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LIQUID ROCKETS

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This review indicates recent developments which have occurred in the liquid rocket engine field, special development areas associated with the liquid engines in current usage, and several trends which may be expected in the design of future advanced rocket engines.

Since the earliest design and development of liquid rocket engines, basic propulsion goals have remained the same: high performance, low weight, simplicity, minimum size, ease and low-cost of development, versatility, engine longevity and reusability, and, most important, high reliability. Every liquid rock engine development program has advanced these goals.

The area ratio and chamber pressure of the early Redstone engine were superceded by the higher performing Atlas and Titan engines. The LOX/alcohol and acid/hydrazine propellants of the early engines were replaced first by LOX/RP in the Atlas, Thor, Jupiter and Titan I, and shortly thereafter by the equivalent-performance, noncryogenic, NTO/Aerozine-50 propellants for the Titan II. Several new rocket engines are now operational or in the latter stages of development. These engines --- the H-1 and F-1 with LOX/RP propellants, the Titan II and Titan III engines with NTO/Aerozine-50, and the RL-10, J-2, and M-1 with O_2/H_2 propellants --- have each contributed state-of-the-art advancements.

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The H-1, LOX/RP engine has clearly demonstrated the capability and reliability of a liquid-propellant rocket engine. The thrust has been uprated from the original design value of 165,000-pounds thrust to its current 200,000-pounds thrust rating, and it still has a potential for higher thrust. The flight test record of the first nine Saturn I launch vehicles is outstanding. The H-1 was specifically designed as an independent plug-in unit. Its record has demonstrated the excellent reliability that can be achieved with an engine cluster for high-thrust applications.

The F-1 engine (Fig. 1), the nation's first high-thrust booster engine, has achieved several milestones during the last year. The LOX/RP engine, which has now completed flight rating testing (FRT), consists of a single thrust chamber injector, and dome; a single direct-drive turbopump; a single gas generator; fuel-pump discharge lines and control valves; LOX pump discharge lines and control valves; and a single start valve, which is the only major engine part requiring electrical energy as a control device.

This engine design incorporates a tank-head start system, a simplified control system, and other concepts proved through predevelopment advanced technology programs. The 1000-psia chamber pressure (the highest chamber pressure of any rocket engine currently being developed) and the 16:1 nozzle area ratio combine to provide a high engine performance level.

Since completing FRT in December, 1964, one (1 month ahead of schedule), a 181-second duration test (in excess of the Qual duration requirement) has been conducted on the engine. The cluster tests of five F-1 engines for the Saturn V booster conducted at NASA Marshall Space Flight Center produced the nation's largest rocket thrust level of 7,500,000 pounds. At Marshall Space Flight Center, five cluster engine tests have been conducted to date on the Saturn S-IC test stage. These cluster tests increased in duration from an initial

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test of 6 seconds to 90 seconds duration. During the latter tests, gimbaling for all four outboard engines was demonstrated. Full-duration cluster tests are planned for the near future.

During development of the F-1 engine special efforts were required in several areas. The regenerative fuel-cooled thrust chamber was designed to a 10:1 expansion area ratio, primarily for easier handling and shipping of the engine, and a gas-cooled skirt was designed which extends the nozzle length nearly 6 feet, and provides 16:1 expansion (Fig. 1). Development of this gas-cooled nozzle skirt was a new innovation in engine design. The turbine exhaust is circumferentially distributed by the exhaust manifold below the heat exchanger on the main thrust assembly. The gas flows between the double walls of the skirt, and is gradually admitted into the main stream through numerous slots along the wall, thus creating and maintaining a cool boundary layer.

As a part of the basic engine development, a new requirement was added in line with the Rocketdyne manrated safety concept. This requirement calls for a thrust chamber injector, as well as an entire engine system, that is dynamically stable. This means that if a system is disturbed from any source, it will quickly damp out the resulting oscillation and return to stable operation.

A comprehensive development effort was focused on this task in the areas of: analysis, model research testing, and full-scale design and testing. The analysis team re-examined all test records, for significant trends, and analyzed design concepts for sources of disturbances. This provided a list of characteristics and requirements for a good injector. Two-dimensional models were used to examine particular features in detail by means of high-

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speed photography and high-response instrumentation. The real proof, however, was in building and testing full-scale hardware.

Rather than run hundreds of tests to accumulate statistics on the engine stability, an artificial disturbance was introduced by detonating an actual bomb inside the combustion chamber near the injector face. This is an area which has been determined to be a sensitive region. Injectors were evaluated on their ability to quickly recover from this disturbance. This extensive injector performance and combustion test program led to the development of a combustion system which not only produced high performance, but also demonstrated excellent dynamic stability. Engine stability demonstration tests on the present F-1 production configuration have shown that all induced disturbances will very quickly self-stabilize.

The next development step known as the Qualification Test Program will formally demonstrate the reliability and performance of the engine prior to the Apollo manned-spacecraft flights. This test program will conclude the development program as presently contracted with NASA.

There is, however, another development phase --- flight support. This includes necessary or desirable modifications for flights following Saturn Apollo. As has been the case in earlier space missions particular flights may require special "tailoring" of engines.

In the area of future improvement, thrust uprating studies for the F-1 engine have shown the engine design to have an extensive uprating potential. An uprating program, based on NASA's Saturn vehicle requirements, could result in increased thrust and performance for this engine, thus providing greater payloads for the Saturn vehicles.

The successful Titan II-Gemini flights and the successful initial flight of the Titan III have further demonstrated the high reliability of these proven liquid propellant booster and upper-stage engine designs. The Tital II and Titan III N_2O_4/Aerozine-50 propellant engines were developed by the Aerojet-General Corp. from the earlier Titan I engines which used LOX/RP propellants. The new dual Titan booster engines are rated at 430,000 pounds thrust at sea level; the upper stage engine provides a vacuum thrust of 100,000 pounds thrust, and achieves increased performance with a high 49:1 area ratio nozzle. The designs for the booster and upper stage engines are similar; both designs use the basic gas generator cycle.

The Titan engines have side-mounted turbopumps and independent engine gimbaling. Solid-propellant cartridges are used for starting; no ignition system is required with the hypergolic propellant.

The Titan II development, operation and many launches have demonstrated that N_2O_4 and Aerozine-50, can be very successfully used in a large high-thrust rocket engine program. Experience has shown that if the proper precautions are taken in facility design and protective equipment for personnel, these propellants can be handled safely and easily. This experience has greatly contributed to making practical the use of other high-performance propellants for future vehicle stages.

The Titan III flight demonstrated the altitude start capability of the booster engines. The Titan III, which provides the Air Force with a high payload launch vehicle, has shown the potential of vehicles designed using both liquid and solid-propellant engines.

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The 15,000-pound thrust Pratt and Whitney RL-10 O_2/H_2 engine has achieved an excellent reliability record. Originally designed for the Centaur, this engine is used in a six-engine cluster for the Saturn I upper stage. The RL-10 employs a cycle in which the thrust-chamber regenerative-heated H_2 drives the turbopump. It has a chamber pressure somewhat lower than other current engines, but achieves high performance with its 40:1 area ratio nozzle. This engine has demonstrated numerous new innovations in liquid-rocket engine design.

Throttling in pump-fed mode of operation on RL-10 has been demonstrated in experimental engine systems; further throttling capabilities with this engine are possible. Operation in a tank-head-pressure idle mode (with boost pumps operating) is also possible with this design; preliminary tests have been conducted in this operating mode.

Restart capability can be achieved with the RL-10 spark ignition system. In the mechanical design area, the engine has demonstrated the performance and combustion stability with throttling, of the concentric-tube injector design. Increased performance is possible with chamber pressure uprating and a higher area ratio nozzle.

The J-2 engine, (Fig. 2), also designed for upper stages, delivers a 200,000-pound thrust, and operates at a chamber pressure of 635 psia. The O_2/H_2 propellants are supplied to the thrust chamber by dual direct-drive turbopumps. The fuel pump has an axial-flow design, and is the first of its kind to be used in a large engine.

The turbopump bearings in both units are lubricated by the propellant being pumped. Thus no lubricating system is required, and the problem of protecting lubricating oil from the low temperatures of the cryogenic propellants and the space environment is avoided. Possible combustion of lubricating oil from seal leakage is also eliminated.

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A fuel-rich gas generator supplies gas to drive the hydrogen pump turbine and then, in series, to drive the oxygen pump turbine. This arrangement gives maximum turbine efficiency and effectively synchronizes pump operation. The exhaust gas is introduced into the midpoint of the rocket-engine nozzle for effective disposal and to recover much of its remaining propulsive force. The pumps are mounted on opposite sides of the thrust chamber and have direct-access, straight-axial inlets. No boost pumps are required.

The J-2 engine is completely self sufficient, carrying its own helium supply for valve actuation and a hermetically sealed electrical control unit which supplies all control logic for engine start, cut-off, and restart. A rechargeable, engine-mounted, hydrogen start tank and a spark ignition system featuring automatic reset provide the basic elements for the multiple restart capability of the engine. Propellant-utilization control is provided by adjustment of the propellant mixture ratio in accordance with vehicle command signals. The engine is also capable of providing gaseous hydrogen and oxygen to the vehicle for propellant tank pressurization.

The successful completion of the Preliminary Flight Rating Test program was accomplished in November, 1964. A total of 16 mainstage tests was conducted during the test program. The total accumulated operating time at full thrust was 2350 seconds, which exceeded the program requirement of 2250 seconds. (Fig. 3)

The successful restart of the J-2 engine was demonstrated on December 9, 1964. A research and development engine was run for 165 seconds and then held for 75 minutes. It was restarted, shut down after 7 seconds for 6 minutes, then restarted, and run for full duration of 310 seconds. To date more than 1167 engine tests have been completed. Of these 24 exceeded 500 seconds in duration.

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A single unit has been fired for a total of over 10,000 seconds. Initial five engine cluster tests using the Saturn S-II test stage tankage have been successful.

An experimental engine program, conducted concurrently with the J-2 development program, has made significant contributions to O_2/H_2 engine technology during the past year. This engine serves as a test bed for advanced concepts applicable to O_2/H_2 engines. This engine has demonstrated the design of an engine system that derives its turbine gas from the main combustor, thus eliminating the necessity for a gas generator and a fuel by-pass system that provides for rapid engine start without preconditioning.

The largest current O_2/H_2 engine is the M-1, which delivers a thrust of 1500 pounds The design employs a high area-ratio bell nozzle, and will operate at close to a 1000 psia chamber pressure. of 1000 psia This engine program, conducted by Aerojet-General Corp. for NASA, has provided additional O_2/H_2 engine technology, and has shown the feasibility of its high-thrust design.

During the past year a rather extensive program on the use of FLOX oxidizers (adding F_2 to basic O_2 oxidizer) has been carried out for booster engine systems. This work has been done using the Atlas sustainer engine which was designed for O_2 as the oxidizer and RP as the fuel.

Work on FLOX has been in progress at varying levels of effort since 1953. First engine tests (with an O_2/RP gas generator) and FLOX 20 (20-percent F_2 and 80-percent O_2) were made on the Thor engine in 1959. These tests demonstrated that the higher theoretical performance can be achieved in the thrust chamber, and that cooling with the FLOX oxidizer is satisfactory without modifications.

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The recent Atlas sustainer engine tests, sponsored by NASA, were made at Rocketdyne using FLOX 30. These tests have demonstrated gas generator and turbine operation, regenerative cooling, and hypergolic ignition, and have shown that the theoretical specific impulse gain of FLOX 30 over the LOX/RP can be achieved in a complete operating engine system. Engine compatibility was achieved with a few relatively minor material changes.

Further FLOX engine testing with higher F_2 concentrations is planned. These successful engine demonstration and performance tests have paved the way for future use of high performing FLOX or other fluorine containing oxidizers in either the booster or upper stages of high performance launch vehicles.

In summary, we can see that during the past year significant strides have been made in liquid-propellant rocket engines and the vehicles they power. The liquid rocket powered Titan-Gemini flights successfully furthered the nation's manned orbital program in the same outstanding manner as did the earlier Redstone-Mercury suborbital and Atlas-Mercury orbital flights. The first flight of the Titan III demonstrated the proved reliability and booster-engine altitude start capability of the N_2O_4/Aerozine-50 Titan engines, and nine successful Saturn I launches to date, have demonstrated outstanding success of the six-engine RL-10 cluster and the eight-engine H-1 cluster. For NASA's Saturn V, the successful F-1 five-engine cluster tests have indicated that the high level of success now being achieved in current liquid rocket engines and vehicles will continue.

The J-2 engine, also scheduled for use in the Saturn V and in the new S-IVB upper stage for the Saturn IB has completed FRT, and has demonstrated restart and full-duration test operation during the past year.

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July 15, 1965 is completion date

The five-engine cluster for the S-II stage has been successfully tested several times. The Atlas-sustainer FLOX test program has shown the feasibility and practical application of this approach for achieving increased performance for liquid rockets.

During the past year continued progress has been made in the AF- and NASA-sponsored advanced technology programs. These programs are directed toward the conception of future high-performance liquid rocket engines having reduced complexity, and toward designs which minimize the cost and time for development of new engines. This effort, which was initiated on a broad basis several years ago, has rapidly delineated promising new approaches to component and system design, and pinpointed critical problem areas. These advanced technology areas include: high-energy propellants, advanced nozzles, new combustor concepts, improved thrust-chamber cooling techniques, and advanced high-performance engine designs, incorporating the advanced component designs now being investigated and tested.

Work on advanced turbomachinery to achieve higher efficiency and low-weight designs can be expected to provide turbopumps capable of the requirements for tomorrows increased performance liquid-propellant rocket engines. New approaches to the design of the rocket engine combustors and nozzles are continually being sought and investigated. Here again the goal is improvement in performance, weight, and reliability. New approaches to engine designs which would permit the basic operating components to be developed and tested to a high performance and reliability level, independent of the engine, are being sought.

In the area of advanced propellants, high performance combinations now being tested offer significant increases in specific impulse.

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As tests on these propellants are accumulated in the areas of performance, combustion stability, and system design, these advanced propellants will provide the vehicle design with a broad spectrum from which to chose, based on the specific requirements of each vehicle or stage.

The potential performance and reliability gains which analysis have shown to exist with these advanced engine concepts, provide a great incentive to the liquid rocket engineer to develop complete engine designs using these promising new concepts for the next generation of liquid rocket powered launch vehicles and spacecraft.

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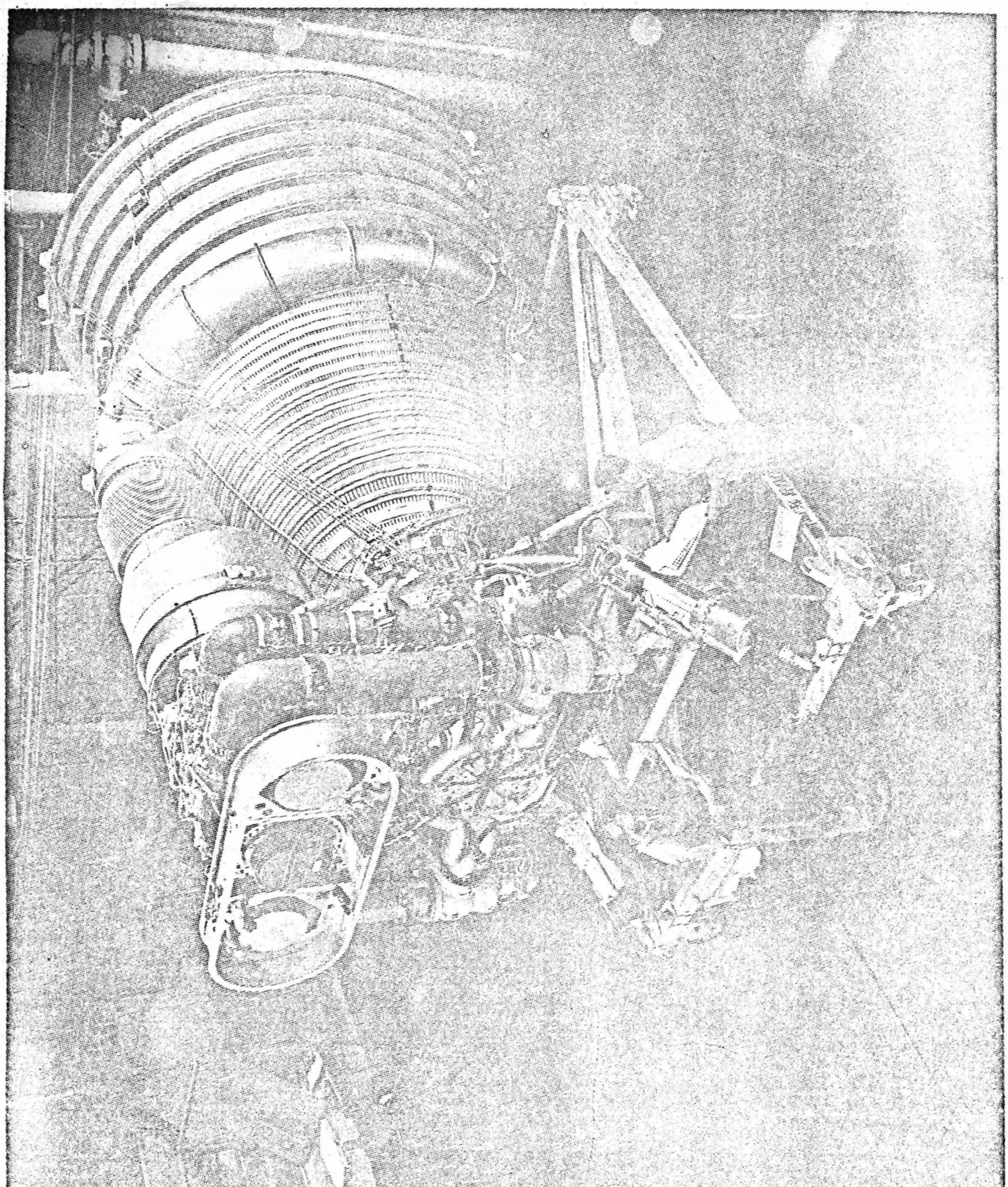

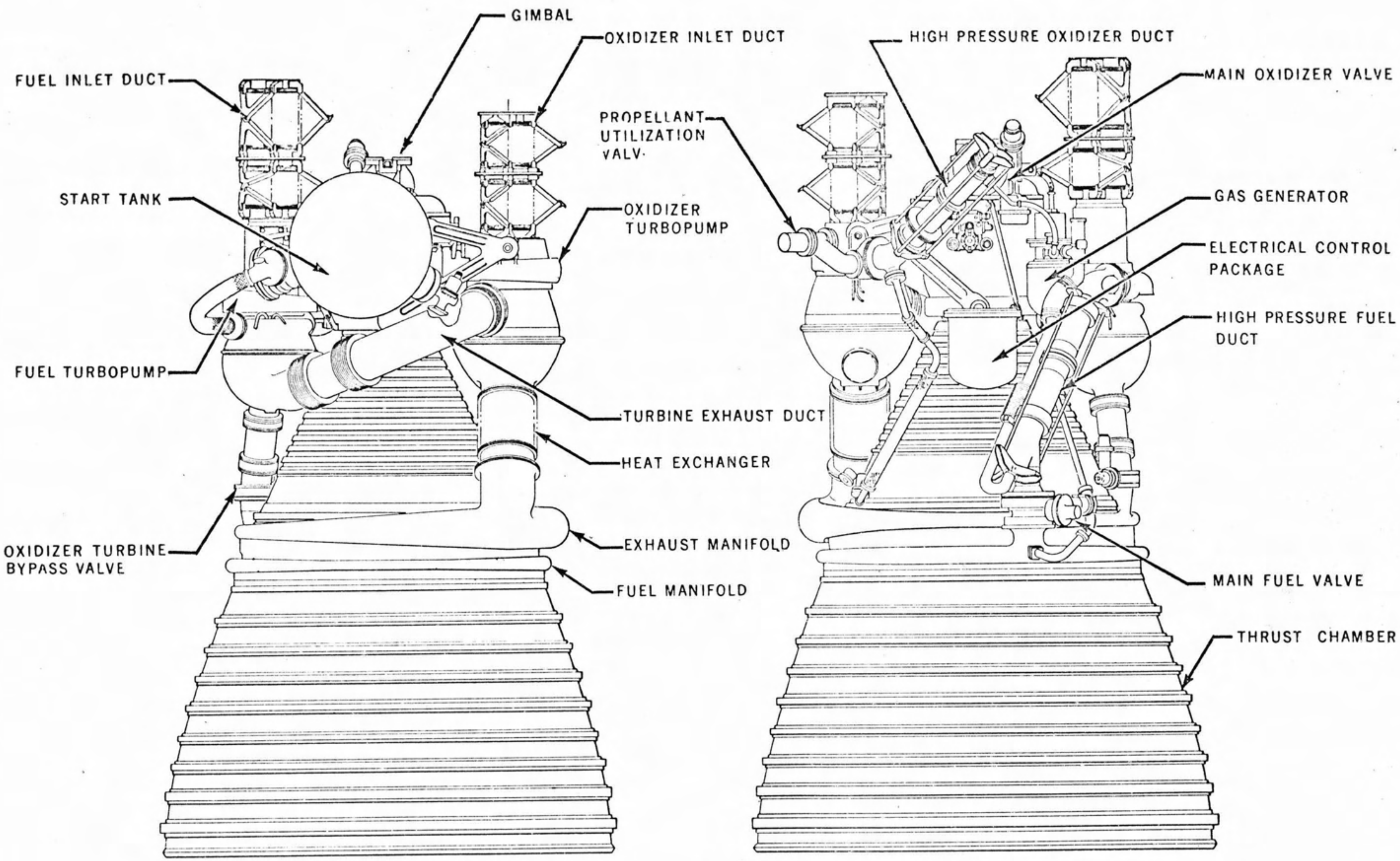

J-2 ROCKET ENGINE