9.19.2
LIQUID ROCKET PROPELLANT PUMPS

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Liquid-fueled rocket engines have been used on all the major launch vehicles, including the large, first-stage booster rockets as well as the upper stages of those same vehicles, and various smaller vehicles such as the lunar lander. The propellant pumps are major components of the engine. They pump a) the oxidizer, usually liquid oxygen, and b) the fuel, which is usually liquid hydrogen, up to the high pressures needed to feed the combustion processes. In the past, a widely used fuel was kerosene in a rocket propellant formulation specified as "RP1."

Of necessity, the pumps for these engines must have the minimum possible size and weight. They therefore run at extremely high speeds. Most have inducers or are fed by inducer pumps. These inducers have extremely high suction-specific-speed capability, N_{ss} exceeding 35,400 ($\Omega_{ss} = 13$) and being as high as 70,000 ($\Omega_{ss} = 26$) in liquid hydrogen[1]. This is so because the hydrogen is nearer its thermodynamic critical point and so generates less vapor volume when it cavitates than do other propellants. (See the discussion under "NPSH-Effects" in Section 2.1. All symbols in this subsection are defined in the nomenclature of that Section 2.1.) The main engine propellant pumps have higher heads per stage than any other centrifugal pumps in existence. As such, they are the world's highest-energy pumps, as indicated in Figure 32 and Table 13 of Section 2.1. Whereas the high-energy pump portion of that section is devoted largely to the challenges of designing such machines for long life—say 40,000 hours or more—the life of a rocket engine pump is measured in minutes; or, in the case of reusable rockets, not much more than a few hours. For good materials choices, such a short operating life means that these pumps are unlikely to suffer failure from cavitation erosion or other wear-related phenomena, despite the high inlet tip speeds of the inducers and impellers. Extreme attention to details of the mechanical design is required in order for these pumps to survive at design conditions—near which they generally operate. A few examples of rocket propellant pumps are given in this subsection, but many others also exist in various configurations[1,2].

THE SATURN V BOOSTER ROCKET ENGINES

The Saturn V booster rocket was used in the Apollo program of the 1960s and '70s, which landed men on the moon. This rocket had a vertical height of more than 350 ft (197 m) at launch. The first or lowest stage was the largest and was propelled by five F-1 engines, each producing 1.5 million pounds (6.7 million N) of thrust. Propellants were liquid oxygen and RP1. Each engine was topped by a turbopump assembly that included both pumps on the same shaft and driven by the same hot-gas turbine. A cross-section of this assembly is shown in Figure 1, the two pumps being arranged in a back-to-back configuration and each having an inducer. The RP1 pump is the one next to the turbine, there being a considerably lower temperature difference between RP1 and the hot gas flowing through the turbine from the combustor than there would be for liquid oxygen. At the design speed of 5,490 rpm, the two pumps together consumed 52,700 hp (39 MW)—and considerably more at overspeed (approximately 6000 rpm). Table 13 of Section 2.1 contains performance figures. Essentially the same data are presented in the following descriptions of the pumps, which are summarized in Table 1. The table has been developed from various sources, including the references cited at the end of this section, as well as information supplied by the Boeing Company.

- *The oxygen pump* took in the liquid axially through a 15.75-in (400-mm) diameter inducer at the opposite end of the assembly from the turbine, as seen in Figure 1. Designed for a suction-specific speed N_{ss} of 35,400 ($\Omega_{ss} = 13$) meant that when ingesting 25,080 gpm (1.58 m^3/s) this machine could operate at an inlet static pressure of 22 lb/in^2 (0.15 MPa) above the vapor pressure p_v of the liquid oxygen. Because this liquid is cryogenic, p_v equals the pressure inside the fuel tank of the first stage of the rocket, which was not much above atmospheric pressure. Actually, the g-force and head of liquid in the tankage above the pump combined to provide additional available *NPSH.* This pump, which was designed for a specific speed N_s of about 2,100 ($\Omega_s = 0.77$), consumed

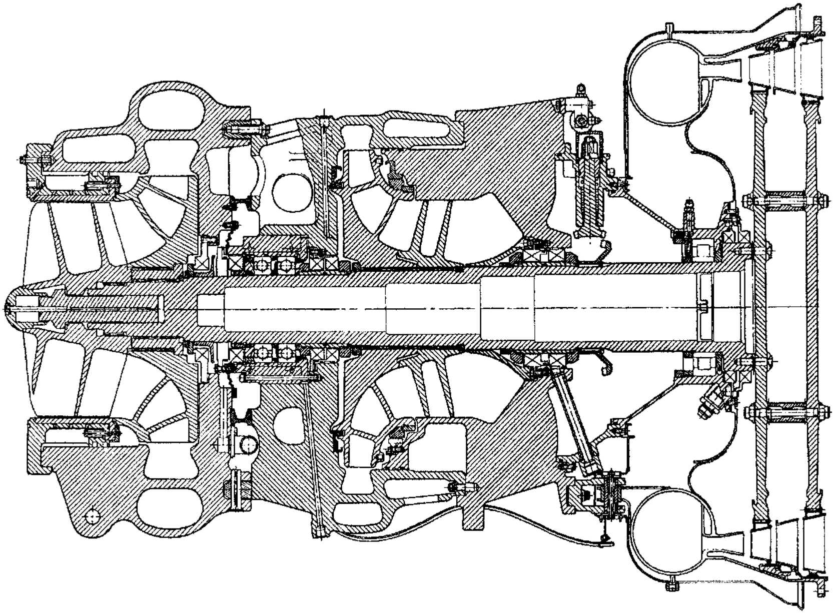

FIGURE 1 F-1 Turbopump assembly, used on Saturn V first stage rocket engine (Courtesy of The Boeing Company)

TABLE 1 Data on liquid rocket propellant pumps*

Parameter	Units	F1 Engine		Space Shuttle Main Engine			
		Oxygen pump	RP1 pump	Oxygen pumps		Hydrogen pumps	
				LPOTP	HPOTP	LPFTP	HPFTP
Shaft power	hp (MW)	30,000 (22.4)	22,700 (19.9)	1,740 (1.3)	27,770 (20.7)	2,900 (2.2)	77,000 (57.4)
Rotative speed	rpm	5,490	5,490	5,450	31,100	15,700	37,400
Mass flow rate	lb/s (kg/s)	3,977 (1,804)	1,762 (799)	964 (437)	1,148 521	161 (73)	161 (73)
Inlet volume flow rate	gpm (m^3/s)	25,080 (1.58)	15,640 (0.99)	6,080 (0.38)	7,240 (0.46)	16,300 (1.03)	16,300 (1.03)
Pressure rise	Lb/in^2 (MPa)	1,530 (10.5)	1,810 (12.5)	332 (2.3)	4800** (33.1)	222 (1.5)	6,840 (47.2)
Head rise (approx.)	ft (m)	3,100 (945)	5,100 (1,555)	670 (204)	9,700 (2,960)	7,240 (2,200)	200,000 (61,000)
Specific speed (stage)	rpm,gpm,ft (universal)	2,095 (0.77)	1,130 (0.41)	3,230 (1.18)	2,700 (0.99)	2,550 (0.93)	1,150 (0.42)
Inducer diameter	in (mm)	15.75 (400)	16.00 (406)	11.725 (298)	4.7 (119)	12.014 (305)	
Impeller exit diameter	in (mm)	19.50 (495)	22.95 (583)		6.80 (173)		12.00 (305)
Overall diameter x length	in x in (mm x mm)	44 x 60 (1,118 x 1,524)		18 x 18 (457 x 457)	24 x 36 (610 x 914)	18 x 24 (457 x 610)	22 x 44 (559 x 1,118)
Turbopump weight	lb (kg)	3,080 1,397		276 (125)	622 (282)	177 (80)	775 (352)

*Compiled from information supplied by The Boeing Company and References 1–5.

**Main stage. Small preburner stage pumps 117 lb/sec (53 kg/s) to approximately 3300 psi (23 MPa) above main stage discharge.

30,000 hp (22 MW) or 57 percent of the total turbine shaft power, and it generated over 1,500 lb/in^2 (10 MPa) of pressure rise.

- *The fuel (RP1) pump*, being in the middle of the turbopump assembly, had to take in the 15,640 gpm (0.99 m^3/s) of RP1 through a side inlet piping configuration, which generally results in less N_{ss}-capability than axial inlet piping. Here the inducer is larger and the flow rate lower than for the liquid oxygen pump, creating the potential for higher N_{ss}; yet it ended up being lower, namely $N_{ss} = 34{,}200$ ($\Omega_{ss} = 12.5$). Nonetheless, this enabled the RP1 pump to operate at a static inlet pressure as low as 16 lb/in^2 (0.11 MPa) above the (negligible) vapor pressure of this liquid. With specific speed N_s just over 1,100 (0.40), this pump consumed the remaining turbine shaft power of 22,700 hp (17 MW) and generated a pressure rise of just over 1,800 lb/in^2 (12.4 MPa).
- Throughout the burn, these pumps deviated no more than about 8 percent from the design value of Q/N; that is, the flow coefficient was essentially constant. Thus, this turbopump

did not suffer from the off-design low-flow conditions of most commercial, industrial pumps, as described in Section 2.1 and Subsection 2.3.2, including those of high energy level, which made it a little easier for this machine to operate at high energy levels.

THE SPACE SHUTTLE MAIN ENGINES

The space shuttle program, which began in the 1970s, dealt with a launch vehicle that was flanked by two large solid-fueled rockets. In the middle at the base were three liquid-fueled "main" engines, each having nearly 500,000 lb (2.2 million N) thrust and propelled by hydrogen fuel and oxygen at a mixture mass ratio of 6:1 (oxygen to hydrogen). Each of these space shuttle main engines (SSME's) has a dedicated pumping system, consisting of a low-pressure single-stage inducer-type pump for each propellant, which in turn feeds a high pressure pump. Three of these four pumps can be seen in the photograph of the engine in Figure 2. Located up above is the low-pressure hydrogen pump, with its large discharge line going off to the right and down to the high-pressure hydrogen pump below. Opposite, on the left, is the high-pressure oxygen pump, with its large inlet line also in view. Engineering of these high-pressure propellant pumps embodied a triple challenge in comparison to the F-1 pumps, because a) this engine was designed to be re-used, so the pumps had to have a life of 7.5 hours with 100 starts; b) the pumps for this engine have higher energy levels than the F-1 pumps, and, c) due to the mission profile, they have to be throttled back further from the design point. Each of these pumps is boosted by a low-pressure inducer-type pump to suppress cavitation enough to maintain performance[3].

The propellant flow system is illustrated in the schematic diagram of Figure 3. (The pump speeds, pressures, and flow rates shown in this figure are somewhat lower than the design conditions of Table 1, which for the SSME pertains to the maximum engine thrust level.) All four of the pumps are driven by turbines and so are called "turbopumps." The system picks itself up by its own bootstraps, so to speak; each low-pressure turbopump boosts the flow to the corresponding high-pressure pump and is driven by the same fluid that it pumps. This driving fluid comes back from each high-pressure pump, the low-pressure oxygen turbopump (LPOTP) being driven by recirculated liquid oxygen, and the low-pressure hydrogen or fuel turbopump (LPFTP) turbine being fed by gaseous hydrogen heated by the thrust chamber, as indicated in Figure 3.

The high-pressure pumps are driven by turbines fed by "preburners," which are combustors that burn hydrogen-rich. Some of the fuel entering these combustors is the gaseous hydrogen coming from the LPFTP turbine exhaust, which cools the turbine housings on the way to the preburners. But most of the fuel supplied to the preburners is the 80 percent of the liquid hydrogen discharging from the high-pressure fuel turbopump (HPFTP), which first flows through the cooling passages of the nozzle walls. [Eleven percent of the oxygen is also fed to the preburners by way of the preburner boost stage that is a part of the high-pressure oxygen turbopump (HPOTP) package. Finally, the partially burned fuel passes as a hot gas into the main combustion chamber, where more oxygen is added and the pressure is 3,000 lb/in^2 absolute (21 MPa)[3,4].] Most of the remaining 20 percent of the hydrogen is that which was already described as cooling the main combustion chamber and, along the way, becomes gaseous and powers the drive turbine of the LPFTP. It also cools the hot-gas manifold and injector and pressurizes (in a small amount) the fuel tank. Approximately 75 percent of the liquid from the high-pressure oxygen turbopump (HPOTP) goes directly to the main combustion chamber, 11 percent to the preburners (as already stated), about 13 percent to drive the turbine of the low-pressure oxygen turbopump (LPOTP), and a small amount is sent to pressurize the tank.[5] A brief description of each pump follows:

- *The low-pressure oxygen turbopump (LPOTP)* consumes 1,740 hp (1.30 MW) and runs at 5,450 rpm. It has a single-stage, axial-flow, inducer-type impeller that is 11.725 in (298 mm) in diameter and is driven by a six-stage liquid-oxygen hydraulic turbine. Pump head rise is 670 ft (204 m) so the HPOTP therefore operates without pressure

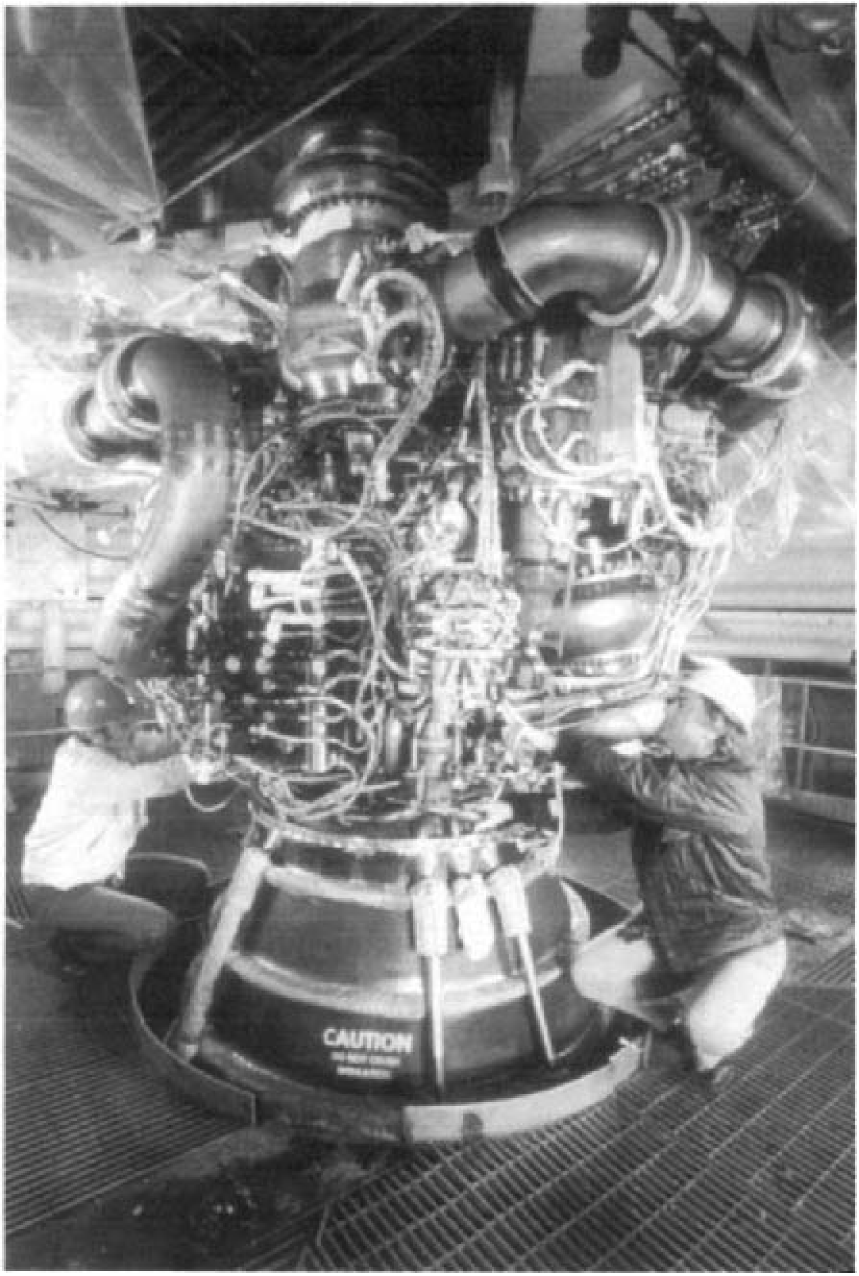

FIGURE 2 The space shuttle main engine (SSME) (National Geographic Magazine, March 1981: Jon Schneeberger/NGS Image Collection)

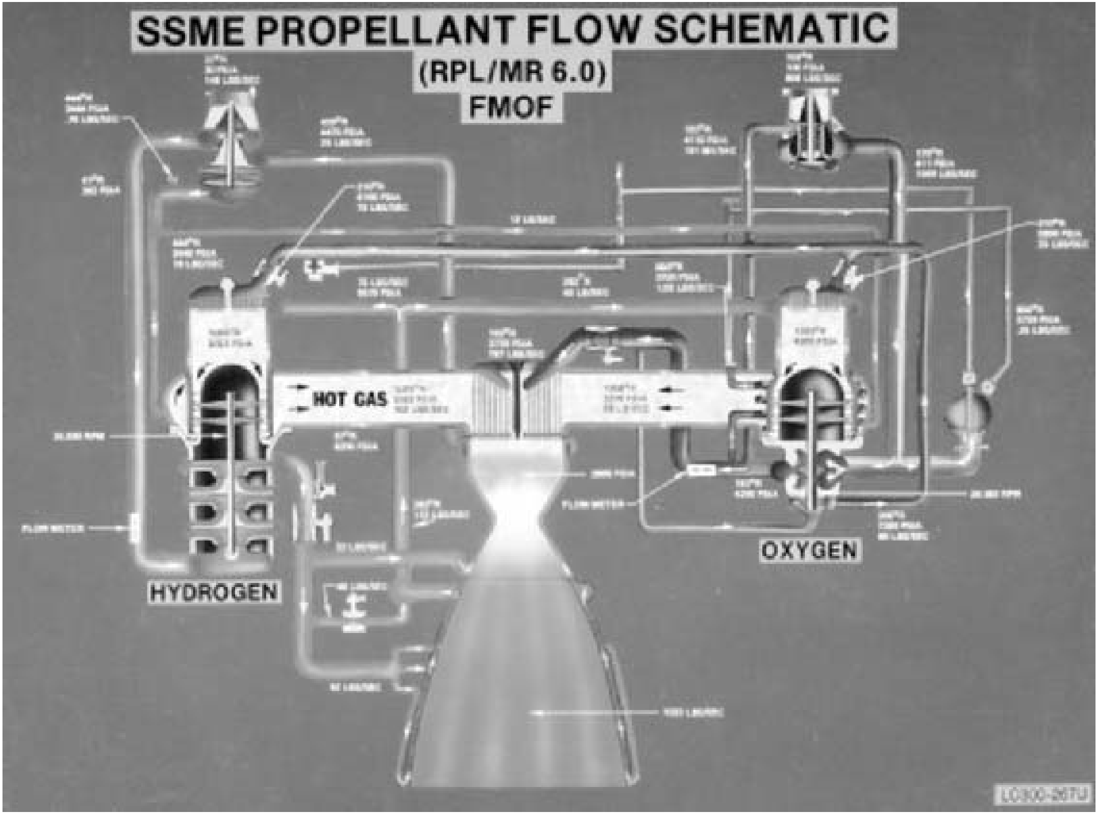

FIGURE 3 SSME liquid oxygen and hydrogen pumping arrangement (Courtesy of The Boeing company)

loss due to cavitation at all engine conditions. Specific speed $N_s = 3{,}230$ (1.18), which is low for an inducer, but this one performs a more substantial pumping task than do inducers running at high speeds on the same shaft as the high-pressure centrifugal stages they feed. The shaft has two ball bearings cooled by liquid oxygen, and the envelope of the package is 18 in (457 mm) in diameter × 18 in (457 mm) long.

- *The low-pressure fuel turbopump (LPFTP)* is similar in concept to the LPOTP. It is a 2,900 hp (2.2 MW) machine that runs at 15,700 rpm. The inducer-type impeller is 12.014 in (305 mm) in diameter and is driven by a two-stage gaseous-hydrogen turbine. It ingests liquid hydrogen to the extent of $\frac{1}{6}$ of the mass flow rate of oxygen. Due to the very low specific gravity of liquid hydrogen (= 0.0708 at atmospheric pressure), the head rise is more than 7,000 ft (2,100 m). $N_s = 2{,}550$ ($\Omega_s = 0.93$). The shaft has three ball bearings cooled by liquid hydrogen, and three seals limit leakage between the pump and the turbine before engine start and during operation.
- Both low-pressure pumps exhibited suction-specific speeds N_{ss} in excess of 35,000 ($\Omega_{ss} = 13$)[4]. They are shown schematically at the top of Figure 3, and the high-pressure pumps are below them.
- *The high-pressure oxygen turbopump (HPOTP)* is shown in cross-section in Figure 4 together with the associated preburner unit. Inducers are shown in the detailed cross-sectional drawing of Figure 5 feeding the double-suction main stage that generates nearly 5,000 lb/in^2 (34 MPa)—making this one of the world's highest-energy pumps (as defined in Section 2.1, Figure 32). And more than 3,000 lb/in^2 (21 MPa) in addition to this pressure is generated in the small booster impeller (on the outer end of the turbopump as seen in Figures 4 and 5) that feeds about 11 percent of the main flow to the preburners for driving both high-pressure pumps. Both shrouds of the main impeller act as orificed balancing disks to keep all but a small preload off the two angular-contact ball bearings, which are cooled by liquid oxygen. Radial loads are minimized by the use of a vaned diffuser. The compact design and high speed (over 31,000 rpm) of this 28,000 hp (21 MW) machine result in operation between the first and second critical speeds. Several seals are utilized,

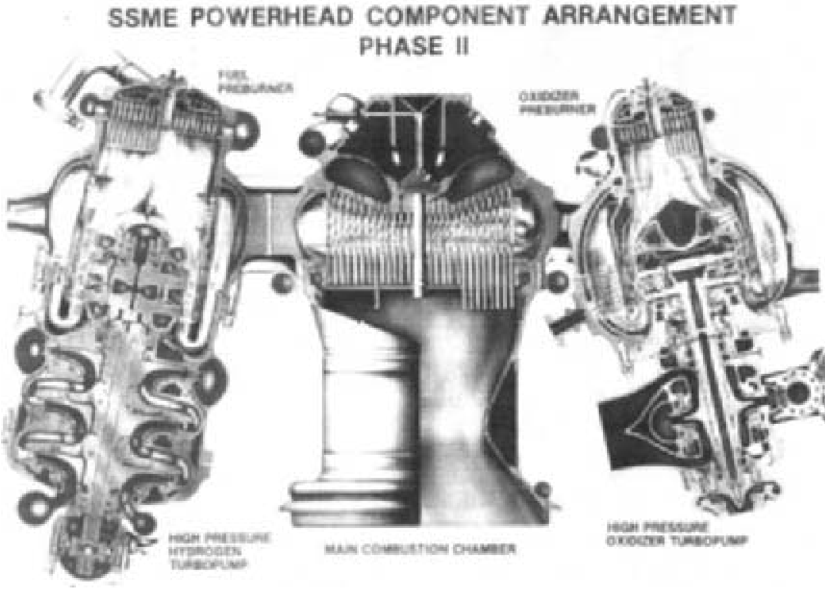

FIGURE 4 SSME high-pressure turbopumps (Courtesy of The Boeing company)

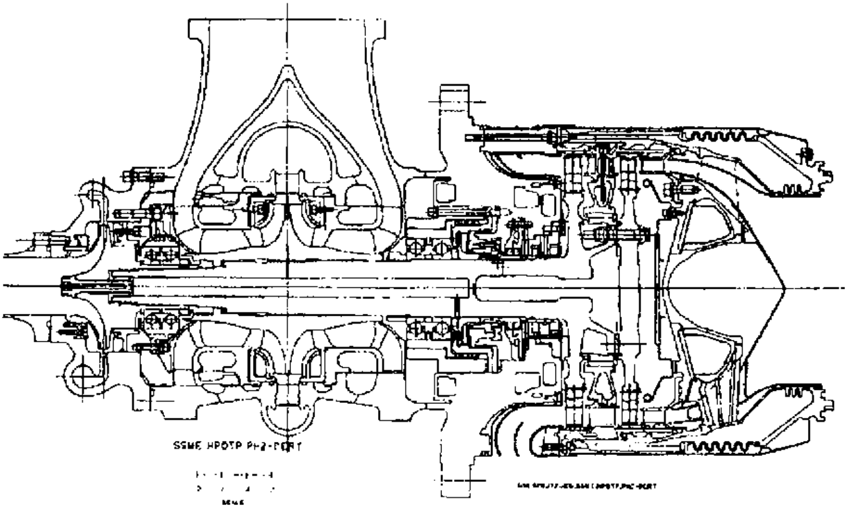

FIGURE 5 Cross-section of SSME high-pressure oxygen turbopump (Courtesy of The Boeing company)

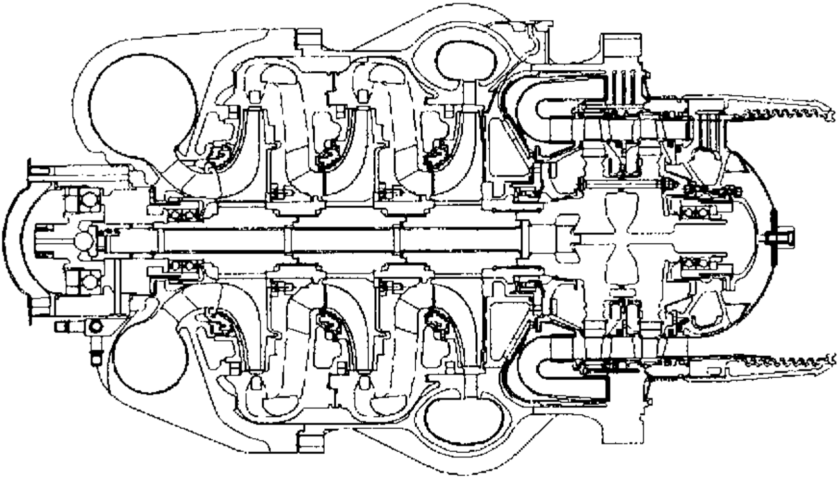

FIGURE 6 Cross-section of SSME high-pressure oxygen turbopump (Courtesy of The Boeing company)

including a helium-purged seal that isolates the hot gas of the turbine from the cold liquid oxygen. Special material combinations are used to prevent sparking, ignition and explosion due to rubbing in the strong oxidizing environment of the liquid oxygen.

- *The high-pressure fuel turbopump (HPFTP)* is also shown in Figure 4. Additional detail is afforded by the cross-sectional drawing of Figure 6. No inducer is needed due to the pressurization of the LPFTP and the more favorable vaporization characteristics of liquid hydrogen. The pump has three identical impellers and diffusers, except that the third-stage diffuser discharges into a scroll or volute, and the third-stage impeller also acts as an orificed balancing disk, which removes all axial thrust (except for a small spring-preload force) from the angular-contact, liquid hydrogen-cooled ball bearings located at each end of the pump-and-turbine package. The head per stage is over 65,000 ft (20,000 m) because of the high pressure rise and low density of liquid hydrogen. This leads to an impeller OD tip speed of nearly 2,000 ft/sec (600 m/s)—probably the highest in existence for a pump and successfully deployed in titanium, which has the benefit of a higher strength-to-weight ratio than the more commonly used steels. The high speed (over 37,000 rpm) keeps this 77,000 hp (57 MW) machine small and light and necessitates operation between the second and third critical speed.

THE RD-170 ENGINE

The RD-170 rocket engine was developed in the Soviet Union and is described in some detail by Sutton[6]. Propellants are liquid oxygen and an RP1 equivalent. Consisting of four nozzles, each of which produces about the same thrust as one SSME, this "four-engines-in-one" configuration is fed by a single propellant pump assembly—similar in concept to the F-1 turbopump. Referring to Table 13 of Section 2.1, the oxygen pump produces a pressure rise of about 8,500 lb/in^2 (59 MPa), which is undoubtedly the highest pressure rise of any centrifugal pump stage in the world, making it the highest-energy pump of Figure 32 in Section 2.1. Not far behind is the RP1 pump at 7,100 lb/in^2 (49 MPa). Assuming the pump efficiency to be 80 percent would yield a total shaft power for both pumps of about 230,000 hp (172 MW). At such high energy levels, as discussed in Section 2.1, the life of this pump must indeed be quite short. However, the design appears to have been successful. The only drawback is the environmental issue concerning the burning of a large quantity of hydrocarbon fuel, which is also an inhibition to further use of the F-1 engine.

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