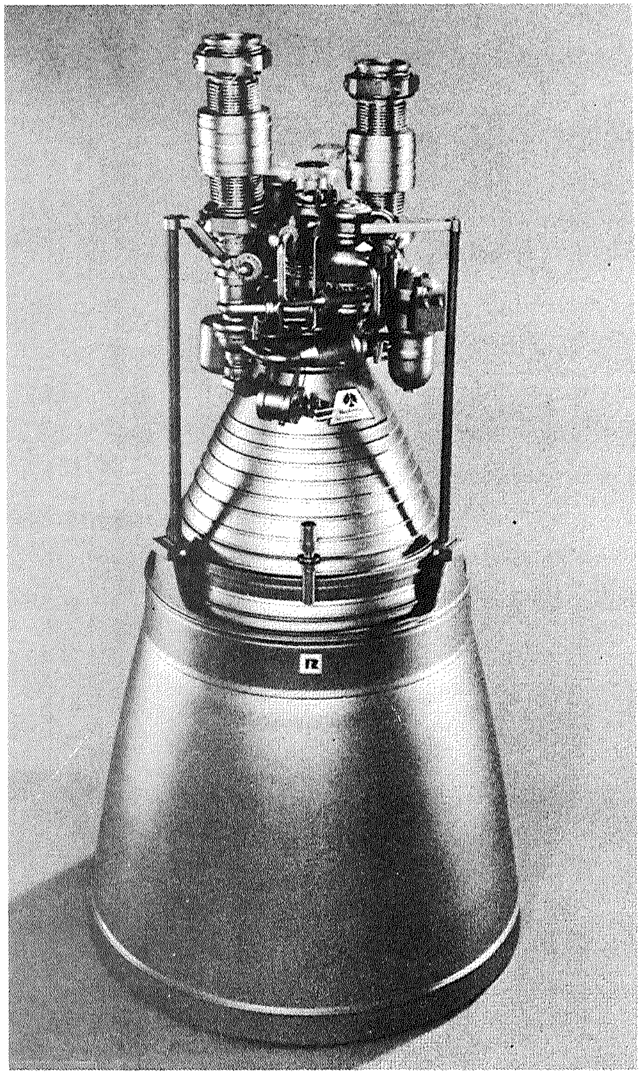






SPACE SHUTTLE ENGINE

The previous charts have discussed some of the features of regenerative cooling. It is now appropriate to explore the requirements and limitations associated with this cooling technique. The Space Shuttle Engine is designed to achieve a high thrust and high performance within a compact envelope. To accomplish these objectives, the engine operates at a chamber pressure of 3000 psi and produces heat flux four times as high as those experienced in the current J-2 engine. To understand the feasibility of regeneratively cooling the Space Shuttle Engine, it is necessary to compare the capabilities of coolant and thrust chamber materials with the engine requirements.



SPACE SHUTTLE ENGINE

PROPERTIES AND PERFORMANCE OF COOLANTS

The characteristics of several coolants are compared in Fig. 8. The high coolant specific heat of the hydrogen minimizes the bulk temperature throughout the cooling circuit. Hydrogen easily ranks as the best coolant in terms of minimizing bulk temperature rise $(1/\Delta P_b)$.

Another measure of cooling ability is the dynamic pressure required to cool a given heat flux. The pressure drop in the cooling system is a direct function of this parameter. Again hydrogen is far superior to other coolants which require from two to six times the amount of pressure drop to cool a given heat flux.

The availability of hydrogen within the Space Shuttle Engine is a prime factor in the ability to cool regeneratively.

PROPERTIES AND PERFORMANCE OF COOLANTS

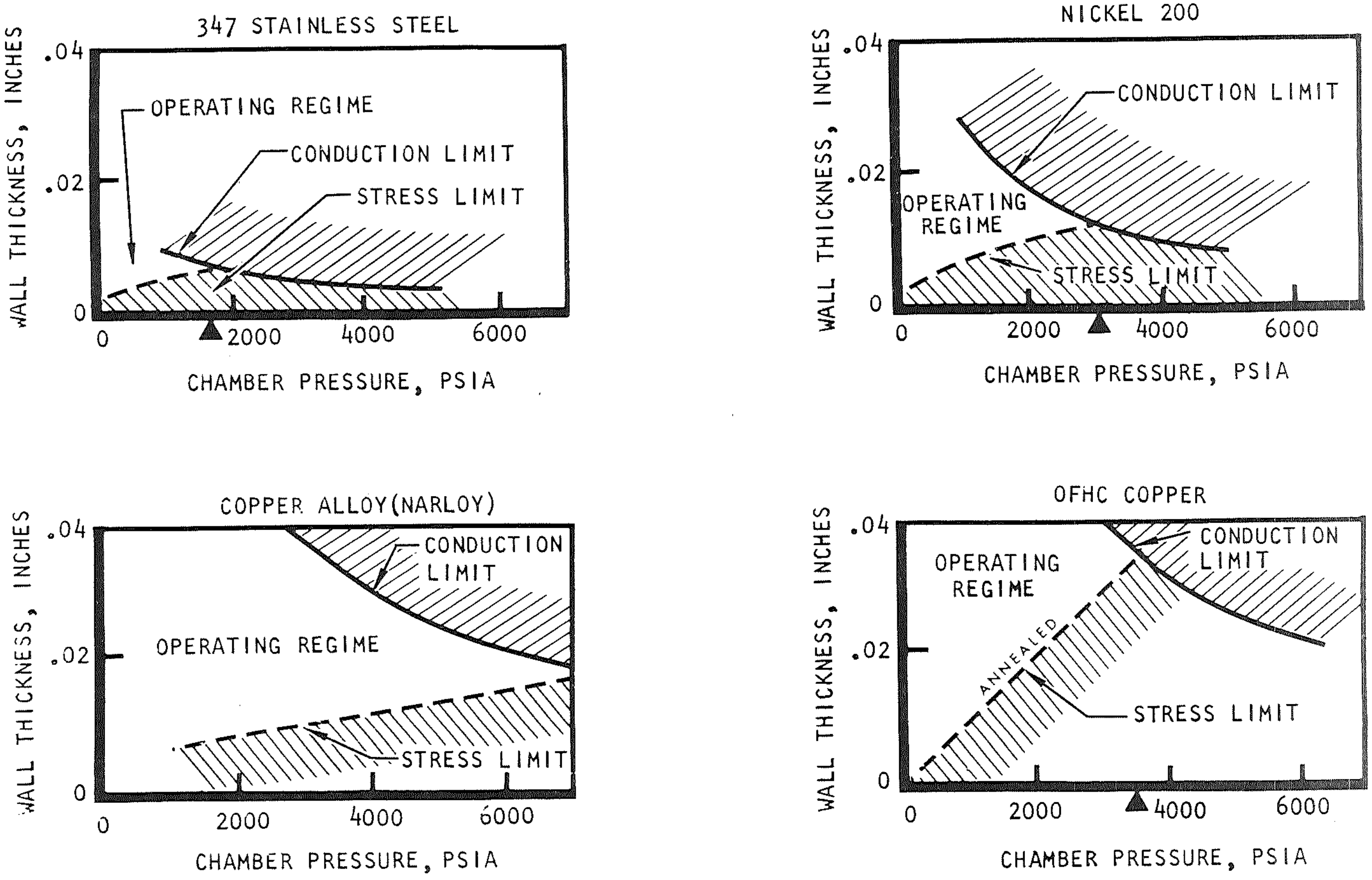
COOLANT	DENSITY (LB_M/FT^3)	SPECIFIC HEAT (BTU/LB_M-^oR)	COOL. TEMP. RISE RATING RELATIVE TO H_2 (%)	PRESSURE DROP RATING RELATIVE TO H_2 (%)
H_2	2.2	3.50	100	100
H_2O	62.4	1.00	29	42
N_2H_4-UDMH (50-50%)	55.5	0.70	20	38
RP-1	52.0	0.44	13	34
CH_4	27.8	0.80	23	61
O_2	20.0	0.32	9	17

ALLOWABLE REGENERATIVE COOLING REGIMES

The effect of the material properties on the allowable regenerative cooling operating regimes is indicated in this figure. Four thrust chamber materials are analyzed in terms of the conduction and stress requirements. The conduction limit represents the maximum wall thickness, which if exceeded will result in excessive wall temperature and/or high coolant pressure drops. Conduction limits are based on a 400°F coolant side wall temperature (typical of the SSF throat). A maximum gas side wall temperature of 1000°F was used for the two copper materials, and 1400°F was used for nickel and stainless steel. The stress limit line represents the minimum wall thickness, which is necessary for structural integrity. Stress limits are based on conservatively designed channel thrust chambers. Yield strengths utilized are consistent with the previous chart.

The figure clearly indicates that stainless steel and nickel are unacceptable candidates for high chamber pressure operation. OFHC copper and copper alloys are the appropriate materials for high chamber pressure operation. Annealed OFHC copper can achieve chamber pressures approaching 4000 psi. Higher pressures can be obtained by strength improvements to the copper. Because of its high strength and high thermal conductivity the copper alloy (NARloy) can be operated at extremely high chamber pressures.

ALLOWABLE REGENERATIVE COOLING REGIMES

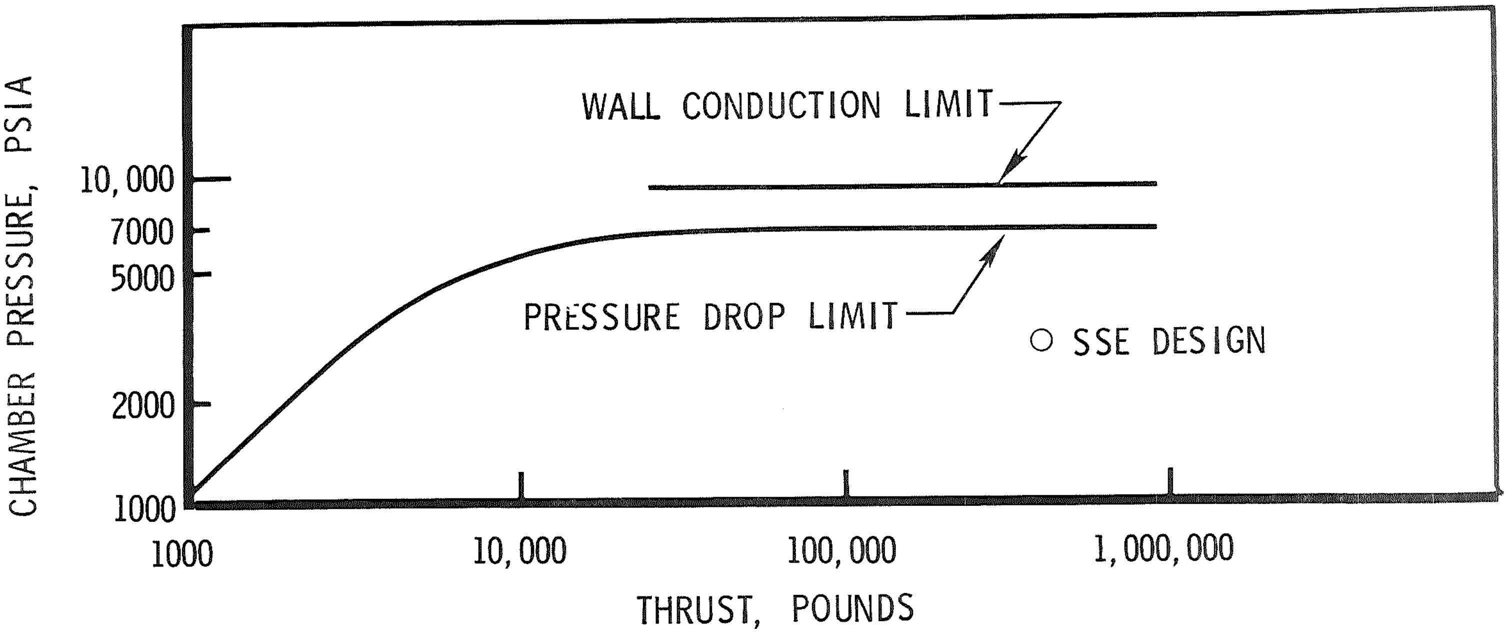


O_2/H_2 REGENERATIVE COOLING FEASIBILITY LIMITS

The combined potential of the hydrogen coolant and the copper alloy (NARloy) material is illustrated in this figure. It is evident that the Space Shuttle Engine design point is well within the capabilities of regenerative cooling. In general, regenerative cooling becomes easier as the thrust level increases. At high thrust the difference between the wall conduction limit, which represents an ultimate limit, and the pressure drop limit, which represents a practical constraint becomes minimal. The pressure drop limit line represents a coolant pressure drop equal to one-tenth of the chamber pressure.

O_2/H_2 REGENERATIVE COOLING FEASIBILITY LIMITS

COPPER ALLOY (NARloy)
T_{wg} = 1000 F



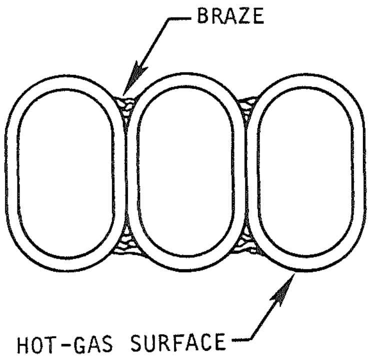
CONSTRUCTION METHODS

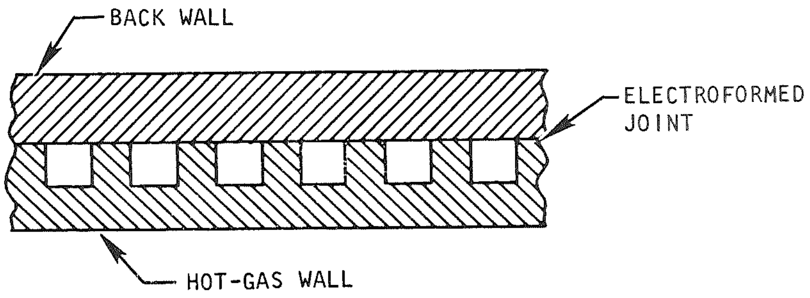
Durable and economical fabrication methods are necessary for a suitable Space Shuttle Engine design.

Although tubular thrust chamber designs are feasible, tubular construction does not take full advantage of high conductivity materials. Tubular construction has been used almost exclusively for nickel and stainless steel chambers.

A far more preferential technique is channel construction. In the channel construction method the coolant passages are formed by channels fabricated on the outer periphery of a chamber liner. The channel construction offers the advantages of having a smooth hot gas wall thereby reducing the heat load and since the channels themselves are machined, the flow areas can be closely controlled. The structure is rugged and durable. One of the chief advantages is the fact that channel construction takes full advantage of the high conductivity of the thrust chamber wall material. Flow or area variations in any single channel are negated by conduction of heat to the adjacent channels.

CONSTRUCTION METHODS





TUBULAR CONSTRUCTION

- LIGHT-WEIGHT
- EXTENSIVE FABRICATION EXPERIENCE
- LITTLE CONDUCTION BETWEEN TUBES

CHANNEL CONSTRUCTION

- SMOOTH HOT-GAS WALL (REDUCED HEAT LOAD)
- CONDUCTION BETWEEN CHANNELS
  - TOLERANCE TO FLOW VARIATION
  - TOLERANCE TO FABRICATION VARIATIONS
- CHANNEL FLOW AREA CAN BE CLOSELY CONTROLLED

RECENT ROCKETDYNE REGENERATIVE COOLING CONTRACTS

The application of regenerative cooling to the Space Shuttle Engine is based on the results of numerous NASA and Air Force studies which have advanced the regenerative cooling technology. The attached figure lists recent contracts associated with regenerative cooling that have been conducted at Rocketdyne. Additional studies have been conducted at other companies and within the NASA and Air Force centers. The documentation is quite extensive, however the security classification of these studies varies.

The results of these studies have demonstrated the capability of regenerative cooling over a wide range of chamber pressures. The advanced construction techniques have been demonstrated and the capability of hydrogen as an exceptional coolant has been verified. Extensive data have also been gathered on the ability of regenerative cooled chambers to achieve a large number of re-used cycles. The following charts present some of these data.

RECENT ROCKETDYNE REGENERATIVE COOLING CONTRACTS

ENGINE APPLICATIONS	TECHNOLOGY
NAS8-19541	NAS8-20349
NAS8-5604	NAS3-11191
NAS8-19	NAS7-65
NAS8-26187	NAS7-715
AF04(611)-11617	NAS8-4011
AF04(611)-11399	AF04(694)-110
AF04(611)-9721	AF04(611)-10916
AF04(645)-2	AF04(611)-67C-0093
DA-04-495-ORD-53	AF04(611)-68C-0061
DA-04-495-ORD-803	AF04(647)-171

COOLANT ENHANCEMENT FACTORS

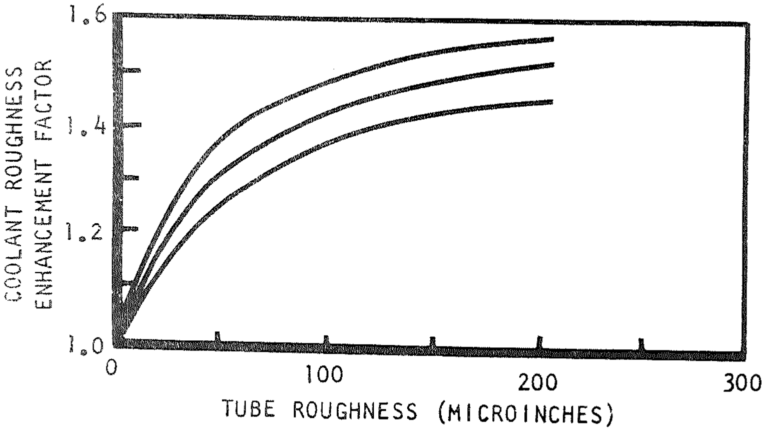
During the technology studies several factors have been isolated which enhance the hydrogen coolant capabilities. These factors are wall roughness and coolant passage curvature. The roughness enhancement is a factor of surface roughness, passage dimensions, and Reynolds number. The roughness enhancement has been demonstrated experimentally and is shown on the adjoining chart for three values of coolant mass velocity.

Curvature enhancement occurs wherever a bend in the coolant passage exists. Enhancement is highest at the outside of the curve and lowest on the inside surface. This enhancement has been experimentally verified in both tubular and channel passages. The enhancement is primarily a function of the turning angle.

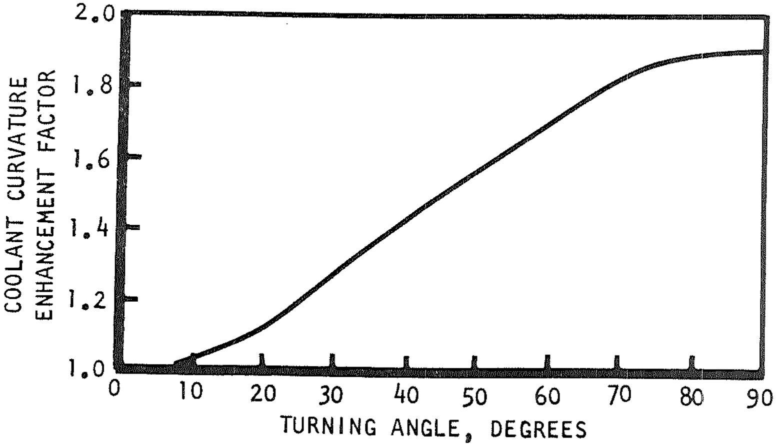
By proper use of these enhancement factors, the cooling capability of hydrogen can be more than doubled in the high heat flux regions of the chamber and coolant pressure drop requirements can be minimized. This advanced technology has been incorporated into the design of the Space Shuttle rocket engine.

COOLANT ENHANCEMENT FACTORS

ROUGHNESS



CURVATURE



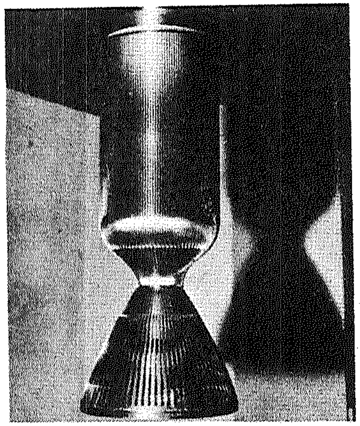
THRUST CHAMBER CONSTRUCTION

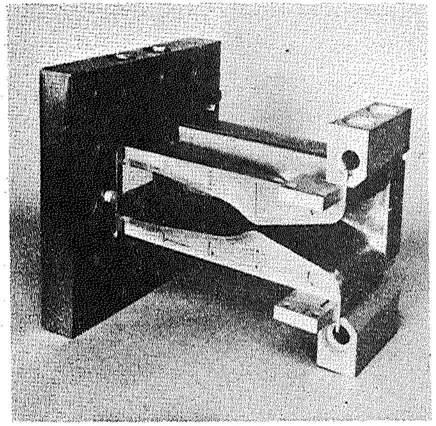
New fabrication techniques and materials have been developed for thrust chambers which offer simplification in fabrication and improved regenerative cooling capabilities. Experimental programs have proven these designs in hot-firing test series.

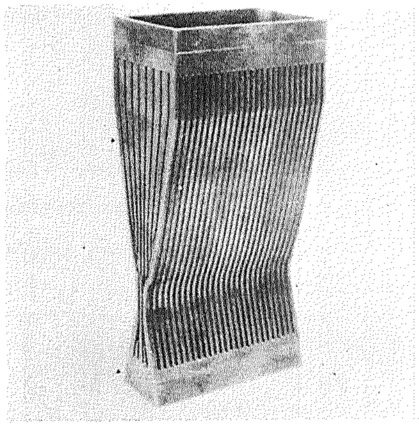
The sequence for fabrication is first to fabricate the thrust chamber liner and form grooves on the outside of the liner. These grooves are then filled, the chamber is coated with a striking agent, and a closeout wall (generally electroforming) is applied to cover the entire liner. The final step in the formation of the coolant passages is to melt the filler out.

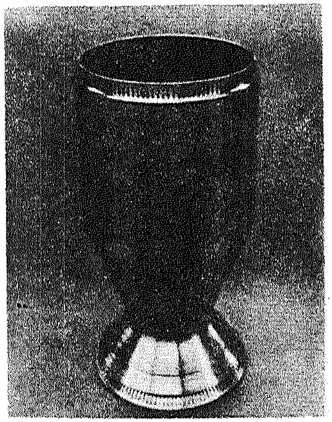
Thrust chambers have been constructed in this manner using liners fabricated from powdered metallurgy, metal spinning, machined from billets, completely electroformed and castings. (In the cast designs, the grooves are cast integral with the basic liner eliminating the need for machining the grooves). Hot firing tests on these chambers have demonstrated the feasibility of these fabrication methods, and their regenerative cooling capability.

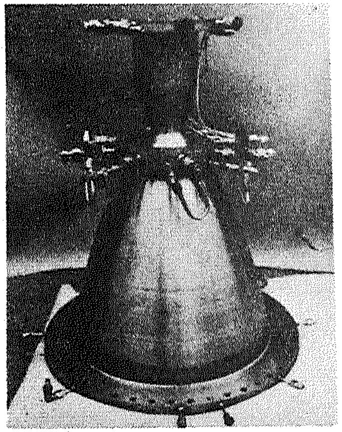
THRUST CHAMBER CONSTRUCTION
NON TUBULAR WALL

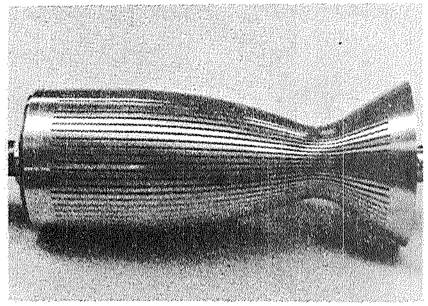

Cu, MILLED CHANNEL WALL
ELECTROFORMED CLOSEOUT


Cu, MILLED CHANNEL WALL
BRAZED CLOSEOUT


NARloy, CAST CHANNEL WALL
ELECTROFORM CLOSEOUT


NICKEL, MILLED CHANNEL WALL
ELECTROFORMED CLOSEOUT


NICKEL, MILLED CHANNEL WALL
ELECTROFORM CLOSEOUT (CHAMBER/NOZZLE)


INCO 625 SPUN LINER
MILLED CHANNEL WALL
ELECTROFORM CLOSEOUT

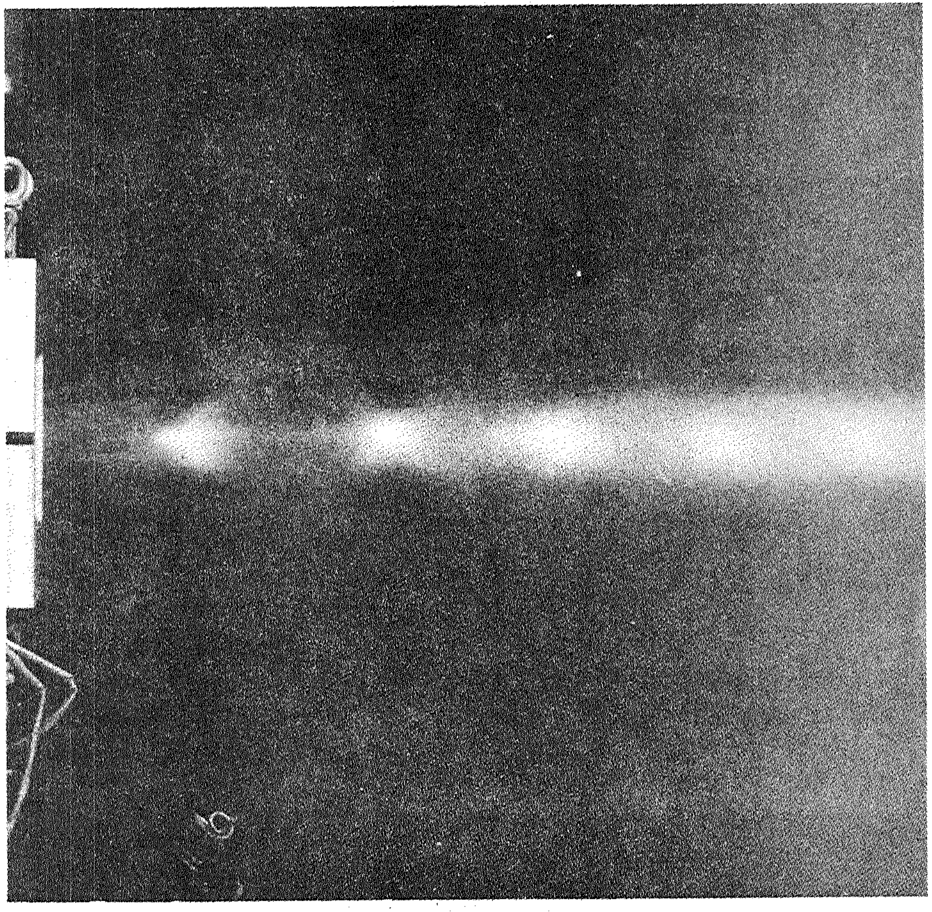
EXTENDED LIFE DEMONSTRATION

Extended life testing to demonstrate the long-life characteristics of regeneratively cooled channel wall thrust chambers has been conducted. Test results have verified the durability of these designs. A regeneratively-cooled chamber was fabricated using copper alloy wall material and electroformed nickel. Five hundred and sixteen hot-firing tests were conducted on this combustor with no hardware damage. The propellants used were oxygen-hydrogen; combustion gas temperature was over 6100°F. Regenerative cooling was used to control the hot gas wall temperature to a maximum of 1000°F.

During each test in the series, the thrust chamber was subjected to a complete thermal cycle. The temperature of the thrust chamber wall varied from the inlet temperature of the hydrogen coolant, to the hot gas design wall temperature (1000°F).

Throughout the test series the combustor remained in excellent condition. The combustor is capable of continued testing.

EXTENDED LIFE DEMONSTRATION
NON TUBULAR WALL THRUST CHAMBER



DESIGN

- O_2/H_2 PROPELLANTS AT MR: 6.0:1
- H_2 REGENERATIVE COOLING
- COPPER ALLOY MATERIAL (NARloy)
- HOT GAS WALL TEMPERATURE: 1000°F (MAX)

TESTING

- 516 TESTS COMPLETED
- THERMAL CYCLE - H_2 COOLANT INLET TEMPERATURE TO DESIGN HOT GAS WALL TEMP.

SPACE SHUTTLE REQUIREMENTS

In conclusion, the Space Shuttle Engine must provide high performance in a compact configuration. It must be capable of long life operation. Regenerative cooling enhances the ability of the Space Shuttle Engine to meet these requirements.

SPACE SHUTTLE REQUIREMENTS

- PERFORMANCE
- HIGH PRESSURE
- LIFE