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SPACE SHUTTLE PROPULSION

by Howard W. Douglass
Lewis Research Center
Cleveland, Ohio

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Howard W. Douglass

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio

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ABSTRACT

The major propulsion systems of the space shuttle presently contemplated by NASA are described. Their characteristics, functions, and status relative to the current technology are discussed. Selected examples are given which are representative of the problems to be solved in the developmental effort required for the shuttle to become a reality.

INTRODUCTION

Students of Latin know well that all Gaul was divided into three parts. Students of shuttle propulsion know that it, too, has three parts: main propulsion, auxiliary propulsion, and airbreathing propulsion (Fig. 1).

1. Main propulsion consists of new high pressure rocket engines for both the booster and the orbiter vehicles. To save on development, manufacturing, and operational costs, engines in the booster and orbiter are to be essentially the same. Since the booster needs much more thrust than the orbiter, the booster will need several times as many engines. Because the orbiter is required to have engine-out flight capability, it must have at least two engines. Thus, the main propulsive systems for both booster and orbiter will comprise multiple engines, clustered for concurrent operation. These rocket engines will be used for launch and flight from earth

to orbit. The booster engines alone will be used for launch. The orbiter engines will perform only in vacuum after separation of booster and orbiter in space.

2. Auxiliary propulsion comprises the multitude of thrusters located throughout the shuttle for use in attitude control and vehicle maneuvering in space. Unlike present attitude control thrusters which are quite small, these shuttle engines will each provide hundreds or thousands of pounds of thrust.

3. Airbreathing propulsion consists of jet engines to be used on both the booster and the orbiter after atmospheric reentry during flight returning to earth. New demands must be met because these engines will have to be started reliably while in flight and after perhaps weeks of exposure to the vacuum and low temperature conditions of the space environment. No jet engine has yet been outside the atmosphere of the earth.

PROPULSION SYSTEMS CHARACTERIZED

Characteristics of the three propulsion systems are indicated in figure 2. Liquid oxygen and liquid hydrogen will be used as the propellants in the main and auxiliary propulsion systems. The total main propulsive thrust for the orbiter must be about a million pounds; and since two or three engines will be used, each will be of 400 or 500 thousand pounds thrust. Assuming the same basic engine and allowing for exhaust expansion differences, then the booster will require 12 or 13 engines.

The notable things about the auxiliary propulsion system are the large number of engines required, possibly as many as 60 for attitude control of the shuttle, and the magnitude of the force to be provided by each. Although not indicated in the figure, the RL10 engine delivering 15,000 pounds thrust can be considered for the orbital maneuvering function of the auxiliary propulsion system.

Relative to airbreathing propulsion, the significant factor evident in figure 2 is that consideration is being given to the use of hydrogen as the fuel.

WHAT'S THE DIFFERENCE?

How will these systems differ from previous ones? Obviously they will have to be reusable, and not expendable, to make the required 100 flights. And they will have to have long life with a predictable life expectancy. And very high reliability, e.g., failure paths of fail operational-fail operational-fail safe. And repeated leak free functioning by valves and seals. And exceptional controls and checkout systems. And the most complex, sophisticated set of interrelations and interactions yet devised. But the real difference is that most every system, subsystem, and component is being pushed close to the limits of existing technology - and all at the same time! In some instances extrapolations are being made beyond established technology; in others the customary early margins in performance expectations are being omitted.

Typical of previous rocket systems, is the Centaur vehicle. When the Centaur development was assigned to LeRC in 1963, a stage gross launch weight of 37,000 pounds was contemplated along with an engine specific impulse of

430 seconds; this would inject a payload of 2100 pounds into lunar transfer. As progress will have it, gross weight and payload weight went in diverging directions, but design margins were found and performance improvements were squeezed out. Specific impulse was improved to 442 seconds and now a 39,000 pound Centaur can inject 2500 pound payloads into lunar transfer.

Don't count on the shuttle to be so forgiving. Both design margins and potential performance growth are absent. But not the schedule! And so the probability of missed targets and expensive fixes is higher than ever before. That's what the difference is.

MAIN PROPULSION

An early photograph (Fig. 3) gives a comparison of a mock-up of the shuttle engine to the J-2 and F-1 engines. At the time, it was thought that the shuttle orbiter engine would be nearly as long as the F-1 engine; now the orbiter engine will be longer because a larger nozzle is needed for higher performance.

In the main propulsion systems using these new engines, high performance is being pushed to the limit. Specific impulse efficiency is intended to be 97 percent. This is now approached by the J-2 and RL10 engines, but only after years of developmental refinement. It has been said that one second of specific impulse is worth 1500 pounds of shuttle payload; or for a given payload it is worth $25M in the cost of each flight.

Theoretically, specific impulse increases with increasing pressure ratio of the exhaust gases expanding through the nozzle. Thus, to get very high specific impulse requires the use of high energy propellants at high pressure ratio. There are two ways to get a high pressure ratio: have a low pressure at the nozzle exit (low back pressure), or have a high pressure at the nozzle entrance (high combustion pressure).

Since an infinite pressure ratio can be had by burning at just any combustion pressure and exhausting to the vacuum of space, the only requirement for the orbiter engine is a large nozzle of high area ratio. Therefore, the orbiter engines do not need high combustion pressure.

For the booster engines, which must exhaust into the earth's atmospheric pressure, a large nozzle area ratio is not helpful unless high combustion pressure is available at the nozzle entrance. Therefore, the hardware and the technology for high combustion pressures limit the pressure ratio available. Consequently, large nozzles are not needed for booster engines.

NASA has ground ruled that the orbiter and booster engines have as much in common as possible, i.e., they should preferably be the same engine. To achieve the utmost performance, this compromise engine would be designed to burn high energy propellants at high combustion pressures using a nozzle of high area ratio. Figure 4 gives comparative data for a preliminary design of the engine in its two configurations for the orbiter and the booster. For practical reasons there will be a common power head comprising everything except most of the nozzle divergent section; then the orbiter nozzle will have a large retractable divergent section and the booster engine will have a shorter fixed section. Presumably the nozzles can be factory-interchangeable; they are relatively straightforward and easy to make. There is no way for the high pressure power head, required for the booster, to be run efficiently at low pressure for the orbiter; it will be very difficult and expensive to develop and produce.

The propellant flow systems and combustion zones are shown in figure 5 for a representative version of the power head. Each propellant turbopump is driven by gases created in a preburner. These hot gases then enter the main combustion chamber and burn further, with additional propellant, at a combustion pressure near 3000 psia. This pressure itself far exceeds that of any existing rocket engine, and the preburner pressure is about double that of the main burner. This necessitates, of course, even higher pump and fluid system pressures, hence most all the hardware, valves, seals, plumbing, pumps, etc. must contain and control either high temperature gases at high pressure, or cryogenic liquids at pressures approaching 7000 psia, or both.

The most significant systems of the power head are the combusters (preburner and main chamber) and the turbopumps. The several illustrations which follow serve to illuminate the nature of some areas of technology concerning these systems.

Over the past twenty years much has been learned analytically and experimentally to improve the designing of thrust chambers and the prediction of performance, stability, and durability. However, most of this work involved only liquid-liquid propellant injection, combustion at only moderate pressures, and simple thrust chamber configurations. In the design of the shuttle engine these distinctions should be clearly recognized.

High pressure combustion will impose severe cooling requirements for the combustion chambers; there is much discussion now over the relative merits and losses of transpiration and regenerative cooling.

Highly efficient high pressure combustion is very likely to lead to combustion instabilities, severe or otherwise, even though well considered design provisions are made for protection against them. Probably no rocket engine yet developed has been immune to combustion instabilities, and these have been simple engines compared to that contemplated for the shuttle. The shuttle engine with its interaction between combustion chamber, preburner, turbine drive, pump, boost pump, and propellant flow loops, will foster dynamics (including instabilities) of a complexity which has been unknown before.

In this most sophisticated of rocket engines, there must be four turbopumps instead of the usual two, i.e., there will be a boost pump for each main pump so that the required pressure rise can be attained efficiently. By thus using pumps in tandem and by staging within pumps, the necessary hydrodynamics can be accomplished within cavitation limits; but extreme problems will be encountered in the rotating seals which must separate turbine drive gases from cryogenic propellants having widely different pressures and temperatures.

Consider, for example, conditions in the main hydrogen pump. Turbine drive gases arrive at one end from the preburner at more than 1500°F and 5000 psia; at the other end liquid hydrogen enters the pump at less than -400°F and about 300 psia. The rotating seals of this pump (Fig. 6) are located along the shaft from the hot, high pressure turbine through the three stages of the pump to the cold, low pressure end. The seals must work under these very severe conditions at very high rotational speeds for many service cycles.

Bearings for this turbopump are placed outboard to alleviate torque loads. This permits the use of smaller bearings, which is advantageous at the very high shaft speeds employed. The bearing DN numbers will be near 2 million, at which some experience has been gained; but more experience is needed on extending the life of bearings used at these values.

These have been but examples of shuttle main propulsion problems. Such problems are formidable, but surmountable. They represent very real challenges. They will require much engineering. If quick fixes must be found under the duress of a tightly scheduled development, they will be very expensive.

AUXILIARY PROPULSION

Similar problems exist for the auxiliary propulsion systems. Both the booster and the orbiter need attitude control devices while in space flight. Additionally, the orbiter will need orbital maneuvering capability.

Propulsive systems to meet these needs are presently not well defined, but obviously will be most complex. The thrusters will burn gaseous hydrogen and gaseous oxygen, but the pressure level has not been selected yet. Pumps may or may not be needed. Heat exchangers definitely will be needed because the propellants must be conditioned to allow for gas-gas delivery to the thrusters. Perhaps compressors could be used to drive the gaseous propellants.

Figure 7 presents schematics of only two of many candidate auxiliary propulsion flow systems; one pumps liquid propellants before they are conditioned, the other compresses gaseous propellants after conditioning.

Separate systems such as these will be needed for each propellant for each thruster. Attitude control functions will require placement of thrusters at a variety of locations in the vehicle; and failure mode requirements will demand redundancy. Valves, large enough to handle gas, must be at each thruster, and must have fast response and positive leak-free sealing for what may add up to a million cycles each in operation. It is evident, then, that the system for storing, conditioning, and delivering propellants to two or three dozen variously located thrusters on demand will have complications.

Within the thrusters, new combustion, cooling, and ignition processes must be understood and applied. Mixing of gas-gas streams of propellants for effective burning is quite different from use of liquid-liquid or liquid-gas streams conventionally employed; and adequate cooling of thrust chamber walls without use of liquids will require considerable ingenuity.

Ignition of propellant gas mixtures, which will vary in temperature to as low as -300° F, must be performed in a reliable, repeatable manner for a large number of cycles. The use of spark plugs is one approach, but problems in tip erosion, power supply, power distribution, and electromagnetic interference must be investigated and solved. Use of catalytic ignition presents an interesting alternative approach.

Catalytic ignition has been under technology development for several years as a possible improvement over the use of spark plugs. Figure 8 is a schematic of one design of a catalytic igniter. The mixing section provides a homogeneous mixture for the catalyst bed, avoiding high O/F striations which are detrimental to the bed. The orifice and reduced area flow tube provide a velocity in the mixed gas above the flame velocity. This avoids flashback. Additionally, the diffusion bed provides a quenching effect to prevent flashback. It also performs a secondary mixing function. This igniter can be very small - not much larger than a spark plug.

Problems in the past have been encountered with catalytic ignition when using cold propellants. Ignition delay sometimes can be very long. However, insulating the igniter and adding small amounts of electrical heat appears to offer a reasonable solution.

Auxiliary propulsion systems must undergo immediate design clarification and development if a shuttle vehicle is to become operative in this decade. Both booster and orbiter will need them. Requirements for the orbiter will be the more stringent.

AIRBREATHING PROPULSION

The jet engines for flyback through the atmosphere present a strange paradox. They may be prepared to burn hydrogen, instead of jet fuel, in either the orbiter or the booster, or both. Or they may be eliminated altogether. Some competent people argue that flyback and landing can be done with the vehicle used as a lifting body more easily and as precisely as can be done with powered approach. This is especially true with the orbiter whose reentry can be well programmed for proximity to the landing site. Certainly the orbiter can profit by freedom from carrying any hardware up and back down just to use on the return; this hardware and its propellant weight can be traded directly pound for pound with payload.

Consideration of the mission as presently conceived, however, presents engine characteristics given in figure 9. The advantages of using hydrogen as fuel are shown by figure 10, where it may be seen that hydrogen benefits the booster considerably by increasing shuttle payload capacity, and also improves the utility of the orbiter. Reduction of engine weight relative to thrust is more significant to the orbiter.

Problems in the use of hydrogen center in the design of the fuel flow system, pumps, and controls as required to afford adequate throttling with a cryogen. Further concern involves the exposure of jet engine materials, moving parts, and lubricants to the space environment prior to use. No difficulty is expected with the combustion performance, based on experiments on engines in test cells and in aircraft (Fig. 11) run with hydrogen about 15 years ago.

CONCLUSIONS

The space shuttle propulsion systems all require new waves of development. This development will stem from a large background of experience; but it will push to the very fringes of technology, or beyond, in an exceedingly complex endeavor. No one impossibility or improbability is evident, but with a multiplicity of problems the whole may exceed the sum of its parts.

The usual design and performance margins are not being provided in shuttle propulsion systems, and this is typical of the whole shuttle approach. With everything being developed at once, one failure could lead to another - the domino effect.

Sophisticated simultaneous development with lack of margins requires that every criterion of the design be met absolutely. This we can do, but it will require skillful and resourceful engineering.

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A SPACE SHUTTLE CONCEPT

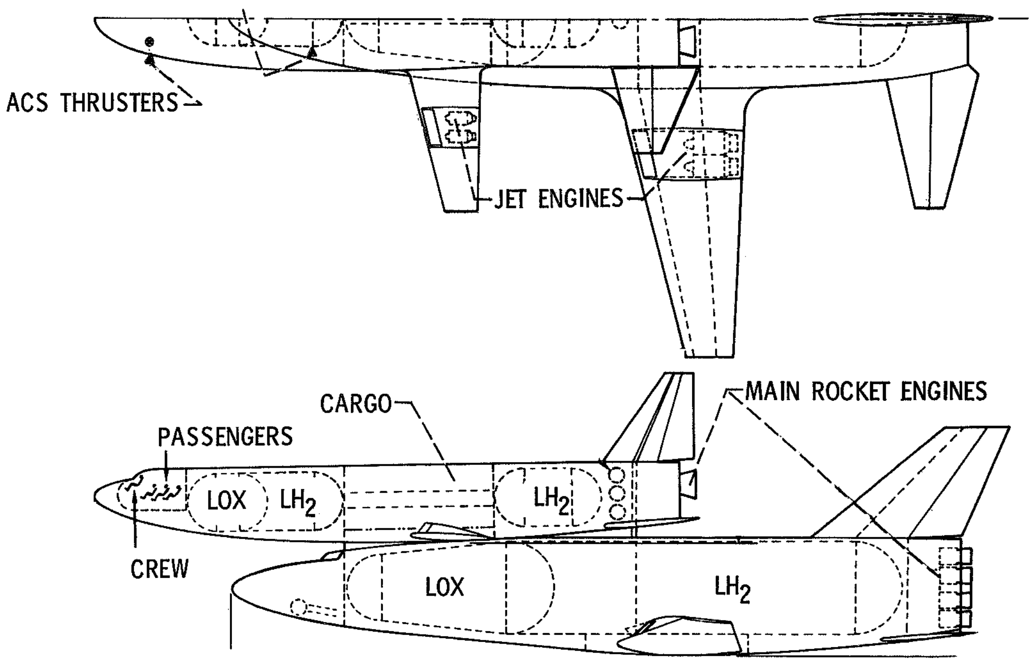

Fig. 1

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SPACE SHUTTLE

BASELINE PROPULSION SYSTEMS

SYSTEM	BOOSTER	ORBITER
MAIN PROPULSION	• TOTAL THRUST 5 MILLION LB • LO_2/LH_2 PROPELLANTS • THROTTLING RANGE 50% TO 109%	• TOTAL THRUST 1 MILLION LB • LO_2/LH_2 PROPELLANTS • THROTTLING RANGE 50% TO 109%
AUXILIARY PROPULSION	• ATTITUDE CONTROL • NO. OF THRUSTERS 15-25 • THRUST - 1500-5000 LB • H_2-O_2 PROPELLANTS	• ATTITUDE CONTROL (& MANEUVERING) • NO. OF THRUSTERS 20-35 • THRUST - 800-3000 LB • H_2-O_2 PROPELLANTS
AIRBREATHING PROPULSION	• FLYBACK & GO-AROUND • TOTAL THRUST 160 000 LB • FUEL - H_2	• GO-AROUND • TOTAL THRUST 60 000 LB • FUEL - H_2 OR JP_4

Fig. 2

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ENGINE SIZE COMPARISON

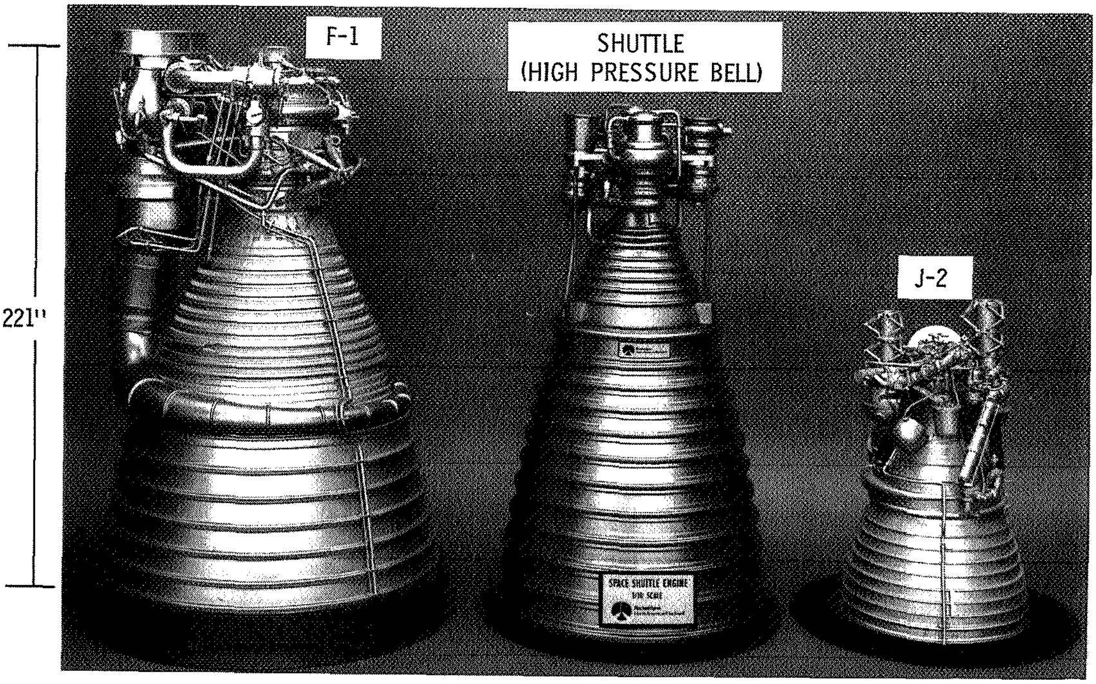

Fig. 3

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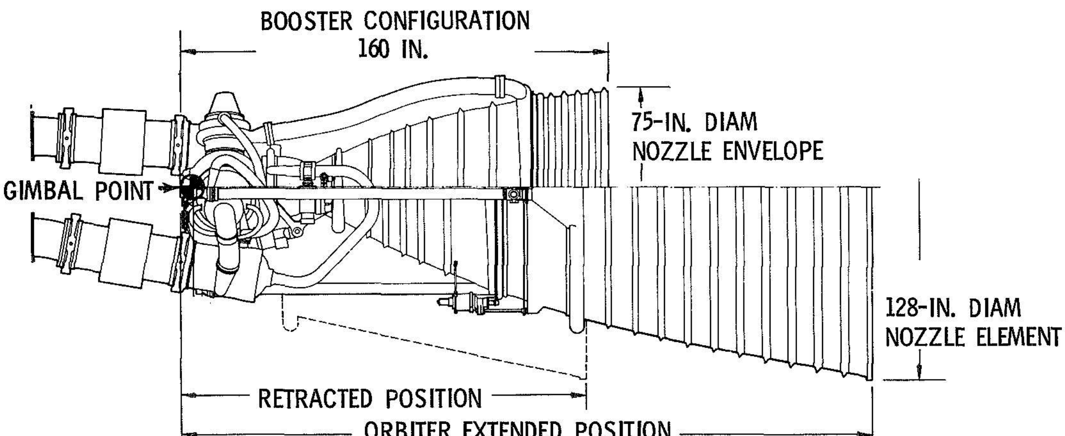
ENGINE CONFIGURATIONS



CONFIGURATION	CHAMBER PRESSURE, PSIA	MIXTURE RATIO	AREA RATIO	THRUST, LB	SPECIFIC IMPULSE, SEC
BOOSTER	3000	6.0	50	400 000 SL	384 SL
ORBITER	3000	6.0	150	477 000 VAC	456 VAC

Fig. 4

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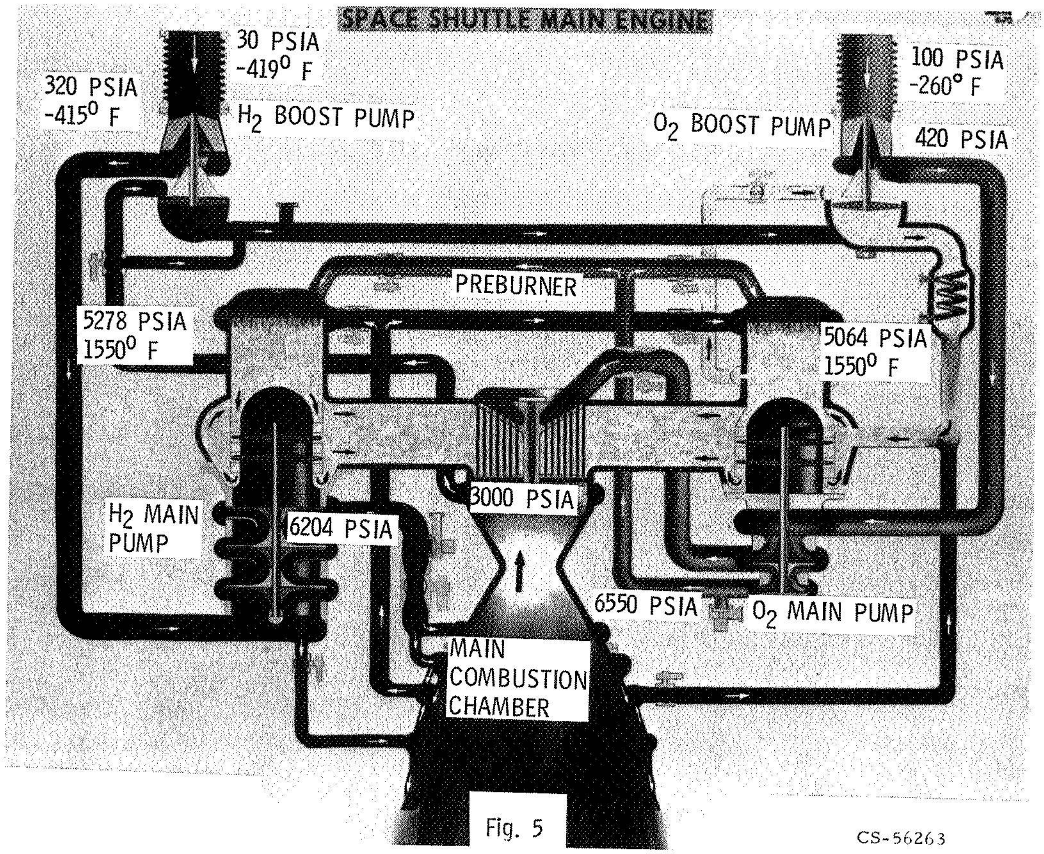

Fig. 5

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HIGH PRESSURE FUEL TURBOPUMP

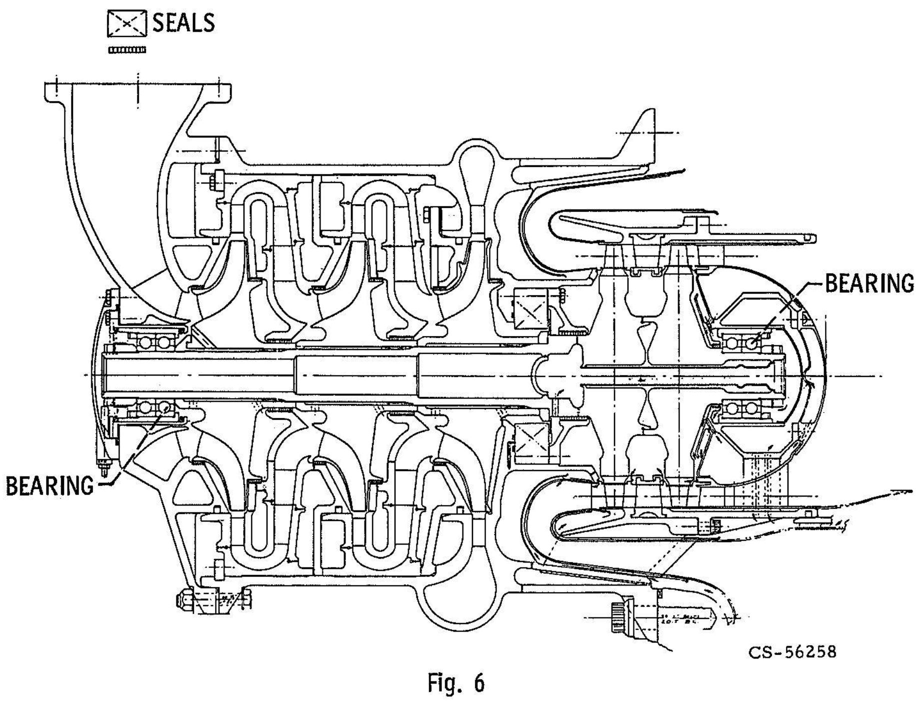

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Fig. 6

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HIGH CHAMBER PRESSURE RCS FEED SYSTEM

PRESSURE BOOST SYSTEMS

P_c = 200-500 PSIA

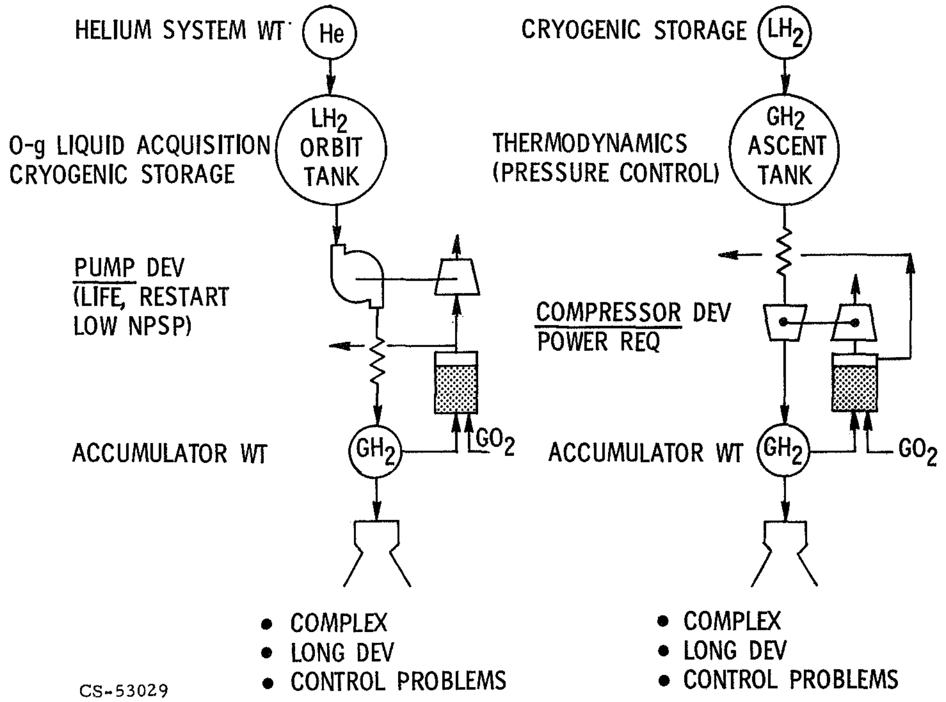

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Fig. 7

CATALYTIC IGNITER

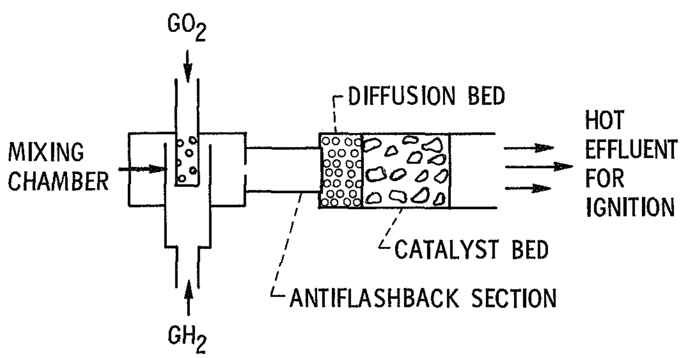

Fig. 8

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BOOSTER AND ORBITER AIRBREATHING ENGINE CHARACTERISTICS

	BOOSTER	ORBITER
1. THRUST REQUIREMENTS	160 000 LB	60 000 LB
2. MISSION PROFILE	400-MILE CRUISE GO-AROUND	----------- GO-AROUND
3. SPACE ENVIRONMENT/FLIGHT	MIN	30 DAYS
4. WEIGHT SIGNIFICANCE	1:4 TO 1:8	1:1
5. TOTAL LIFE, HR	500	50

Fig. 9 CS-53035

TYPICAL EFFECTS OF HYDROGEN AND LIGHT-WEIGHT ENGINES ON SHUTTLE PAYLOAD

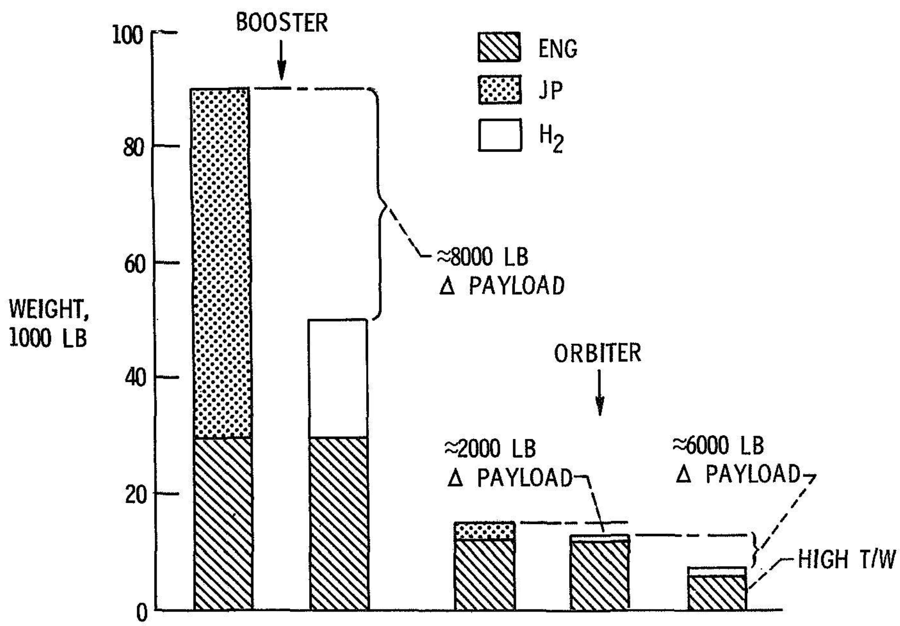

Fig. 10 CS-53036

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AIRCRAFT WITH PUMP-FED LIQUID-HYDROGEN FUEL SYSTEM

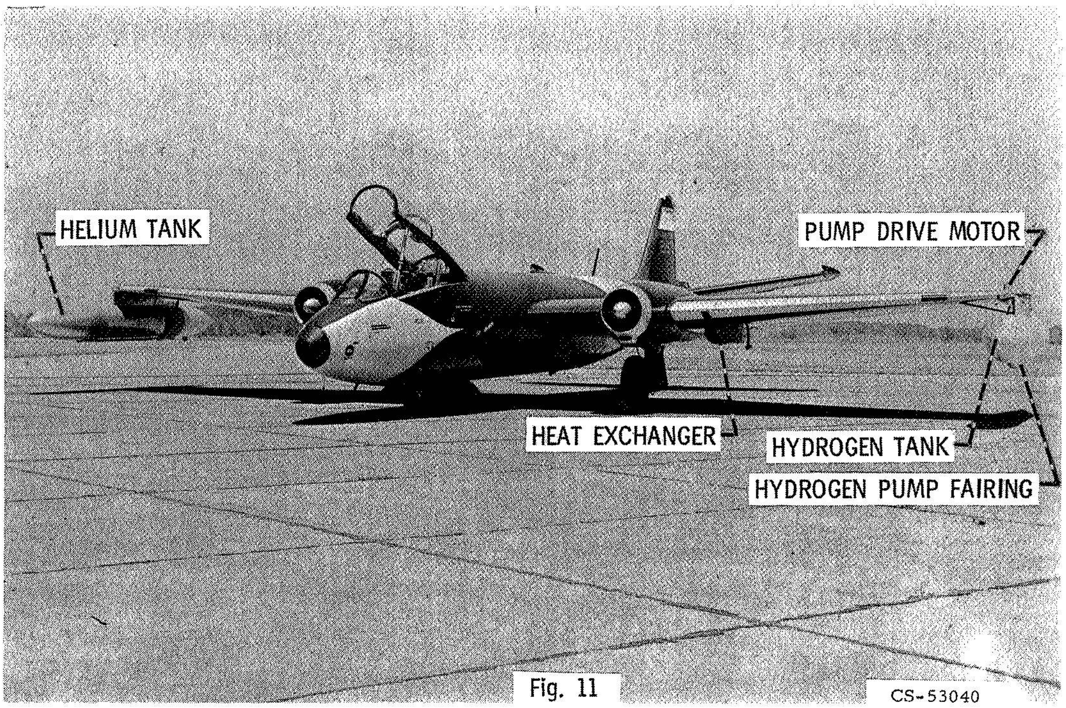

Fig. 11