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Shelley, J.S.; LeClaire, R.; Nichols, J., "Metal Matrix Composites for Liquid Rocket Engines"

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Metal Matrix Composites for Liquid Rocket Engines

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Summary

This article presents an overview of current research and material requirements for Metal Matrix Composite (MMC) technologies being developed for application to Liquid Rocket Engines (LRE). Developments in LRE technology for the US Air Force are being tracked and planned through the Integrated High Payoff Rocket Propulsion Technologies Program (IHPRPT). Current efforts and research requirements for three types of MMC systems are discussed: Aluminum, Copper, and Nickel matrix material systems. Potential applications include turbopump housings, rotating machinery, and high stiffness flanges and ductwork.

Introduction

Liquid rocket engines are just beginning to capitalize on improvements in materials and process technologies that have made significant impacts on the performance of aircraft and stationary power generating turbines. Turbine inlet temperatures of jet aircraft engines have increased by over 160% since 1955.[1] The development of new alloys and improved casting technologies, changing from polycrystalline alloys to directionally solidified single crystals, has been responsible for 120°C (250 °F) of that temperature increase through increased temperature capability of jet engine turbine blade materials. In its drive to reduce emissions, increase efficiency, and reduce maintenance load, the electrical power generating industry, through a DOE consortium, has been developing ceramic materials. By the end of 1999, SiC/SiC combustor liners with environmental barrier coatings had survived 8000 hours of field testing, cutting NO_x emissions by 40% and CO emissions by 80%.[2] The liquid rocket engine industry wants to enable similar system level performance improvements through the application of new materials and processing technologies.

The Integrated High Performance Rocket Propulsion Technology Program (IHPRPT) has established performance improvement goals for rocket propulsion through 2010. A working group of IHPRPT, the Materials Working Group (IMWG), was established in 1997 to help guide the insertion of new materials technologies into rocket propulsion. All advancements in liquid rocket engines can be measured by improved thrust-to-weight (or increased specific impulse, thrust achieved divided by weight flow rate of propellant consumed), increased reliability, and decreased cost. In the past, these areas have been inextricably connected in that advancing one area has typically involved a compromis~~ing~~ in the other two areas. For example, increased performance could be achieved, but only with a concomitant increase in cost and decrease in reliability. Of course, an optimum advancement would allow a simultaneous increase in performance, reliability, and a decrease in cost. The government currently has the IHPRPT program in place in an attempt to achieve just such simultaneous and optimum advancements. IHPRPT is a joint DOD, NASA, and industry effort managed by the Air Force Research Laboratory and divided into three phases of improvement demonstration.

IHPRPT phase II goals are to be demonstrated through component-level tests in 2005. Some of the goals to be demonstrated are a thrust-to-weight increase of 60%, cost reduction of 25%, and a Mean Time Between Replacement (MTBR) of 60 missions. These overall goals are broken down into component level objectives for weight reduction and increased performance. Approaches to meet objectives combine evolutionary engineering improvements, engineering design changes, and advanced materials insertion. Materials technologies can influence both evolutionary design improvements and enable new engine technologies. Evolutionary improvements include reducing weight of ducting, bellows, and flanges, improving performance of cryogenic fuel pumps, and decreasing the weight of nozzle and exit cone structures. Two new technologies need materials and process technologies to be fully developed. The full-flow engine cycle and transpiration cooling concepts have existed as design concepts for years, but need high temperature oxidation resistant materials and finely controlled porous materials, respectively, to enable their demonstration. The following sections detail the design requirements and operational environments in LREs, then discuss specific MMC materials technologies currently under consideration.

Liquid Rocket Engine Overview

The purpose of the liquid rocket engine (LRE) is to accelerate a mass to overcome gravity or change orbital velocities.[3] LREs generate acceleration by converting the chemical energy from fuel and oxidizer in the propellants to kinetic energy of mass flow through the nozzle. On the Space Shuttle Main Engine (SSME), for example, this energy conversion process involves pumping large volumetric flow rates of cryogenic propellants (443 kg/sec (975 lbs/sec)) of LOx and 74 kg/sec (162 lbs/sec) of LH_2 to extremely high pressures (48 MPa (7000 psi)), and combusting the propellants to transform their chemical energy into thermal energy at a temperature of 3300 °C (6000 °F).[4] The combustion products are then accelerated through a converging-diverging nozzle to transform their thermal energy into orderly kinetic energy exiting the nozzle at very high velocities to produce thrust (2 MN, 0r 470,000 lbs). **(Insert pretty picture of the SSME)** The example of the space shuttle main engine illustrates the two major taxonomies in the rocket engine for which IHPRPT is tracking performance improvements.

The two taxonomies are Propellant Management Devices (PMDs), and Combustion and Energy Conversion Devices (C&ECD). PMDs include the propellant pumps and the turbines that drive them, and ducting ~~and regenerative cooling devices~~. C&ECD hardware includes the propellant injection system, main combustion chamber, nozzle, exit cone, and other combustion devices such as the preburners and gas generators necessary to drive the turbines.

The specific components, arrangement of components, and environments endured by those components depend on the power cycle of the engine. The power cycle of the engine is named for both the flow path the propellants follow and the disposition of the propellants downstream of the power turbines. There are two general classes of power cycles in the rocket engineer's world: open and closed.[5] In an open cycle, the spent turbine gases are exhausted either directly overboard or downstream of the nozzle throat. Such a disposal method allows a greater pressure drop across the turbine, but the rocket engine suffers a performance loss because this mass of turbopump drive propellants is not accelerated to the same velocity as the rest of the propellant exhausted through the main combustion chamber. To reduce the performance losses as much as possible, it is desirable to attain the highest practical turbine inlet temperature. This temperature is always limited by the capability of the turbine materials. The huge F-1 and cryogenic J-2 rocket engines used on the Saturn-5 launch vehicle are examples of an open cycle called the gas generator cycle. **Figure X (insert a figure here)** is a flow schematic illustrating ~~the power cycle of a~~ gas generator cycle in which the turbine drive energy is produced by combusting a small quantity of propellants exclusively used to power the turbopump.

The closed cycle is so called because all the rocket propellants are exhausted through the main combustion chamber. There are several methods for adding energy to the turbine drive fluid while still combusting all of the propellants. Two of the closed engine cycles currently in use are the staged combustion cycle and the expander cycle. The SSME is an example of the staged combustion cycle engine, which uses a hydrogen rich steam as the turbine drive fluid. **Figure X (insert a figure here)** illustrates a flow schematic for a staged combustion cycle in which a small preburner partially combusts a portion of the fuel and oxidizer, then the turbine exhaust fluid is sent to the combustion chamber with the rest of the propellants and all propellants achieve the maximum nozzle exhaust velocity. The second type of closed cycle is the expander cycle which uses forced convective cooling of the combustion chamber with one of the propellants to provide a high-energy turbine drive fluid. While most rocket engines employ regenerative combustion chamber cooling, only the expander cycle uses this heat exchanging technique to provide turbine drive energy without additional combusting devices. Because no additional combustion is employed, expander cycle engines have the lowest turbine inlet temperatures. Figure X (insert a figure here) illustrates a flow schematic for an expander cycle engine.

Variants of the aforementioned engine cycles also exist. One variant which is an engineering design change currently under development is the full flow staged combustion cycle. In the full flow engine cycle, the fuel turbopump is driven with a fuel rich steam and the oxygen turbopump is driven with an oxidizer rich steam. **Refer to figure X (insert a figure here)** for a flow schematic for a full flow staged combustion cycle engine. In contrast, the staged combustion cycle used on the SSME drives both the fuel and oxidizer turbopumps with hydrogen rich steam. The oxidizer rich environment is a difficult environment in which to operate because ignition and sustained combustion are likely if materials are not properly selected. Nonetheless, some materials have been identified which perform suitably in this oxidizer rich environment for ducting, turbines, and turbine housings. Development of materials with higher specific strengths and higher temperature capability suitable for application in this hot oxidizer rich environment would enable both weight reductions and performance gains in full flow cycle engines.

In current design practices, the rocket industry prefers to use strengths-of-materials based design methodologies and ad hoc failure criteria, even for critical components. As with other industries, fracture mechanics and probabilistic structural design methodologies are applied only in specialized circumstances. While high and low cycle fatigue have often been considered as design drivers for turbine components, time-dependent failure modes such as thermal cycle induced creep and environmental cracking are relatively new to the rocket community with the advent of reusable rocket engines like the SSME. For that reason, the rocket industry tends to select materials for use in a specific application based on the results of specific tests. The uniaxial tensile tests result in not only yield and ultimate strength information, but also a strain-to-yield, or strain-to-failure, value, which is referred to as ductility. Ductilities greater than 6% are desired for the strength-of-materials design approach to result in a conservative structural design. Ductilities as low as 3% are acceptable in particular cases. Because of the extreme environments to which rocket components are subjected, materials are frequently selected for use based on properties other than strength or ductility. Oxygen compatibility, hydrogen embrittlement resistance, fatigue strength, joinability, or high thermal conductivity are some of the other driving parameters for material selection for specific components.

Having created a framework of rocket engine components and requirements, the remainder of this paper will discuss specific material systems currently under development for application to rocket components. Where possible, material property requirements to meet Phase III IHPRPT goals have been estimated and driving parameters discussed.

Aluminum Metal Matrix Composites

The rocket industry is turning to Al MMCs primarily to reduce weight of structural components. The potential applications of Al MMCs are numerous throughout the engine, but basically fall into three categories: stiffness driven components, "warm" temperature applications, and cryogenic applications. Stiffness driven components include flanges, thrust chamber jackets, and support structures. These components transfer loads from one structure to another through both bonded and bolted joints. While not in direct contact with either hot combustion products or cryogenic propellants, these components tend to be subjected to moderate thermal and chemical environments. Current systems use nickel-based superalloys in these applications for both high stiffness and compatibility with mating surfaces. The driving parameters for materials for use in these applications are high stiffness (moduli greater than 220 GPa (32 ksi) are desired), weld or braze-ability, physical compatibility with dissimilar materials, and bearing strength in bolted joints. Near net shape processing techniques which are capable of fabricating generally axisymetric (sp?) shapes with multiple radii of curvature are necessary. Secondary thermal processes such as brazing and welding are commonly used during subassembly fabrication. Ceramic particulate and discontinuous fiber reinforced Al MMCs are being developed for these applications. MMCs with inserts and mixed reinforcement types (particulate, chopped fiber, and continuous fiber) are desired for these applications to functionally grade a welded interface to a stiff bolted joint. Methods of joining MMCs and dissimilar materials also require development.

"Warm" temperature applications for aluminum ~~Al~~ MMCs are considered high temperature applications for aluminum, but moderate temperature environments in rocket engines. Turbine rotating components, stationary elements, and housings in expander cycle engines run at temperatures up to 260 °C (500 °F). "Warm" propellant ducting and backup structures also operate in this thermal environment, but at lower stress levels. Rotating machinery has the most severe requirements in this area with the material strength requirements for single stage pump designs pushing 862 MPa (125 ksi). These components are directly exposed to (usually) hydrogen-rich turbine drive gases and require both creep and fatigue resistance. Nickel-based superalloys are currently used for these components. There is a desire to move away from expensive machining of forged billets for these components, however, extremely complex shapes with good surface finishes are required.

Complex shapes with smooth interior surfaces are also needed for cryogenic pump components. Housings, inducers, impellers, and stationary guide vanes must operate at the -253 °C ~~(-485 °F)~~ -423°F, check °C temperature of liquid hydrogen. Meticulous design practices are employed to account for varying shrinkage between components during cool down to maintain tight tolerances and carefully engineered flow paths. Hydrogen compatibility is required along with fatigue resistance. Forged and machined titanium alloys are currently used for these components because of their good properties at low temperatures. Strengths in the range of 1350 MPa (200 ksi), ductilities greater than 6%, and fatigue limits greater than 275 MPa (40 ksi) at temperature with densities less than 4 g/cm^3 (0.14 lb/in^3) are desired to improve on the performance of the current Ti alloys. Low, or controllable, CTEs would allow greater design flexibility. As with other components, near net-shape processing techniques are desired to alleviate the reliance on expensive forging and machining processes.

Current Al MMC material and process development efforts in this area are exploring near-net shape casting techniques, joining to dissimilar metals, preforming techniques aimed at increasing ductility, and functionally grading properties by selective control of preform density.

Copper Metal Matrix Composites

The applications for copper MMCs in rocket engines are more limited than for aluminum MMCs. The two properties of copper which make it attractive as a matrix material for rocket engine components are its oxygen compatibility and high thermal conductivity. Oxygen compatibility is essential for oxidizer PMDs in the full-flow engine cycle described above. In the full flow cycle, the oxygen turbopump housing and ducts will be in direct contact with high-temperature oxygen-rich steam. These applications require strength at temperature and creep resistance as well as oxygen compatibility. To be considered for use in an oxygen-rich environment, a material must not support combustion at 69 MPa (10,000 psi) oxygen, and can not be susceptible to ignition by impact of an 1.5 mm (0.06 in) diameter aluminum particulate in a supersonic stream of oxygen.[6] Operating conditions can be varied to account for material capabilities, but strengths of 413 MPa (60 ksi) are required at 260 °C (500 °F) with densities less than 7.5 g/cm^3 (0.27 lbs/in^3) for some applications. As with Al MMCs, near-net shape processing techniques that create good surface finishes with little machining require development.

Heat conduction applications are primarily thrust chamber liners, either regeneratively cooled or transpiration cooled. While most regenerative cooling schemes require the high conductivity of copper, increased strength, creep, and fatigue resistance are needed to overcome deformation due to thermal cycling stresses. The thrust chamber liner is exposed the 20 MPa (3000 psi) combustion gases on the inner surface and cryogenic propellants on the outer surface where it mates with the structural jacket. The exact material requirements depend on the thrust chamber design. However, the high heat transfer rates required cool the combustion chamber liner have precluded use of copper matrix composites in the past. Previous efforts attempted to develop continuous graphite fiber reinforced copper composites for heat transfer applications; however, fiber wetting and delamination problems could not be overcome at that time. Little effort is currently on going in this area. It is hoped that many of the fabrication and processing techniques developed for aluminum MMCs will transfer to copper MMC technologies with only minor adjustments.

Nickel Metal Matrix Composites and other Materials

The primary driver for development of Nickel based MMCs is the full flow cycle engine. Turbine components require high strength, creep and fatigue resistance at temperature along with oxygen compatibility and corrosion resistance. Nickel-based superalloys are the materials of choice for these components in current development systems. While increased strength, stiffness, and creep resistance may be achieved by creating composites with SiC particles or fibers, oxygen compatibility can not be compromised for components in the oxygen-rich drive gas environment of the full-flow cycle engine. As stated in the section on copper MMCs, to be considered for use in an oxygen-rich environment, a material must not support combustion at 69 MPa (10,000 psi) oxygen, and can not be susceptible to ignition by impact of 1.5 mm (0.06 in) aluminum particulate in a supersonic oxygen stream.[6] As stated in the aluminum ~~Al~~ MMC section, strengths greater than 862 MPa (125 ksi) at temperature are desirable for some turbine designs with material densities less than 6.5 g/m^3 (0.23 lb/in^3). While there are efforts working to improve the oxidation compatibility of nickel-based superalloys ongoing, no efforts investigating nickel MMCs are currently funded.

Injector faceplates and bodies also require oxidation resistance, corrosion resistance, and hydrogen embrittlement resistance at temperature. Injectors meter and direct the flow of propellants into the main combustion chamber. Current systems use cobalt alloys, some of which are actively cooled. While not in direct contact with combustion products, the injector must withstand heat soak from the combustion chamber. Extreme thermal environments and pressures up to 62 MPa (9000 psi) are projected for this component in future engines. Monolithic silicon nitride is being applied to the injector body, but the difficulty of mating the ceramic body to a metallic thrust chamber has not been overcome to permit testing of this ceramic injector. Because of the generally axisymetric shape of the injector body, continuous fiber composites have been suggested for this application, however component mating requirements create challenges for continuous fiber composites. Materials for advanced injector and preburner are not currently being developed.

Where are we headed in the future?

MMCs are considered mid-term material solutions to rocket component needs. On the current IHPRPT roadmaps, components employing MMCs should be demonstrated in 2005 with advances continuing through 2010. In the far term, weight and turbine inlet temperature goals may force the community away from metallic materials and toward ceramics and CMCs. PMCs are currently being studies for application to moderate temperature and chemical environment components. However, ductility requirements, geometric constraints, and environment compatibility needs in rocket engines ensure that metal matrix composites will play an important role in rocket technology development for the foreseeable future.

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[1] J.C. Williams, “Material Requirements for High Temperature Structures in the 21st Century”, *Phil Trans R. Soc. Lond. A*, 351 (1995), pp435-449.

[2] N. Miriyala and J. Price, “Liners Tested 10000 h”, *CFCC News*, 11 (1999), pp1-2.

[3] For discussion see Suton and Ross – ? Need more complete citation.

Public ? Release?

[4] SSME handbook

[5] Huzel and Huang - Need more complete citation - Title, year, etc.

[6] H.D. Beeson, W.F. Stewart, and S.S. Woods, “Safe Use of Oxygen and Oxygen Systems”, ASTM, stock number MNL36 (2000); and ASTM G 125.

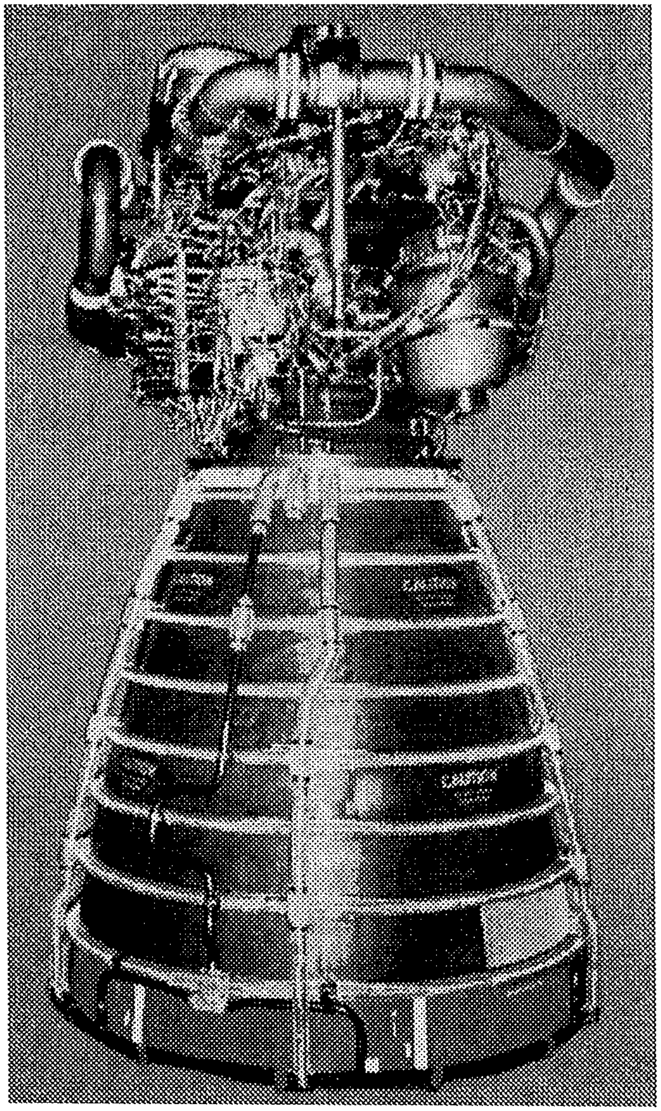
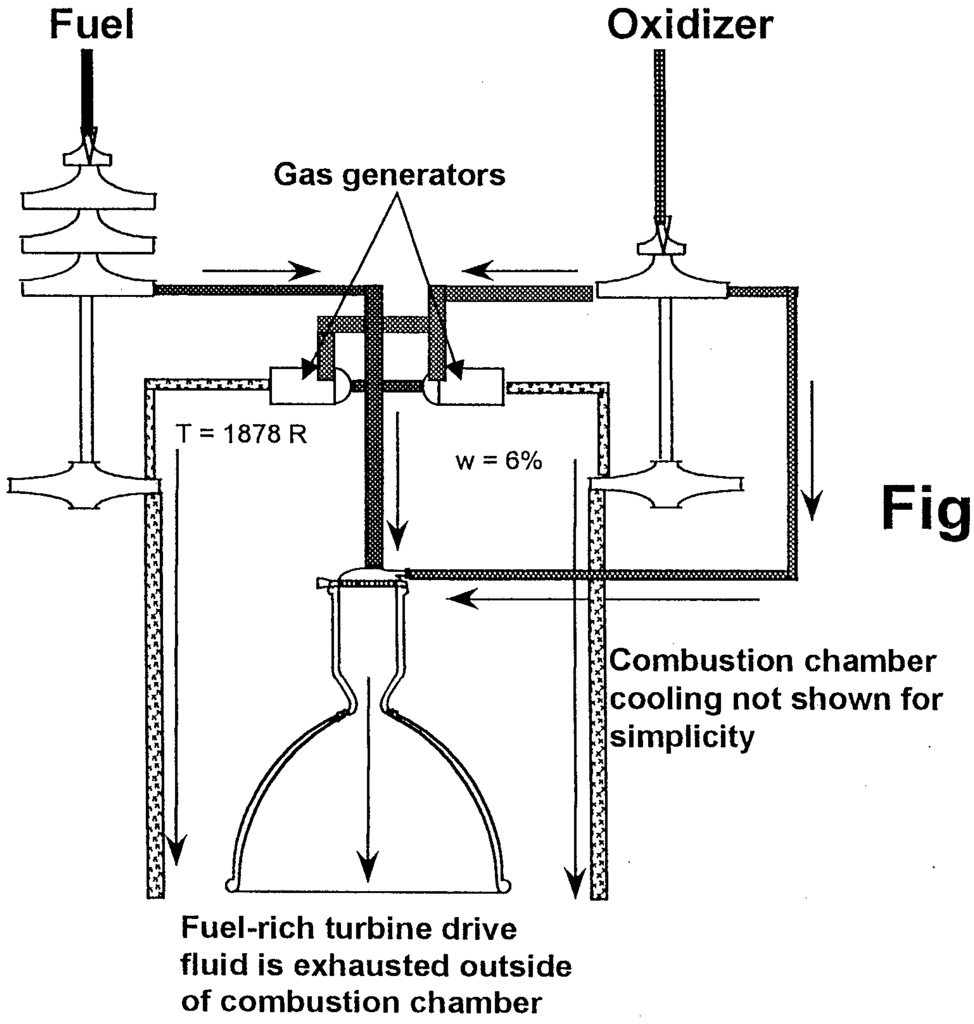


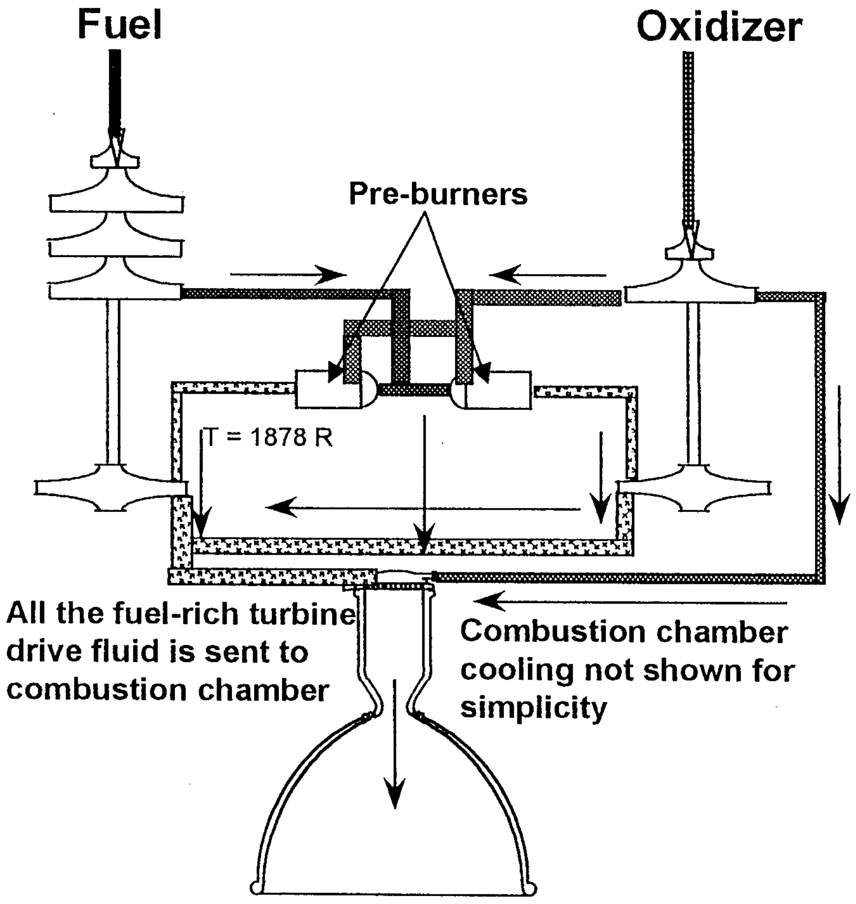
Figure 1. Space Shuttle Main Engine (SSME)



Combustion chamber cooling not shown for simplicity

Fuel-rich turbine drive fluid is exhausted outside of combustion chamber

Figure 2. Gas generator cycle



All the fuel-rich turbine drive fluid is sent to combustion chamber

Combustion chamber cooling not shown for simplicity

Figure 3. Staged combustion cycle

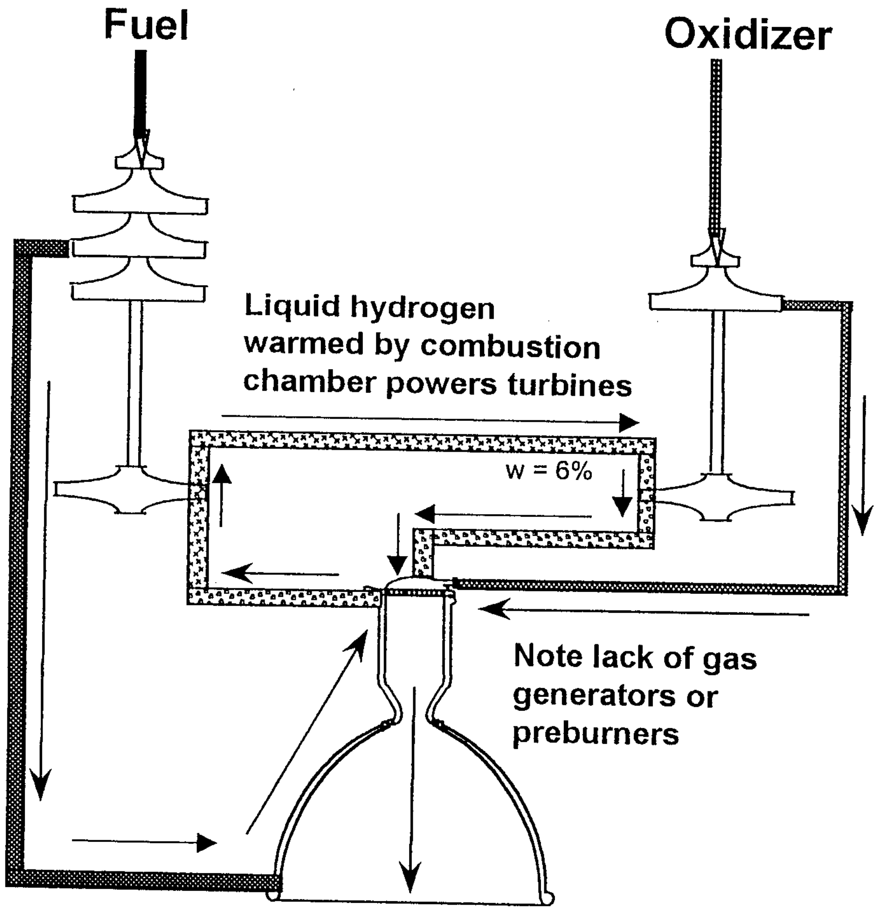


Figure 4. Expander cycle

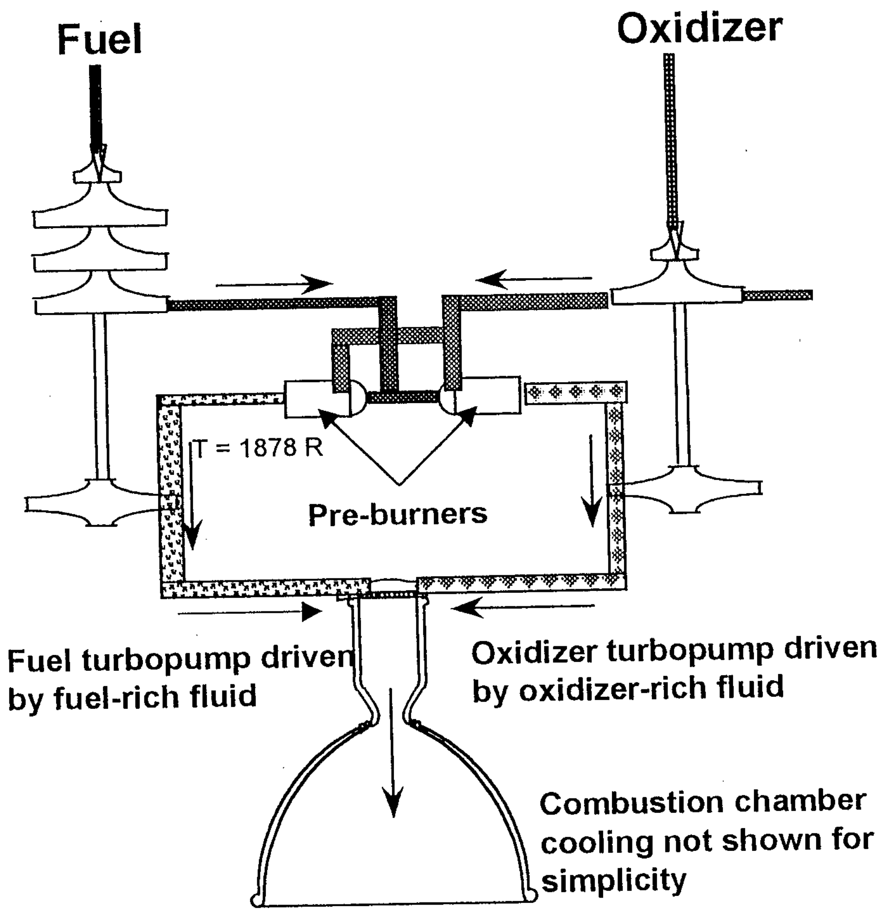


Figure 4. Full-flow staged combustion cycle