June 29- July 2, 1964

RECENT NASA EXPERIENCE WITH HYDROGEN ENGINES

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AIAA Paper
No. 64-270

1st AIAA Annual Meeting

Washington, D. C. June 29 – July 2, 1964

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Summary

This paper presents a review of the experience which has accumulated in the development of the Liquid Hydrogen J-2 and RL10 Rocket Engines. These engines are being developed by the Rocketdyne Division of North American Aviation and Pratt & Whitney Aircraft, a Division of United Aircraft Corporation respectively. A brief description of the configuration, performance, and operation of each engine is presented, followed by a description of recent progress in areas which are unique to liquid hydrogen burning engines and, in particular, to engines which must operate in the environmental conditions encountered in the second or third stage of a space vehicle.

General

The decision of NASA to use hydrogen as a fuel for upper stages evolved largely through the development of hydrogen technology to a point where hydrogen appeared to be a practical way of achieving high performance for space vehicles. Work was in progress on the use of hydrogen as a fuel in rocket engines as early as 1956. Since that time we have seen the RL10 engine through a major portion of its development cycle, and are well along in the J-2 engine development. This paper presents some of the progress which has been and is being made in the development of these hydrogen engines. Development areas are broken down into two categories:

1. Those unique to hydrogen-burning engines and

2. Those unique to high-altitude or "space" operation

Hydrogen Engines Described

Before we go into the development problem areas and their solutions, let us compare the hydrogen engines we are developing now for our Saturn and Centaur space vehicles, the J-2 engine and the RL10 engine. As shown on Figure 1, the RL10 engine stands 5 feet 8 inches high while the J-2 is 11 feet tall. The RL10 operates at less than half the chamber pressure but has a greater expansion ratio than the J-2.

Although both engines burn liquid hydrogen and liquid oxygen, they are based on different operating cycles. The RL10 uses the "Regenerative" or "Topping" Cycle where the hydrogen heated in the process of thrust chamber cooling is expanded in a two-stage turbine to drive the single geared turbopump as shown on Figure 2. Thrust level is controlled by bypassing a portion of the fuel around the turbine. Initial turbine spin is accomplished by main tank supplied hydrogen which is expanded by the relatively warm thrust chamber.

The J-2 engine uses a gas generator to drive separate fuel and oxidizer turbopumps as shown on Figure 3. Initial turbine spin is accomplished by gaseous hydrogen from a pressurized start tank, and the turbines are driven in series.

The RL10 engine uses centrifugal flow pumps for both fuel and oxidizer, while the J-2 uses a centrifugal flow oxidizer pump and an axial flow fuel pump.

Development of Hydrogen Engines

Pump and Chamber Cooldown

Once an engine has been started, cryogenic liquid propellant pumps operate like any high performance fluid pump. However, the use of cryogenics involves two special considerations: the need to precondition the propellant supply lines and the pumps prior to start; and the desirability of minimizing losses of liquid because of boil-off during non-operating (coast) parts of the mission. Keeping the propellants in liquid form at the inlet involves:

1. Minimum heat input to the propellants from the stage and engine hardware,

2. A means for disposing of warm liquid or gas which is created by initial contact with the hardware and

3. Maintaining the lowest possible heat input during "hold" or "coast" periods to reduce boil-off.

There are several approaches to accomplishing the above, each of which has its advantages and disadvantages. One method is to start the engine with wet pumps. In this method, the main engine propellant valves are located downstream of the pumps. The vehicle tank "pre-valves" are opened some time before the engine is started, and the propellants trickle down into the engine, through the pumps to the main valves. Thus, the bulk of the engine feed system is exposed to

RL 10 ENGINE APPROACHES TO COOLDOWN

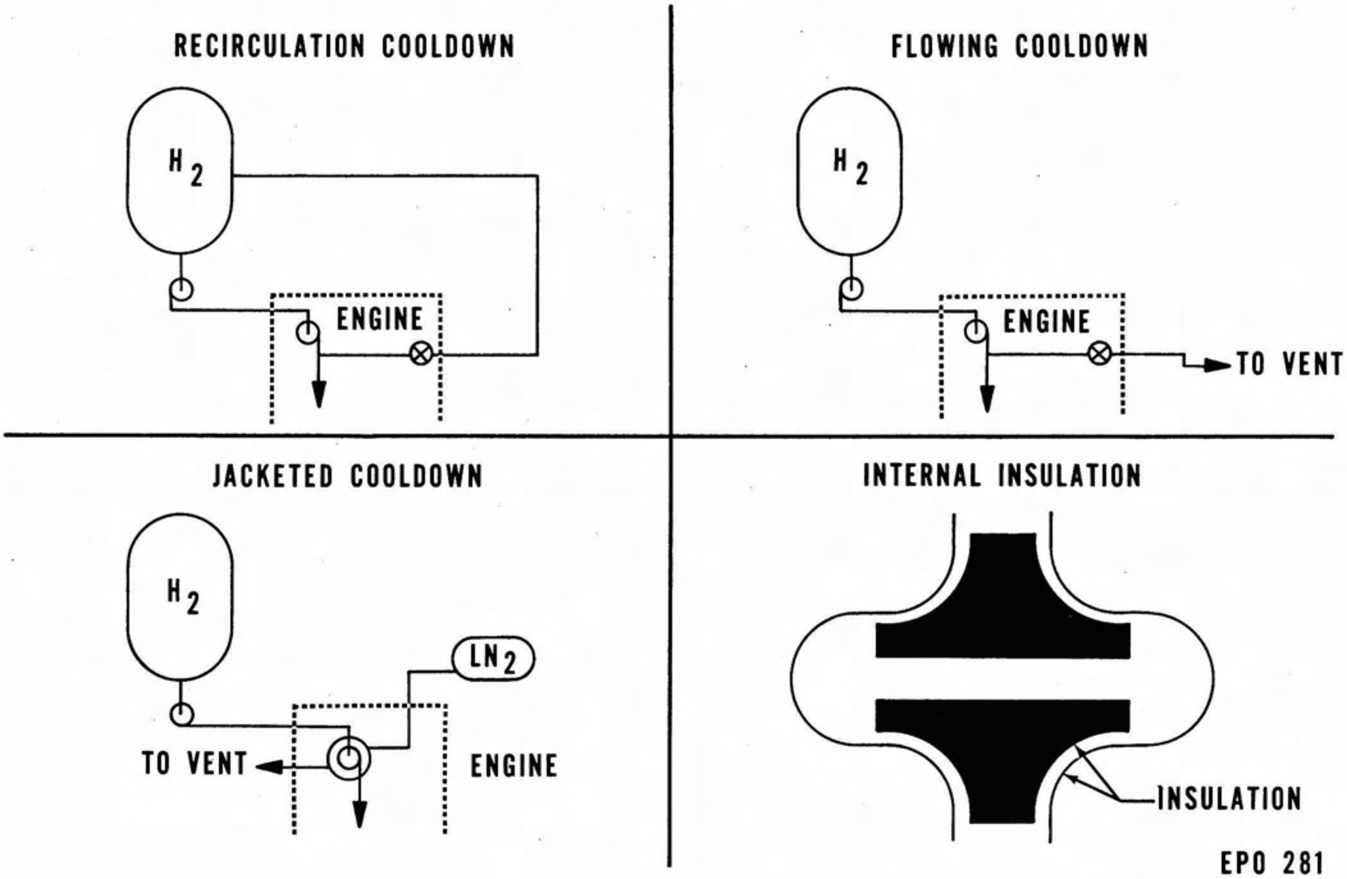


Figure 5

cryogenic temperatures long before the engine is required to start. The boiloff gases rise through recirculation lines to the vehicle tanks and the gases are replaced by more liquid in the "topping" process. Such a system is used on the LOX side in the J-2 engine as shown. The hydrogen pump is cooled by circulating hydrogen from the tank, through the pump, and back into the vehicle tank. A recirculation pump forces the hydrogen through the lines.

In the RL10 engine, the main valves are located upstream of the pumps. This system prevents high boiloff losses during coast periods due to heat input to the turbopump but requires a "pre-chill" cycle in which propellants are passed overboard through the pumps for a certain time period before start to assure liquids at the pump inlet.

Our experience in liquid hydrogen pumping has shown that the pumps do not have to be at the liquid temperature in order to supply propellants to the engine. However, heat input to the propellants must be limited to prevent evaporation to a gas in order to accomplish pumping. There are several ways of limiting the heat input to the propellants in the pump. The pumps can be precooled on the ground prior to launch and then subjected to a short in-flight rechill. This approach is used in the Centaur vehicle where liquid helium from a ground supply is circulated through the hydrogen pump prior to launch. Heat input to the pump during first stage operation is counteracted by a short in-flight rechill using the vehicle's liquid hydrogen to bring the pumps back down to the temperature required for start. This process also flushes the vehicle lines to provide liquid at the pump inlets. External insulation of the pump can be used to further reduce in-flight cooldown time. Another method of eliminating cooldown time which has shown particular promise on the RL10 engine involves insulating the internal surfaces of the hydrogen pump with a sprayed on "Kel-F" material. The internal insulation slows the heat transfer rate to the hydrogen from the warmer pump components during start-up. An insulated hydrogen pump which has undergone 1-3/4 hours of operation at liquid hydrogen temperatures is shown on Figure 4. The above cooldown approaches are summarized on Figure 5.

Liquid hydrogen, because of its low temperature, high heat capacity, and excellent heat transfer properties, is one of the best coolants known. Thus, liquid hydrogen is used to cool the thrust chamber in liquid hydrogen engines. In the RL10 engine, the initial heat of the thrust chamber is used to expand enough hydrogen to start the turbine. Once combustion is established in the chamber, the heat of combustion continues to produce enough gas in the tubular chamber walls to drive the turbine.

Performance

Since the major advantage of using hydrogen engines is their high performance, this subject warrants some discussion. Current NASA engines have a minimum specific impulse value between 420 and 430 seconds, depending on the choice of expansion ratio and engine cycle.

Both the J-2 and RL10 engines use the same type of high-performance propellant injector. Cross-section of one of the elements of this type of injector is shown on Figure 6. The oxygen is injected into the chamber through a number of tubular orifices, which extend to the injector face. Hydrogen is fed into the cavity behind the rear face of the injector. The injector face is made of a porous material. About 95% of the hydrogen flows into the combustion chamber through annular orifices formed between perforations in the porous face and each of the oxidizer orifices. The other 5% of the hydrogen flows through the porous injector face and serves to keep the injector face cool to reduce thermal stresses in the injector. It has not been necessary to place baffles on the injector of hydrogen engines since there have been no instances of combustion instability when operating within specification limits of hydrogen inlet temperature. Experience has shown that as long as the hydrogen is in the gaseous state when it is injected into the combustion chamber, combustion is stable.

This type of injector has demonstrated combustion efficiencies as high as 98.5% of theoretical, C* based on shifting equilibrium, and has shown that it is capable of performing successfully under conditions of reduced flow rates and "off-design" mixture ratios.

Vehicle Applications

Hydrogen engines have been found to be adaptable to two or more vehicle applications with a minimum of modification, for example, essentially the same RL10 engine is used in a two-engine cluster in the Centaur stage and in a six-engine cluster in the Saturn I S-IV stage. The J-2 is planned for use in one stage of the Saturn IB vehicle and in two stages of the Saturn V vehicle. A significant development on the vehicle side has been in supplying cryogenic propellants to these engines at the right temperature and pressure to permit satisfactory engine operation. The necessary tank pressurization, ullage rockets, boost pumps, and/or vacuum jacketed lines must be provided to keep the propellants in their cryogenic state and to provide a pressure above the engine's minimum net positive suction head (NPSH) One of these developments has been the vacuum jacketed flexible inlet lines for the J-2 engine (See Figure 7). It was necessary to develop an 8 inch diameter vacuum jacketed line which would flex over an angle of 7.6°, compress and extend ±4-1/2 inches, and hold up under many cycles of flexing at liquid hydrogen temperatures.

Progress in Areas Unique to Upper Stage Engines

The choice of hydrogen as a fuel for the upper stages of space vehicles has resulted not only in solution of problems related specifically to hydrogen engines, but has resulted in the accumulation of extensive data on cryogenic engines which must operate in a space environment. To get the maximum performance under space conditions, it is desirable to use the highest feasible nozzle expansion ratio. But high expansion ratio engines must be tested under simulated space conditions to prevent flow separation in the nozzle. Flow separation can cause overheating at the separation point and/or excessive side forces. Thus, the high-altitude rocket developer has the choice of either building space-simulating test stands or designing the engine nozzle so it will flow full at sea level conditions. For relatively small space engines, up to the RL10 size, it is practical to build steam ejectors which produce the vacuum to simulate engine starting in space, and supersonic exhaust diffusers which allow the engine to maintain its own simulated space environment while operating. As the engines get larger, however, these facilities become quite expensive. The choice on the J-2 engine, for example, was to sacrifice space performance slightly by designing a nozzle that would flow full at sea level and thus enable ground testing of both the engine and stages incorporating the engine without the use of steam ejectors and diffusers. In ground firings of the J-2 engine, we have found it necessary to restrain the engine to prevent starting side loads from distorting the chamber. Our development program on this engine includes work towards redesigning and testing modifications to the thrust chamber and test setup to prevent adverse effects on the engine structure during ground testing.

Other areas which are affected due to the operation of engines in the vacuum of space are lubrication and sealing. The NASA liquid hydrogen upper stage engines use cryogenic fluids to cool the engine moving parts to eliminate wear due to friction. Thus moving parts within the engine are supplied with some of the best cooling mediums known to man. Moving joints external to the engine; particularly those exposed to the vacuum of space such as the engine gimbal and actuator joints, must be lubricated and/or sealed to prevent "vacuum-welding" of metal-to-metal surfaces. Special lubricants have been developed for these purposes which perform well at wide temperature extremes and which stay in place in a "hard vacuum."

Since a gaseous environment such as air or nitrogen serves as an impedance for high voltage electrical flow, it is often desirable to maintain this type of environment in portions of the engine electrical system. Sealants had to be developed which would prevent the escape of these gases prior to and during engine operation in space to assure that the ignition and other electrical systems would operate properly.

So far, two vehicles incorporating hydrogen upper stage engines have flown successfully. The Centaur AC-2 vehicle, incorporating two RL10 engines in its second stage, was flown last November (See Figure 8). The Saturn S-IV-5 vehicle, with six RL10's in its second stage, was flown in January of this year. In both flights, the engines started, operated, and shut down as predicted. Performance was within 1% of that which was predicted from ground firings. An area of development which remains to be proven in flight is restarting in space. Restarting of hydrogen engines after a coast period is part of the overall NASA plan for landing a man on the moon and for other space missions. We believe that restarting a hydrogen fueled engine in space may not be as large a problem as some had anticipated. Data from the Saturn and Centaur flights have shown that heat input to the engine turbopump during coast is not as high as had been anticipated. If this is true, engines may not have to be rechilled prior to subsequent starts, a feature which would save valuable cryogenic propellants. Since there is no natural convection under space conditions, the principal heat input is radiation from the sun (a small radiation source compared to the surrounding blackness of space). Further, we have run tests on the RL10 engine which show that hydrogen engines can be run at low thrust levels on liquid or gaseous propellants forced into the engine by tank pressure alone. This feature would allow self-settling of propellants and provide a natural mode for rechilling the engine and vehicle lines if it is required.

To sum up our development and flight experience with hydrogen engines, we have demonstrated the following things:

1. That hydrogen can be pumped (We have developed methods of pump cooldown which permit pumping of cryogenics.)

2. That hydrogen is an excellant coolant (It can be used to cool regeneratively cooled chambers and for cooling bearings.)

3. That the "topping" cycle can be developed into a highly reliable engine system (Driving a turbine with hydrogen gas heated in the thrust chamber walls is practical.)

4. That a hydrogen engine will operate satisfactorily under actual space conditions (Successful Saturn and Centaur two-stage flights showed this.)

5. That a hydrogen engine can be throttled to 10% thrust and back

6. That a hydrogen engine can operate in the "pressurized" mode on liquid or gaseous fuel (Thrust of 2 to 3% of related thrust is achieved.)

7. That a hydrogen engine can be started by hypergolic ignition of the fuel with a mixture of LOX and .5% O_3F_2

8. That performance of H_2 engines in flight can be predicted within ±1% (Less than predicted flight instrumentation accuracy.)

9. That hydrogen space engines can be built reproducibly.

10. That 98.3% combustion efficiency can be achieved in an H_2 Engine

11. That combustion stability is not a problem. In fact stability is one of the characteristics of LOX/H_2 engines as compared to the more conventional propellant combinations such as LOX/RP engines.

12. That a hydrogen engine can provide gaseous hydrogen for vehicle tank pressurization

13. That gimbal lubricants can operate in space

14. That the "common-engine" approach is economical for hydrogen engines in two or more applications.

15. That the hydrogen engines can withstand vibrations in excess of those encountered during typical flight conditions

16. That turbopumps can be prechilled on the ground to shorten in-flight cooldown time (increase of payload made possible by shorter coast)

17. That heat input to the engine during flight is less than expected

18. That clusters of two, six or possibly more engines can be ignited, run, and shut down simultaneously

19. Pumping Hydrogen can be accomplished with an axial flow pump

20. Vacuum jacketed, flexible inlet lines can be used for hydrogen

21. Static sealing techniques for hydrogen are practicable

22. Dynamic sealing techniques have been developed for liquid hydrogen which results in minimum leakage

23. A self-regenerating start cycle is practicable (The storage of hydrogen bled from the the engine to be used for restart)

24. That a metal porous face injector can be used to reduce thermal stresses in the injector

25. That mechanically independent turbopumps, connected hydrodynamically can be used to independently control fuel and LOX flow

Conclusion

NASA's commitment to use hydrogen for upper stages was the right decision. The successful operation of Centaur vehicle AC-2 and the good Saturn performance on it's first two stage flights confirm this. We have shown that hydrogen stages using hydrogen-burning engines can be flown, and we have explored the limits of liquid hydrogen engine technology in the smaller size ranges to demonstrate applicability of these engines to other systems which require a high performance and a high degree of controllability and reproducability. We are confident that we are going along a path which will allow hydrogen engine technology to keep pace with the other rapidly advancing facets of the launch vehicle, spacecraft, and overall space program.

FIG. 1

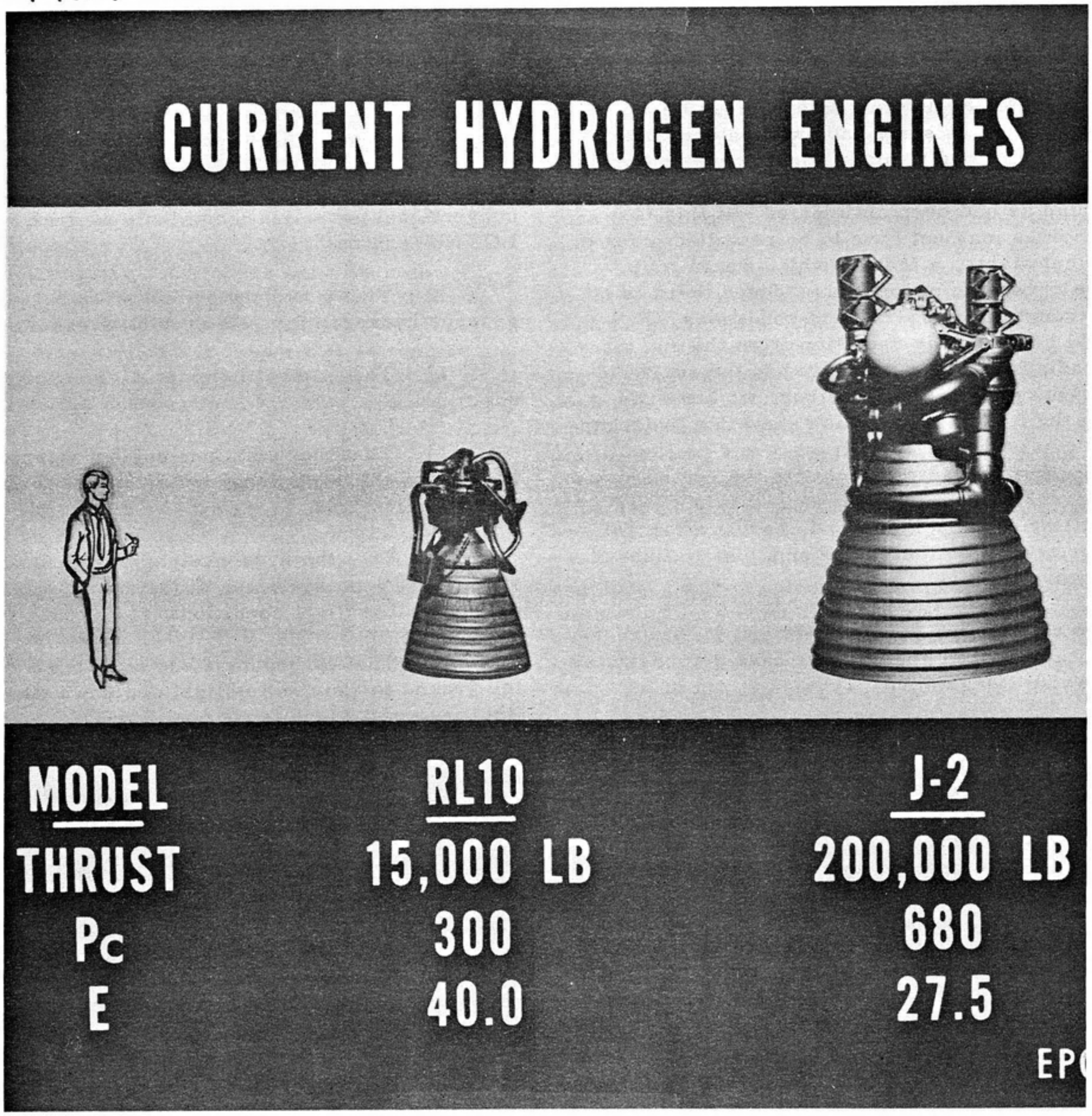


FIG 2

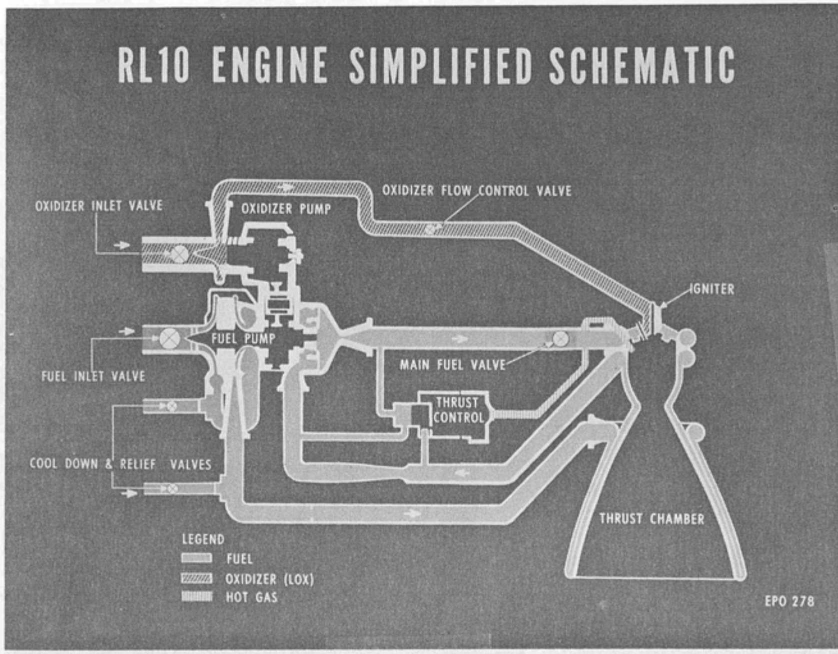


FIG 3

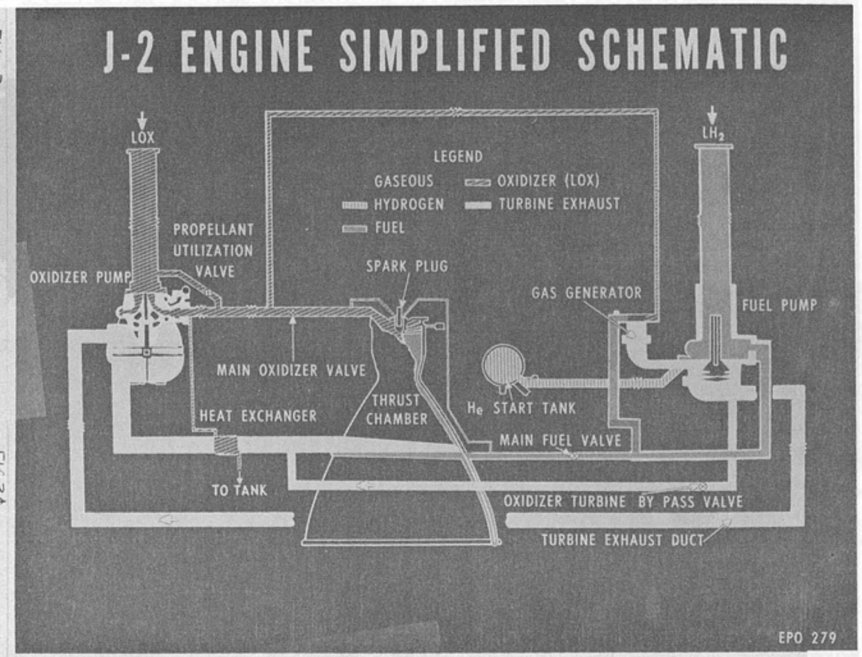


FIG 4

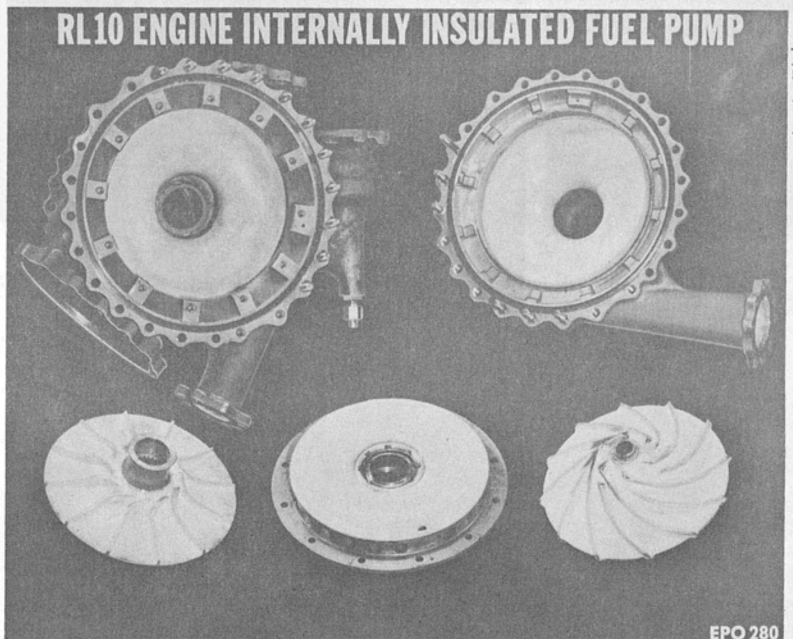
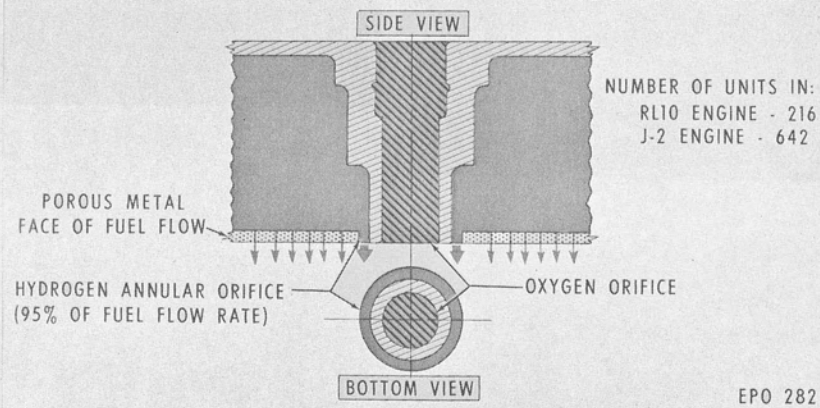


FIG. 5 APPEARS ON PAGE 2

FIG. 6

TYPICAL INJECTOR ELEMENT - HYDROGEN ENGINE



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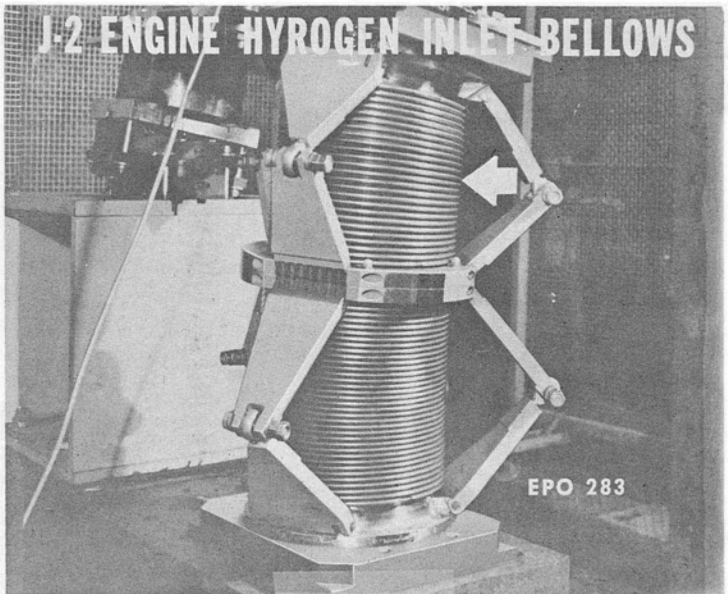

FIG. 7 ↑ FIG8 ↓

FIG 9. ↓