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FLIGHT OPERATION OF A PUMP-FED LIQUID-HYDROGEN FUEL SYSTEM

By David B. Fenn, Loren W. Acker
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WASHINGTON April 1960

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

TECHNICAL MEMORANDUM X-252

FLIGHT OPERATION OF A PUMP-FED LIQUID-HYDROGEN FUEL SYSTEM*

By David B. Fenn, Loren W. Acker, and Joseph S. Algranti

SUMMARY

A pump-fed liquid-hydrogen fuel system was developed and flight tested in a B57 bomber. The aircraft was flown to an altitude of 50,000 feet and a Mach number of 0.75 with JP-4 fuel in both engines. One engine was then switched to hydrogen operation for approximately 11 minutes.

The liquid-hydrogen pump used for these flights was a five-cylinder positive-displacement type submerged in the bottom of the hydrogen tank.

The hydrogen flow regulator was able to maintain a constant engine speed even though pump speed and discharge pressure oscillated.

INTRODUCTION

Considerable attention has been given to the improvement of turbojet aircraft performance through the use of high-energy fuels. Liquid hydrogen is one such fuel that is attractive because of its high heat of combustion and its potentialities as a heat sink for cooling the high-temperature components of both the engine and airframe. An analysis of the performance possibilities of liquid hydrogen for increasing the range and operating altitudes of several types of aircraft is presented in reference 1.

In the investigation reported in reference 2, a twin-engine medium bomber was modified to burn hydrogen in one engine. In that installation, liquid hydrogen was stored in a wingtip tank and was pressurized with helium gas. In an operational-flight fuel system, however, a liquid-hydrogen pump should be used instead of a pressurized tank. The use of thinner tank materials and the elimination of high-pressure helium tankage would offset the weight of the pump.

*Title, Unclassified.

To demonstrate the feasibility of pumping boiling liquid hydrogen in flight, the aircraft fuel system reported in reference 2 was modified by the addition of a five-cylinder reciprocating pump. In an effort to avoid the cavitation problems associated with pumping boiling liquids, the pump was designed with the pistons operating at low speed and with the inlet side of the pistons submerged in the bottom of the wingtip hydrogen tank. Reference 3 contains design details of the pump, together with some preliminary performance data. The other parts of the present fuel system were the same as described in reference 2.

The present report contains a brief description of the major fuel system components and their operation in flight. Data are included to show the overall performance of the system during a typical flight.

APPARATUS

The aircraft used for this investigation was a B57 twin-engine bomber. A photograph of the airplane with the hydrogen system installed is shown in figure 1. The hydrogen pump was covered by a fairing at the bottom of the left wingtip tank, and its hydraulic drive motor was located on top of the wingtip (fig. 2).

Helium gas was stored at high pressure in the right wingtip tank to purge the hydrogen tank after the fuel was exhausted and to purge the hydrogen flow system before and after operation.

A schematic diagram of the hydrogen fuel system is presented in figure 3. With the exception of the hydrogen pump, this system is essentially that reported in reference 2. Liquid hydrogen was pumped from the bottom of the storage tank through a shutoff valve in the pylon to a heat exchanger used to vaporize the fuel. The metered JP-4 fuel flow from the engine speed control was bypassed through the hydrogen regulator to the JP-4 fuel tank in the airplane. This JP-4 flow was used in the regulator to control the flow of hydrogen gas to the engine.

Hydrogen Pump

The hydrogen pump (ref. 3) was designed to operate at 240 rpm with a capacity of 55.1 gallons per minute and a discharge pressure of 130 pounds per square inch. A partial section through the pump is presented in figure 4. The intake side of the pump was completely submerged in liquid hydrogen to minimize cavitation. The five cylinders of the pump were each 3 inches in diameter and were arranged in a circle around a driving wobbler with a $1\frac{1}{2}$-inch stroke. Spring-loaded intake and exhaust valves were installed in the pistons and cylinder heads. The individual cylinders discharged into a vacuum-insulated manifold that was outside of the hydrogen tank.

Pump Control

In order to avoid changing the fuel flow control developed for use with the pressurized tank system reported in reference 2, a pump control was devised to maintain a constant pump discharge pressure (approx. 55 lb/sq in. abs) over a wide range of hydrogen flow rates. The hydrogen pump was a positive-displacement type so that the discharge pressure was a direct function of the torque applied by the hydraulic motor. A positive-displacement hydraulic motor was selected to produce a torque proportional to the applied hydraulic pressure. Thus, the hydrogen-pump discharge pressure was a function of the hydraulic pressure applied to the hydraulic motor. A variable-delivery hydraulic system was used to supply the hydraulic motor with constant-pressure oil over a wide range of hydraulic oil flow rate. This allowed the rotative speed of the hydrogen pump and hydraulic motor combination to change in response to changes in hydrogen demand without affecting the hydrogen-pump discharge pressure.

Heat Exchanger

A heat exchanger was included in the hydrogen system to supply a single-phase fluid to the hydrogen flow regulator and to simulate a system in which the heat sink of the fuel is utilized to cool hot parts of the engine or airframe. This heat exchanger (fig. 5) was designed to vaporize 520 pounds per hour of liquid hydrogen (the engine flow) by cooling 1.75 pounds per second of ram air from -23° to -85° F. Details of the heat-exchanger design and its performance characteristics are included in reference 4.

Hydrogen Flow Regulator

The hydrogen flow regulator is shown in figure 6 and is described fully in reference 5. The regulator was a ratio controller that utilized the metered JP-4 fuel flow from the standard engine fuel control to control the flow of hydrogen gas from the heat exchanger. The JP-4 side of the regulator contained a piston with an orifice such that a force proportional to flow was transmitted through a connecting lever to the hydrogen side. The hydrogen flow acted on a similar piston connected to a pressure-balanced valve. The pistons moved until sufficient hydrogen flow was established to balance the connecting lever. In this manner the unit controlled the volume flow of hydrogen in a constant ratio to the flow of JP-4 fuel.

PROCEDURE

The aircraft was flown to an altitude of approximately 50,000 feet with JP-4 fuel in both engines. After cruise altitude was reached, the hydrogen tank was vented to atmosphere through a check valve. The check valve was used to maintain a pressure of approximately 10 pounds per square inch absolute in the tank before the hydrogen run and to prevent air from entering the tank if the pressure decreased during the run. The hydrogen pump was started and allowed to pump against the closed discharge valve (supply shutoff, fig. 3) while the hydrogen flow system was being purged with helium gas.

The transition from JP-4 fuel to hydrogen operation was accomplished in two steps: dual fuel operation and complete hydrogen operation. Engine speed could be altered at any time with the standard airplane throttle by adjusting the JP-4 flow to the hydrogen regulator which, in turn, changed the hydrogen flow to the engine. When the liquid-hydrogen supply was nearly exhausted, the hydrogen flow was stopped and JP-4 was routed back to the engine. The hydrogen flow system and supply tank were purged with helium gas before the aircraft was landed. A more complete description of the transition from JP-4 to hydrogen operation and vice versa is contained in reference 2.

RESULTS AND DISCUSSION

Three successful flights were made with the liquid-hydrogen pump. The pump was submerged in boiling liquid hydrogen at approximately 10 pounds per square inch absolute. The normal boiloff of the liquid in the tank was sufficient to prevent the tank pressure from falling below this value during the hydrogen run. On each flight the airplane was flown to an altitude of about 50,000 feet with JP-4 fuel in both engines. At cruise altitude the left engine was switched from JP-4 to hydrogen operation. After approximately 11 minutes of hydrogen operation, the supply tank was nearly empty and the engine was switched back to JP-4 operation. These fuel transitions were accomplished on each flight without incident.

Transition of Hydrogen

A typical time history of the transition from JP-4 fuel to hydrogen is shown in figure 7.

<u>Pump deadheaded.</u> - The pump was started while the hydrogen flow system was being purged with helium. Because the pump discharge valve was closed, the pump rotated only until the discharge pressure increased to the value set by the hydraulic supply pressure to the pump drive motor.

The hydrogen pump then stopped while the trapped liquid hydrogen boiled and finally leaked past the relief valve and/or back through the pump valves into the tank. As soon as the discharge pressure fell below the set value, the pump rotated and the cycle was repeated. Each time the pump rotated, the hydraulic pressure at the motor fell slightly because of the pressure loss in the long supply line between the hydraulic pump and motor.

Dual fuel operation. - Practically no change in engine speed occurred when hydrogen flow was initiated and the JP-4 flow was split between the engine and the hydrogen regulator. The hydrogen flow during dual fuel operation was approximately 350 pounds per hour. With the pressurized tank system reported in references 2 and 6, the engine speed decreased initially because of the loss of JP-4 fuel and recovered when hydrogen reached the engine. The pump capacity used in the present investigation was sufficiently large to fill the system quickly to avoid a decrease in engine speed.

Fuel System Oscillations

Although the hydrogen regulator was able to maintain a constant engine speed during hydrogen operation (fig. 7), the pump discharge pressure and pump speed oscillated. The amplitude and frequency of these oscillations were a function of hydrogen flow rate. With the engine operating on hydrogen alone, the oscillations were of a higher frequency and slightly lower amplitude than with the reduced flow of dual fuel operation. It is believed that these oscillations were caused by overfilling of the heat exchanger when the pump rotated, in an effort to bring the pump discharge pressure up to the value set by the hydraulic system. The pump was so large that, when it rotated to pressurize the system, it filled the heat exchanger with liquid much faster than the engine could use it. Consequently, an excess of liquid was present in the heat exchanger when the pump stopped (point A, fig. 7) at the pressure set by the hydraulic system. The hydrogen regulator throttled the gas flow out of the heat exchanger to maintain constant engine speed. However, the engine demand plus the leakage back past the pump valves into the tank was less than the evaporation rate of the excess liquid in the heat exchanger; this caused the pump discharge pressure to continue to rise after the pump had stopped (points B to C, fig. 7). When the excess liquid had been used by the engine, the pressures fell below the set value, allowing the pump to rotate again. As soon as the pump started, the hydraulic supply pressure to the motor decreased because of the pressure drop between the hydraulic pump and motor. This effectively lowered the set value of pump discharge pressure and allowed it to continue to fall while the pump accelerated (points D to E, fig. 7). When the pump discharge pressure increased to the set value again, it stopped and the cycle was repeated.

The oscillations encountered with the pump-fed system were entirely different from those found with the pressurized system reported in reference 6. With the pressurized system, engine speed oscillated at a frequency of about 8 cycles per minute during the initial portion of some of the runs. In this case the heat exchanger, starved of liquid hydrogen, caused engine speed to decrease. When the system had cooled completely, it became stable.

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Transition from Hydrogen to JP-4 Fuel

A typical time history of the transition from hydrogen to JP-4 is presented in figure 8, which has been reproduced to a larger scale than figure 7. When the supply of liquid hydrogen was exhausted, the pump discharge pressure decreased and the pump speed increased in an effort to maintain the pressure. As the pump discharge pressure continued to fall, the JP-4 flow to the regulator increased in response to the decrease in engine speed. The engine returned to normal operation within a few seconds after the JP-4 flow was routed back to it, and the hydrogen system was purged with helium.

Heat-Exchanger Icing

The heat-exchanger performance data of reference 4 indicate that the tube walls were cold enough (350° R) to form ice in the heat exchanger if sufficient moisture was present in the ram air. During the present flights, a camera was installed in the heat-exchanger inlet duct. Photographs of the inlet air side of the core (fig. 9) were taken before and during hydrogen operation at an altitude of approximately 50,000 feet. No ice was visible on the heat-exchanger tubes.

CONCLUDING REMARKS

A positive-displacement liquid-hydrogen pump was used to operate one engine of a twin-engine medium bomber at an altitude of approximately 50,000 feet. JP-4 fuel was used in both engines for the climb to cruise altitude. One engine was then switched to hydrogen operation for about 11 minutes. When the hydrogen was exhausted, the engine was switched back to JP-4 fuel. Three successful flights were made with the pump, and on each occasion the fuel transitions were made without incident. The hydrogen flow regulator was able to maintain a constant engine speed even though pump speed and discharge pressure oscillated.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, December 18, 1959

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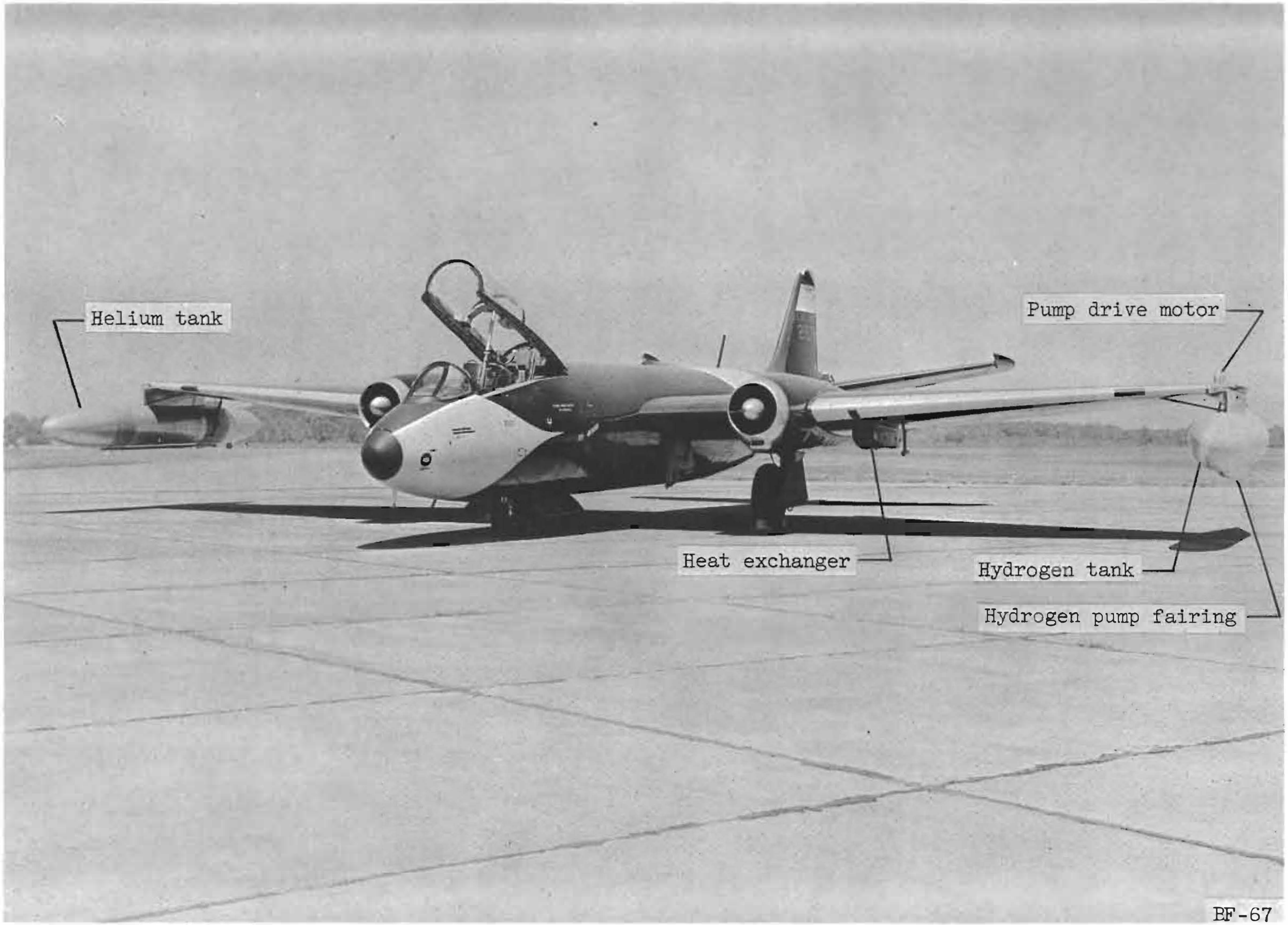

Figure 1. - Aircraft with pump-fed liquid-hydrogen fuel system.

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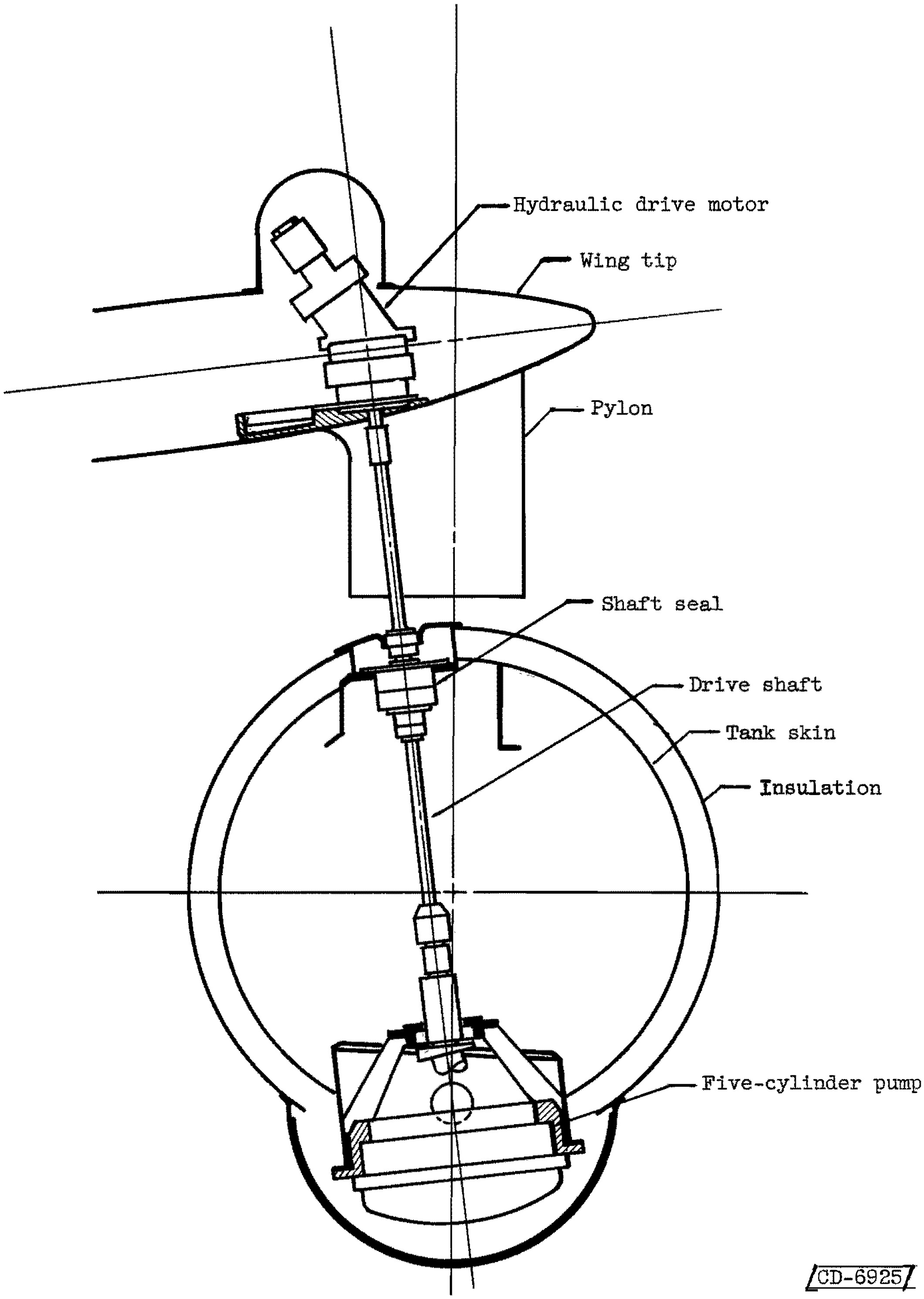

Figure 2. - Front view of pump and drive-motor installation in wingtip tank.

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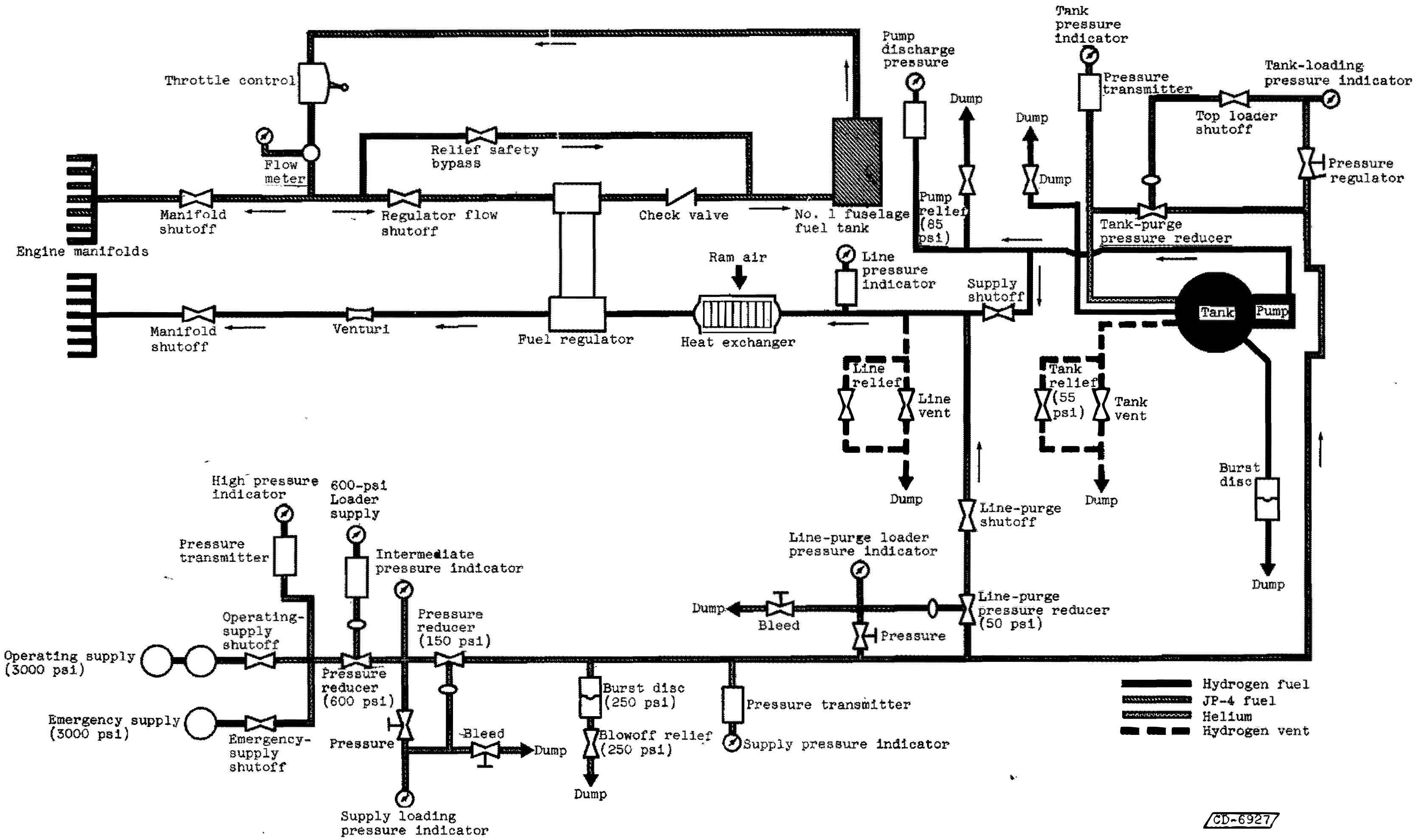

Figure 3. - Pump-fed liquid-hydrogen fuel system.

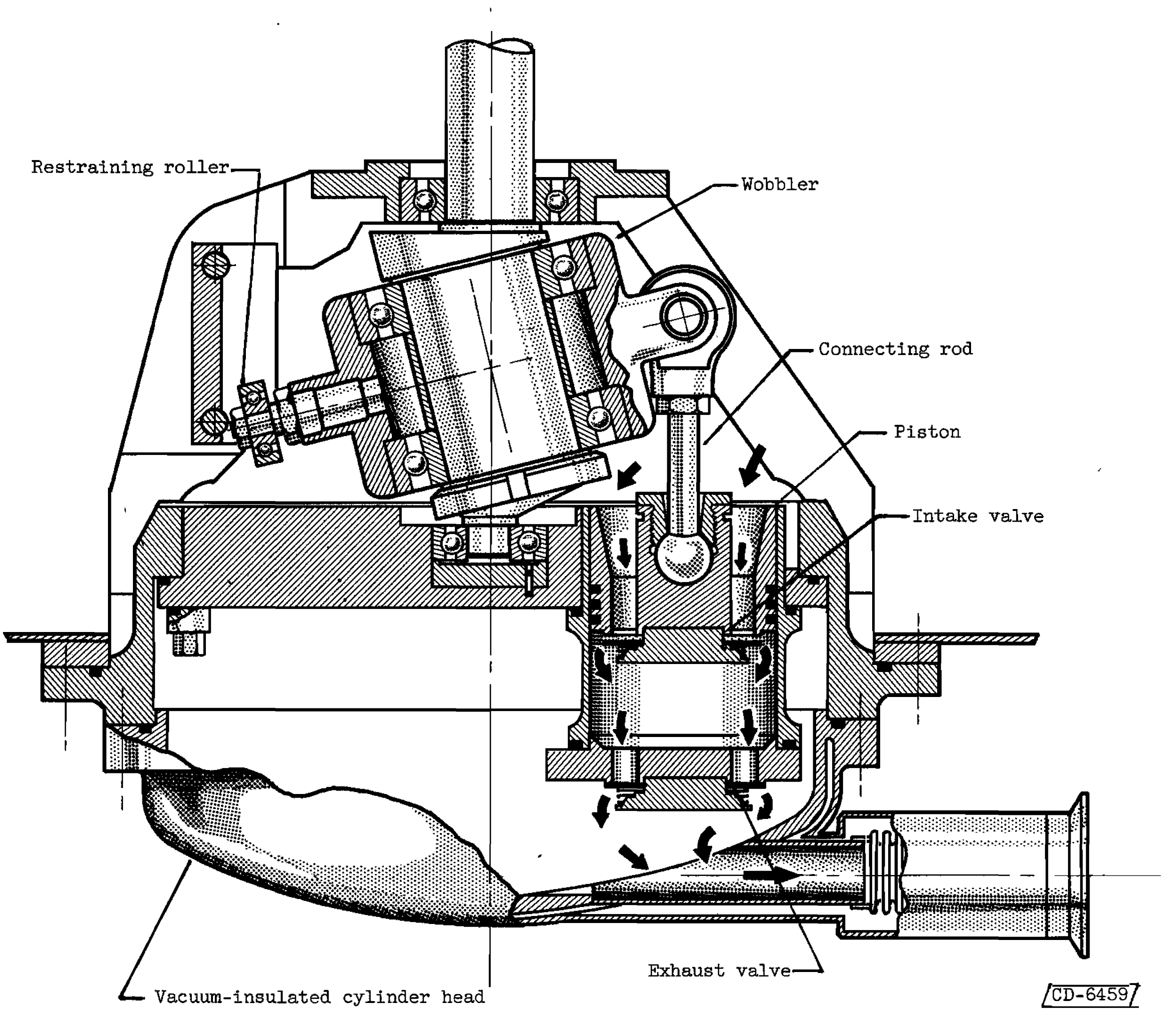

Figure 4. - Section through five-cylinder pump as constructed for flange mounting in bottom of tank.

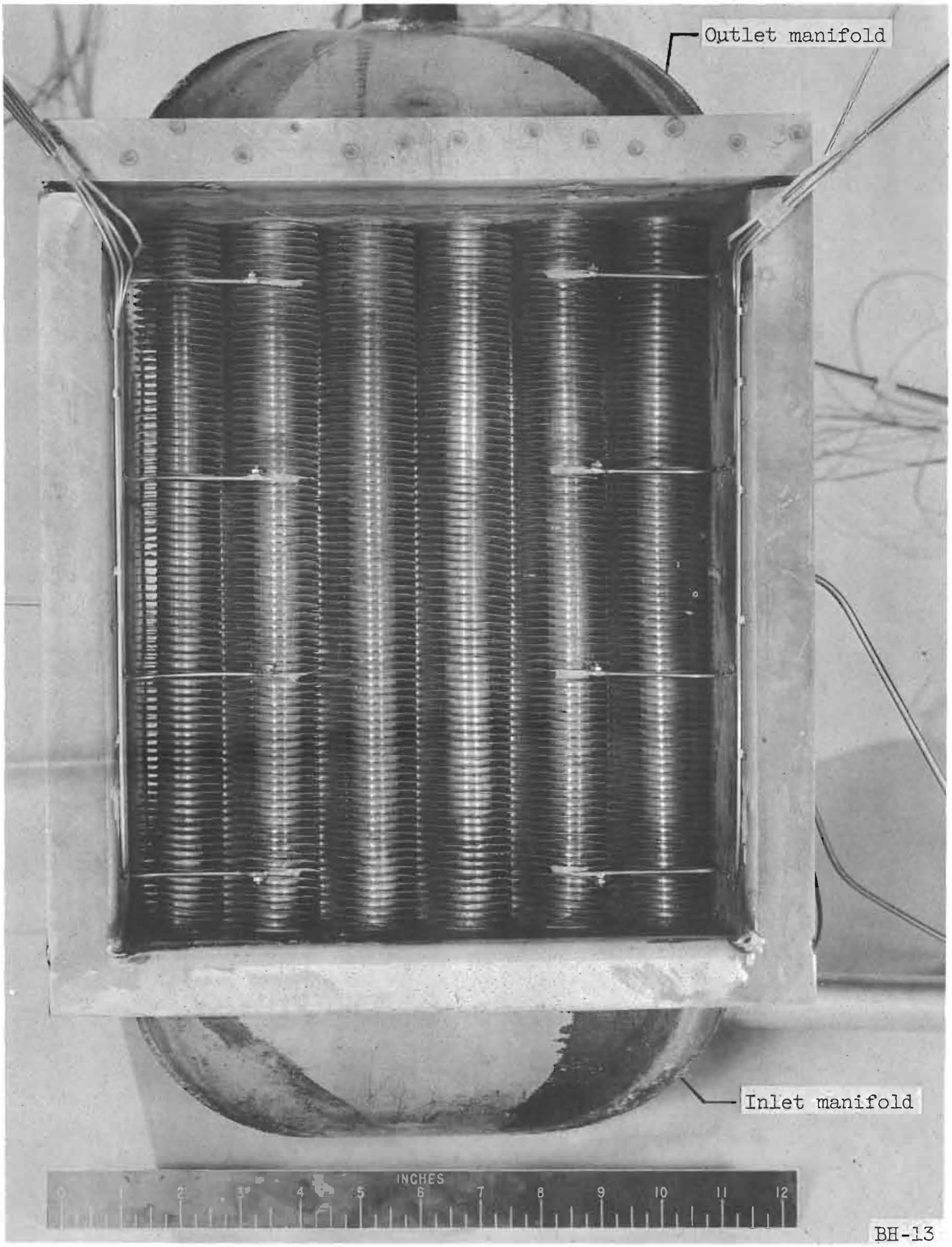

Figure 5. - Heat exchanger.

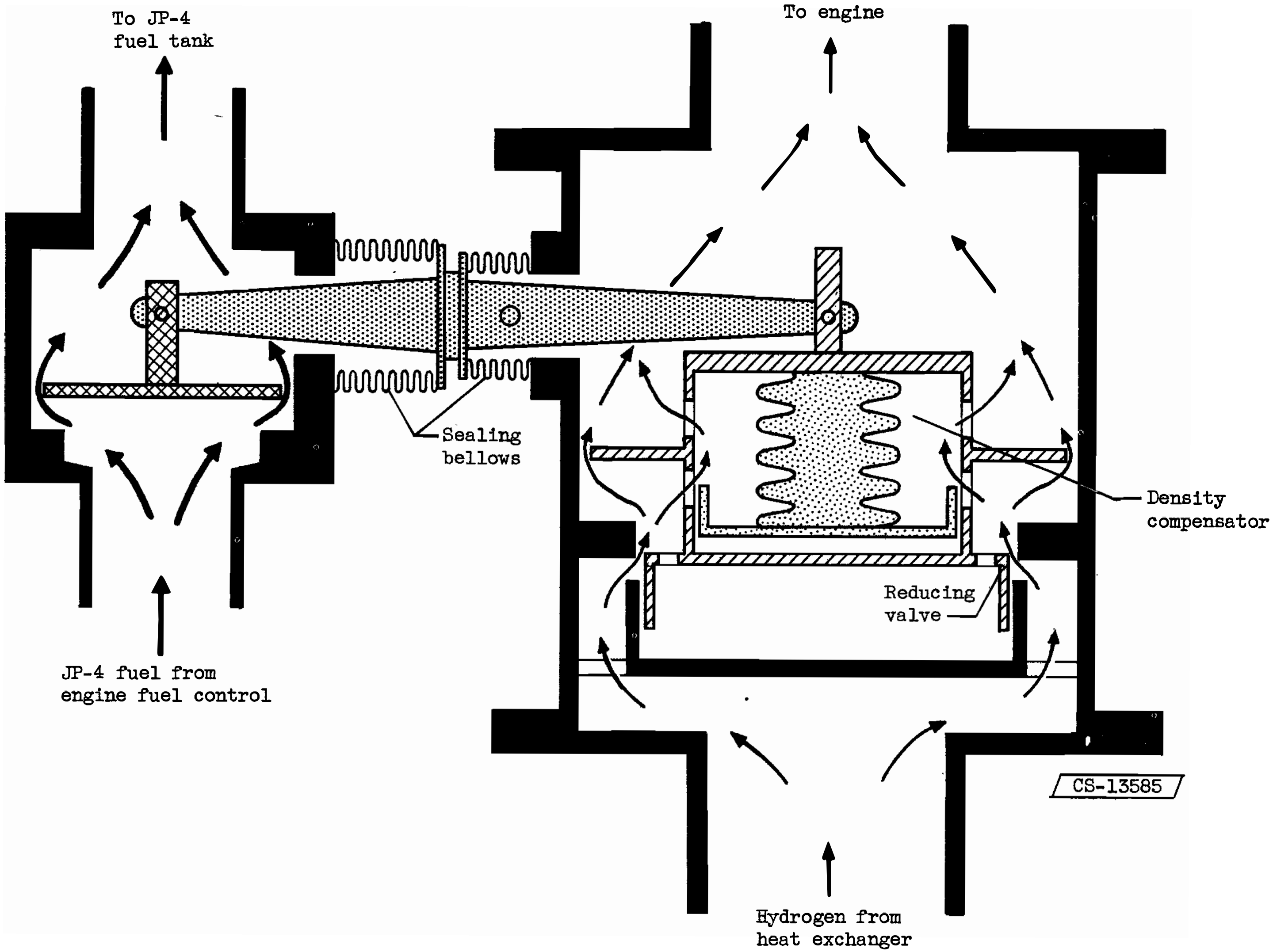

Figure 6. - Hydrogen flow regulator.

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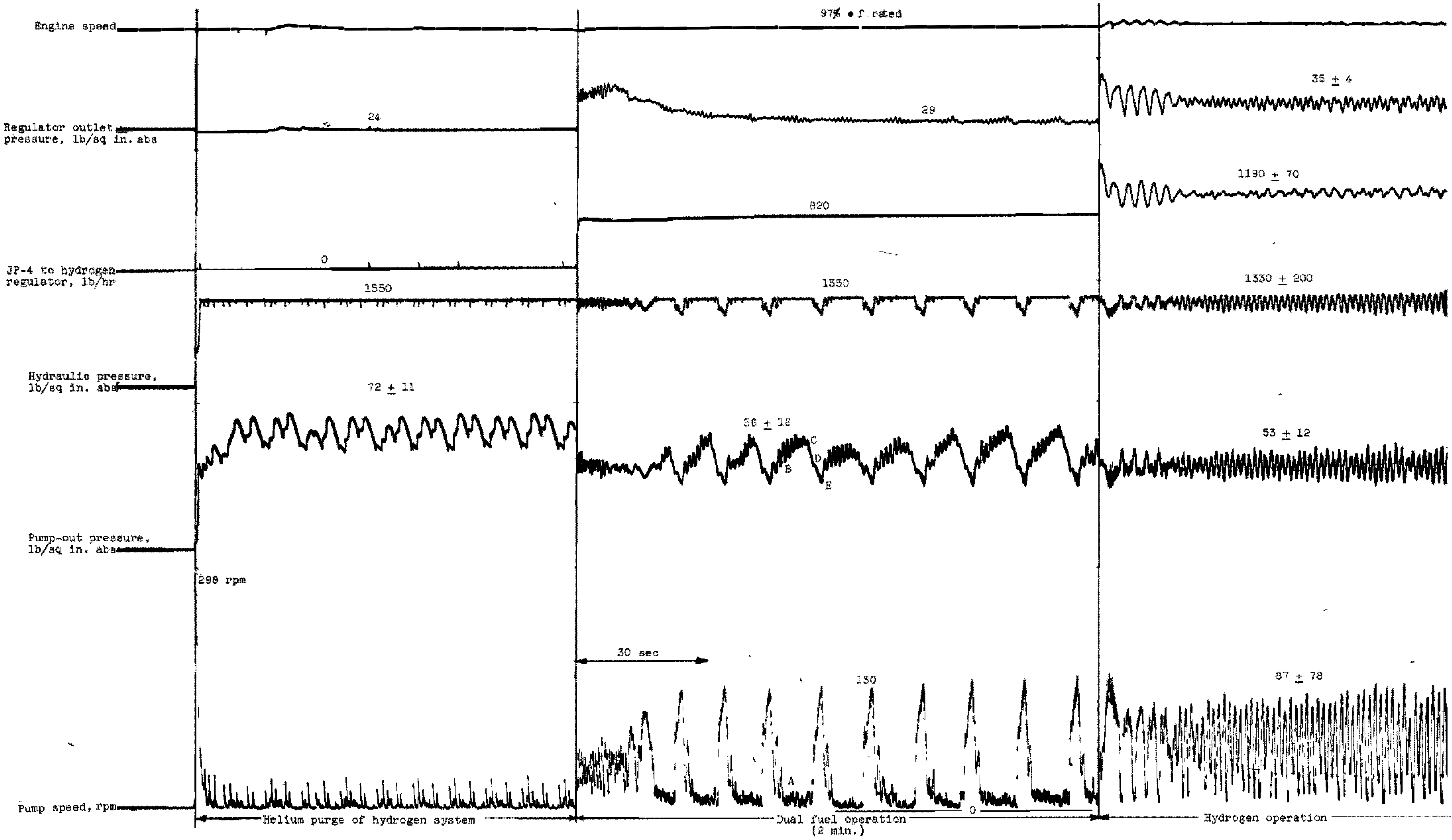

Figure 7. - Transition from JP-4 fuel to liquid-hydrogen operation.

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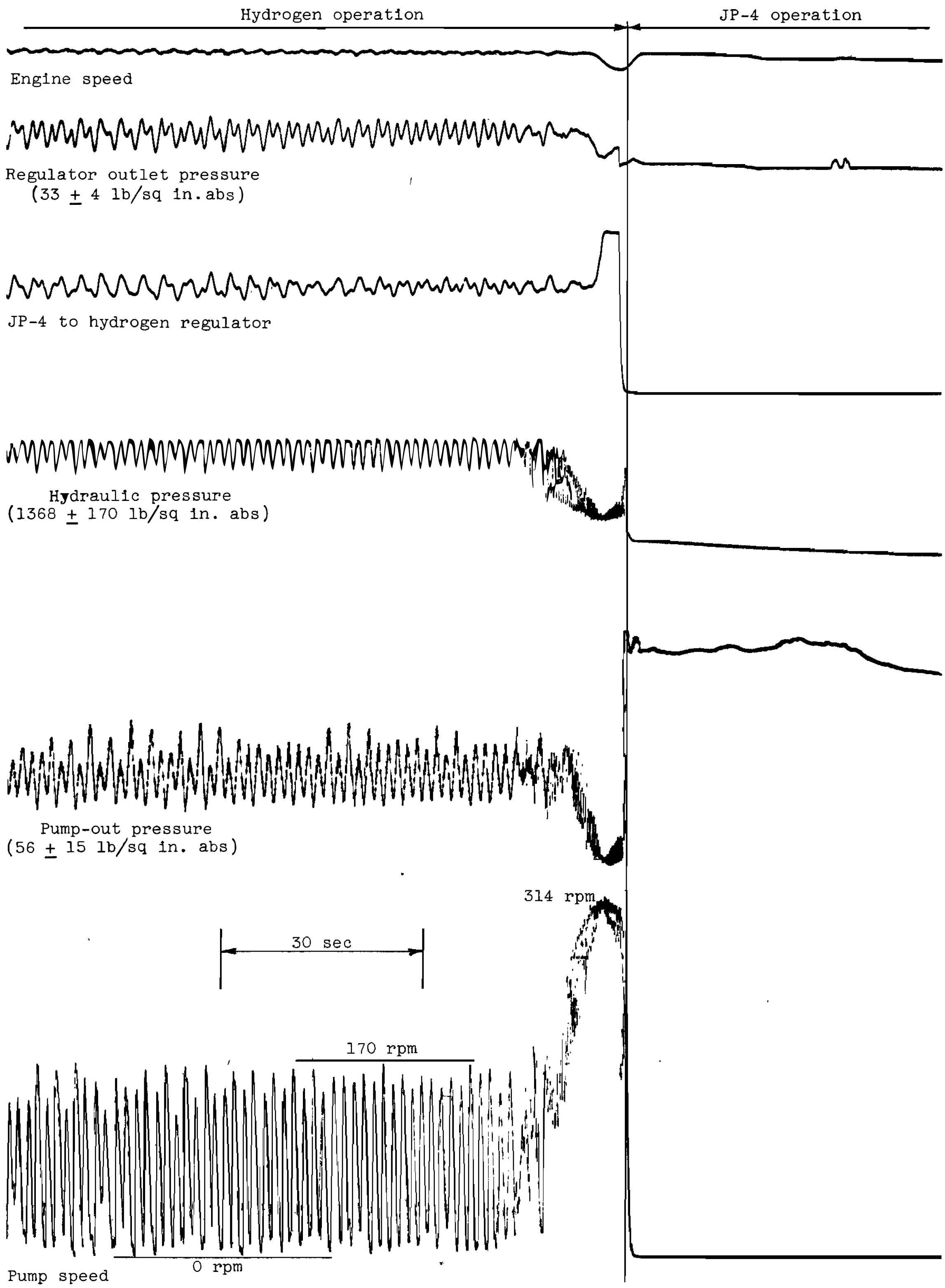
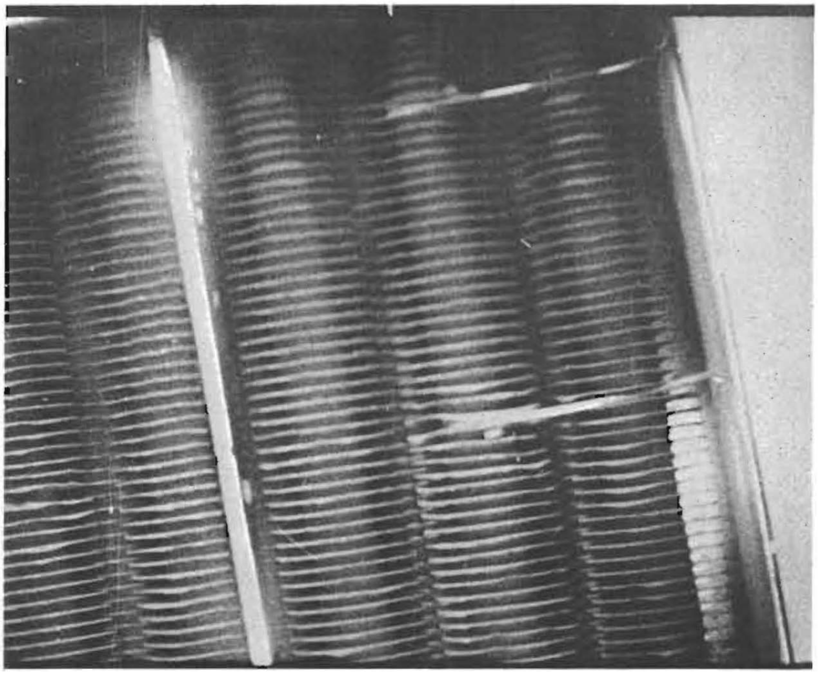
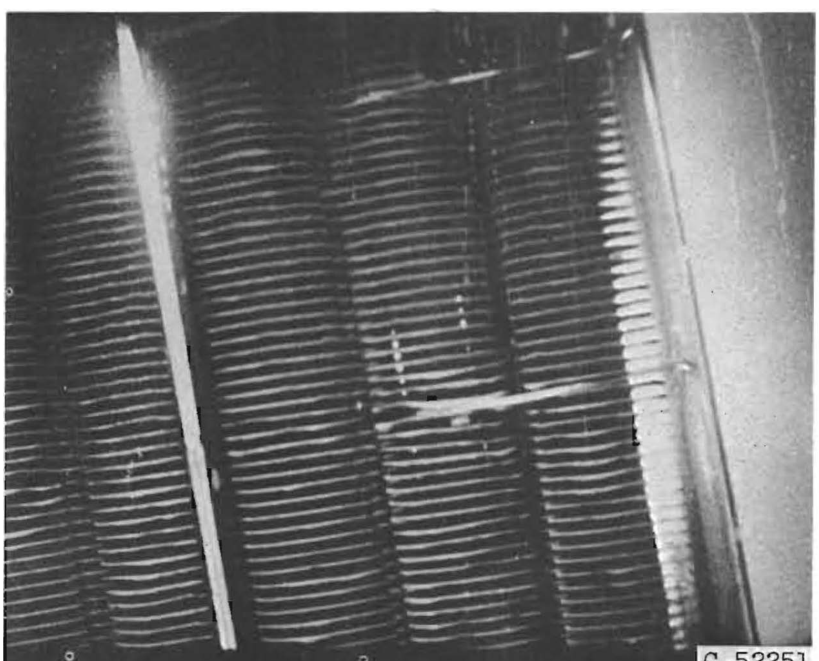


Figure 8. - Transition from liquid-hydrogen to JP-4 fuel operation.



(a) Before hydrogen operation.



(b) During hydrogen operation.

Figure 9. - Inlet air side of heat exchanger. Altitude, 49,700 feet; Mach number, 0.7; total temperature, 430° R.

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A B57 bomber was flown at an altitude of 50,000 feet and a Mach number of 0.75 with hydrogen in one of the two turbojet engines. The liquid-hydrogen pump was a five-cylinder positive-displacement type submerged in the bottom of the hydrogen tank. Some oscillations of pump speed and outlet pressure were observed, but the hydrogen flow regulator was able to maintain constant engine speed.

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