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RESEARCH MEMORANDUM

FLIGHT INVESTIGATION OF A LIQUID-HYDROGEN FUEL SYSTEM

By Donald R. Mulholland, Loren W. Acker, Harold H. Christenson, and William V. Gough

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WASHINGTON
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RESEARCH MEMORANDUM

FLIGHT INVESTIGATION OF A LIQUID-HYDROGEN FUEL SYSTEM

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SUMMARY

A twin-engine light bomber was modified to utilize hydrogen fuel in one of the two engines during flight at an altitude of 50,000 feet. The fuel was stored as a liquid in an insulated wingtip tank. A pressurized fuel system was used in lieu of a pump for liquid hydrogen. The fuel system provided for vaporization of the fuel in a ram-air heat exchanger and regulation of hydrogen vapor flow to the engine by means of a specially designed regulator. The regulator utilized the metered JP fuel flow from the standard engine throttle control to regulate vaporized hydrogen flow to the engine.

Three completely successful flights were made using hydrogen fuel. The airplane climbed on JP fuel to cruise altitude, where the engine was shifted to hydrogen fuel and then back to JP fuel after the hydrogen supply was exhausted. Transition was made to hydrogen fuel without serious effects on engine operation. Steady-state and transient operation were both highly satisfactory. Heat-exchanger performance compared favorably with simulated altitude performance in the laboratory. During operation with hydrogen, the engine produced a very heavy and persistent condensation trail, while the engine using JP fuel produced none.

Data are presented to show the effect of tank agitation on fuel pressure and fuel losses. Jostling of the liquid during flight and especially during taxiing substantially reduced the rate of pressure increase in the tank.

Hydrogen gas created by fuel boiloff was periodically vented from the tank during flight, and on two occasions unused liquid hydrogen was jettisoned from the fuel tank without incident.

INTRODUCTION

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The desire for improvement of United States military air capability to operate at higher altitudes and to fly farther has led to an

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investigation of the use of hydrogen as an aircraft fuel where the fuel would be stored as a liquid. During the past 2 years a number of studies have been made at the NACA Lewis laboratory relative to this use of hydrogen. The results of analytical studies indicate that a very substantial gain may be obtained in altitude and range by the use of hydrogen in turbojet engines as opposed to JP fuel (ref. 1). Combustion performance of hydrogen over a wide range of pressure conditions has been highly satisfactory even when it was introduced into the combustor at temperatures as low as 50° R (refs. 2 and 3).

Furthermore, satisfactory combustion has been attained in very short combustors, which would allow for the possibility of relatively short engines compared with present JP fuel engines and would in turn give commensurate savings in engine weight and space requirements (refs. 4 and 5).

The practical problems associated with the handling of liquid hydrogen, because of its low density (4.42 lb/cu ft) and low temperature (-423° F), are unique and require special equipment design along with special heat insulation techniques for the storage tank (ref. 6) and other parts of the hydrogen handling system.

In view of the foregoing over-all advantages, a program was instigated at the NACA Lewis laboratory in January, 1956, to construct an aircraft fuel system for flight operation. By this means the practical problems, many of which can only be exposed by actual flight, could be investigated. The system devised is not to be considered an ultimate design, even though some parts of the system would no doubt have direct application in an ultimate system. A pressurized fuel system was used, since a satisfactory liquid-hydrogen pump was not available for aircraft application.

The fuel system was designed to supply one turbojet engine of a twin-engine light bomber. The supply was to be sufficient to operate the engine for 20 to 30 minutes at 98 percent of rated speed at an altitude of 50,000 feet and a flight Mach number of 0.72.

The duration of flight using hydrogen fuel was to be only long enough to firmly establish satisfactory fuel-system and engine operation. For this reason, only one of the two engines was modified for operation with hydrogen fuel. The hydrogen was stored as a liquid in the fuel tank, and it was burned as a cold vapor. No efforts were made during this program to utilize the fuel as a heat sink.

Presented herein is a complete description of the fuel system and its operation during flight. Discussion is also presented of fuel storage characteristics, engine operation during transition to hydrogen fuel, and results of fuel venting and jettisoning during flight. The flight instrumentation for the liquid-hydrogen fuel system is described in the appendix by Scott H. Simpkinson and Jacob C. Moser.

APPARATUS

The aircraft used for the hydrogen flight program was a B-57 twin-engine bomber. A photograph of the airplane with the hydrogen system installed is shown in figure 1. This aircraft is capable of cruise at a 50,000-foot altitude and carries a crew of two in forward and rear seats under a single canopy. Only the forward seat contained the pilot's controls. The rear cockpit was modified to accept a special control panel for the hydrogen system.

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General Arrangement of Systems

The arrangement of the hydrogen system on the aircraft is shown in figure 2. A schematic drawing to illustrate the functioning of the hydrogen system and the associated equipment is given in figure 3. The liquid-fuel supply tank was mounted on the left wingtip of the airplane (fig. 4). A vacuum-jacketed liquid-fuel line from the hydrogen tank extended inboard just aft of the single main spar to the bottom of a ram-air heat exchanger, which was mounted in the ammunition bay just outboard of the engine nacelle. The liquid-hydrogen fuel was vaporized in the heat exchanger, and an unjacketed line then carried the cold vapor from the top of the heat exchanger through the special hydrogen regulator, also mounted in the ammunition-bay area, to the hydrogen fuel manifold surrounding the engine.

The fuel supply to the engine was controlled by two shutoff valves shown in the schematic diagram (fig. 3). One was located in the liquid line near the tank (valve 5), and the second was located in the vapor line near the engine (valve 3). A manually controlled fuel-tank vent valve (valve 10) was provided to relieve the tank pressure when it reached a certain maximum due to accumulation of fuel boiloff. Emergency provisions were included in the system to empty the liquid hydrogen from the tank. These were a manually controlled dump valve (valve 6) and a rupture disk in the tank to relieve tank pressure automatically if other means of pressure relief failed. The helium supply necessary for purging and pressurizing was carried in a tank mounted on the right wingtip.

The JP fuel system in the airplane was altered to utilize the metered JP fuel flow to control the flow of hydrogen to the engine. This was accomplished by adding a JP fuel bypass from the existing throttle control through the hydrogen flow regulator and back to the main JP fuel tank. Shutoff valves (valves 1 and 2) were installed in the JP fuel system to direct flow in the bypass line and in the main engine supply line.

The hydrogen-system control panel installed in the rear cockpit of the airplane is shown in figure 5. In addition to the basic indicators for engine operation and pressure gages for the hydrogen system, the control panel contained a master switch for changing the engine fuel from JP fuel to hydrogen. Also, the control panel contained indicators for a combustible-gas-alarm system which sampled air in the wing cavity at several locations near the hydrogen fuel system.

Hydrogen Fuel System

<u>Fuel tank and support</u>. - The wingtip was selected for the hydrogen supply tank for ease of installation, and it also seemed desirable as a safety measure in this first system to keep the fuel supply well away 4603
from the engine. Further, the hydrogen fuel tank was to be installed so that it could be dropped, and the wingtip was selected as a satisfactory location for separation of the tank from the particular aircraft used for this work.

Figure 6 shows details of the hydrogen-tank construction. The tank had an inner liner made of all-welded 302 stainless steel to operate at a pressure of 50 pounds per square inch gage. The center section of the liner was a $26\frac{1}{2}$-inch-diameter cylindrical section $11\frac{1}{2}$ feet long with $4\frac{1}{2}$-foot conical sections added on each end. The fore and aft tips were rounded to $4\frac{1}{2}$-inch radii. The over-all tank length was $20\frac{1}{2}$-feet, and the volume was approximately 60 cubic feet. A conventional type of intercostal construction was provided along the top of the tank with standard U-bolts for tank support from the bomb rack.

Four internal circumferential I-sections were attached to the main intercostal members to support the tank shell laterally. These circumferential sections were discontinuous at the bottom of the tank to allow residual liquid to drain along the bottom. The tank skin was welded to the I-sections at intermittent 30° intervals around the tank to allow for relative movement between the skin and the I-sections.

Welding on a liquid-hydrogen tank must be of the highest quality because the joints are subjected to repeated thermal shocks as the tank is filled and emptied which can cause failure of poorly welded joints and consequent leakage of the fluid. Accordingly, the flight-tank welded joints were completely inspected by radiography. During the present investigation, the tank was thermally shocked 11 times by being filled with hydrogen, and there was no indication of welded-joint failure.

Details of the tank insulation are shown in figure 6. The entire tank was covered with two 1-inch layers of rigid-type expanded polystyrene plastic insulation. Aluminum foil was installed over the plastic insulation, and a four-ply resin-impregnated Fiberglas covering was placed on the outside. The Fiberglas was used to form a relatively tight outer shell and to serve as a protective cover against aerodynamic erosion and general handling hazards. The aluminum foil prevented reaction of the Fiberglas resin with the plastic insulation. The external Fiberglas surface was sanded and painted to provide a smooth finish. Further details of the tank insulation and its effect on heat leak are contained in reference 7.

Two openings were provided in the tank, as illustrated in figure 6. A dip tube attached to the pylon was installed in the forward opening. The dip tube is described subsequently along with the pylon. The rearward opening contained a rupture disk to relieve the tank if other means of
4603 pressure relief should fail. The blowout-disk was designed to rupture at 75 pounds per square inch. A tube extended to the bottom of the tank from the blowout-disk opening so that when the disk ruptured, liquid would be exhausted rather than gas. A $3\frac{1}{2}$-inch-diameter metal vent tube was connected to the rupture-disk outlet to exhaust the liquid. This tube was also used to exhaust all vent gas from other parts of the hydrogen system. The vent tube was faired along the top of the tank and exhausted approximately 5 inches aft of the rear tip of the tank. Resin-impregnated Fiberglas cloth was used to fair over the vent tube. The cavity formed between the Fiberglas cloth and the vent tube was filled with "foamed-in-place" plastic insulation material.

Valving and plumbing. - Most of the plumbing for control of the hydrogen system was concentrated in the pylon and in the bomb-rack support for the tank. Figure 7 shows a photograph of the pylon with plumbing installed. This location was convenient, since it provided easy access to most of the valves. Also, it was considered appropriate as a safety measure to concentrate the valves and fittings outside the wing to prevent a large accumulation of gas if a leak should develop.

Figure 8 shows the general arrangement of the hydrogen and helium systems in the pylon. The dip tube which extends into the tank is a multipurpose device. It contains three tube connections through the top flange into the tank. Two of the connections open into the vapor space at the top of the tank and serve to (1) pressurize the tank with controlled helium pressure from a pressure-regulating valve (valve 11, fig. 3) and (2) to relieve the tank pressure by venting off the gas through a manually controlled vent valve (valve 10). The third connection to the dip tube extends through the dip tube directly to the bottom of the tank to handle liquid hydrogen. This connection at the top of the dip tube branches two ways, so that when the main fuel supply valve (valve 5) is open hydrogen fuel flows to the engine, and when the fill and dump valve (valve 6) is open the liquid fuel is jettisoned. The tank is filled by disconnecting this same line at the rear of the pylon and attaching the transfer line from the ground supply Dewar tank.

All the lines used to exhaust either liquid or gaseous hydrogen were connected into the vent tube, which was attached to the rupture-disk outlet as previously described.

The helium system in the pylon was used to pressurize and purge the tank, and to purge the main fuel line to the engine. Helium was also used to purge the tank annulus between the tank inner shell and the Fiberglas outer covering (where the plastic-foam insulation was installed around the tank) to replace the air which would have liquefied against the tank inner shell when liquid hydrogen was introduced into the tank. Reference 7 presents additional discussion regarding the effects on heat transfer of helium and air in the tank annulus.

The dip tube served not only to handle the flow of liquid hydrogen 4603
in and out of the tank, but also to determine the liquid level in the tank by means of capacitance measurements. Figure 9 shows details of the dip tube. It was fabricated of three concentric stainless-steel tubes held in position by four equispaced Teflon rings. Holes were drilled in the two outer tubes above and below each spacer to ensure that the fuel would seek the same level in the annulus between the tubes as in the tank. Electrical leads were attached to the tubes and extended out of the top flange of the dip tube through glass-fused terminals to the fuel-level indicator in the cockpit.

All the valves used in the hydrogen system were commercially available valves, some of which were altered for this application. The valve used to handle liquid hydrogen and cold hydrogen gas is shown in figure 10(a). This type of valve was utilized for the hydrogen supply shutoff in the pylon (valve 5) and at the engine manifold (valve 3), for tank filling and dumping (valve 6), and for tank venting (valve 10). The valve contained Bakelite spacers to insulate thermally the pneumatic operator in the warm helium side of the valve from the cold valve body to prevent freezing the neoprene O-rings in the operator. Limit switches were installed on the valve shaft to provide a cockpit indication of the fully opened and fully closed positions of the valve.

The type of valve used for fuel-line purge (valve 18) and fuel-line vent (valve 8) is shown in figure 10(b). This valve was furnished commercially with a neoprene diaphragm in the operator. It was altered to utilize a piston operator with a Teflon O-ring. Other O-rings in the valve were also changed to Teflon and two microswitches were installed on the valve stem to indicate the valve position.

The pylon plumbing system was arranged so that the "cold" valves and plumbing were grouped in the rear part of the pylon and the helium control valves in the fore part of the pylon. "Foamed-in-place" plastic insulation was used around the cold valves and lines to reduce heat leak (fig. 7).

Heat exchanger. - A photograph of the heat-exchanger installation in the ammunition bay of the outer wing is shown in figure 11. The heat exchanger consisted of 28 integrally finned copper tubes of 5/8-inch inside diameter and 12 inches long. The liquid hydrogen entered a stainless-steel manifold on the bottom and passed through the finned tubes to a similar manifold on the top. The liquid hydrogen was vaporized by ram air passing across the finned tubes. A detailed description of the heat exchanger along with discussion of its operation with hydrogen under simulated altitude conditions is given in reference 8.

A ram-air scoop was installed over the heat exchanger and fastened to the wing structure as shown in figure 12. The ram-air duct was designed for a maximum airflow of 1.75 pounds per second for a flight Mach number of 0.72 at 50,000 feet. A mass airflow control flap was installed on the rear of the duct so that the ram-air flow could be restricted when hydrogen was first introduced into the heat exchanger during flight in order to increase the rate of cool down to the steady-state operating conditions.

Hydrogen regulator and JP fuel system alteration. - The hydrogen regulator is shown in figure 13. It is essentially a ratio controller which utilizes the normal JP fuel flow for the engine to control the hydrogen gas flow from the heat exchanger. Thus, during operation on hydrogen, the JP fuel flow requirement, as metered by the normal engine control system, is bypassed through the hydrogen regulator and discharged back to the main JP fuel supply tank. The regulator has two parallel flow passages, each containing a piston and orifice interconnected by a lever arm. A force proportional to the metered JP fuel flow is transmitted through the lever arm to operate a variable-area valve in the hydrogen side. The variable-area valve then meters enough hydrogen flow across the piston in the hydrogen side to balance the force from the JP fuel side. In addition, the hydrogen side of the regulator contains a temperature-compensating orifice that allows increased volume flow of hydrogen gas during the initial period of operation when the entire system is being cooled from the ambient temperature to the equilibrium operating temperature of approximately 50° R. Reference 9 gives a complete discussion of the hydrogen-regulator design and operation.

A shutoff valve (valve 2) was provided in the JP fuel bypass line as well as in the main JP fuel line to the engine (valve 1) so that the JP fuel flow could be directed from the engine to the hydrogen regulator when the change to hydrogen fuel was made. An orifice was installed in the JP fuel bypass line to match approximately the pressure drop in the main JP fuel line to the engine so that JP fuel flow through engine speed control would be within the governing range of the speed control when the engine fuel was changed to hydrogen.

Fuel and vent lines. - Construction details of the vacuum-jacketed line that carried liquid hydrogen from the pylon to the heat exchanger are shown in figure 14. This fuel line was made up of two concentric stainless-steel tubes. The inner tube was 1 inch in diameter and the outer tube 2 inches in diameter. A bellows was installed on the inner line to accommodate contraction as the line was cooled to liquid-hydrogen temperature. Bakelite spacers held the inner tube concentric with the outer tube.

The flange construction for the special vacuum-jacketed line is also shown on figure 14. Two flat-faced flanges containing a double hollow-metal O-ring seal were used to connect the line sections. The flanges were held together by a V-band clamp. The annulus formed between the two O-rings was connected to the fuel-tank vent tube so that any leakage which might develop across the inner O-ring would be vented overboard. The flat-flanged type of joint used is a higher-heat-leak joint than the bayonet-type joint commonly used in cryogenic plumbing. However, the bayonet-type joint was not easily adaptable to the aircraft installation because of space limitations for assembly, and heat leak of the flanged joints was not objectionable.

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The fuel line downstream of the heat exchanger for gaseous hydrogen contained the same type of joint construction, but the line was a single tube without provision for vacuum jacketing or insulation.

The vent system in the pylon used to vent hydrogen gas was constructed of aluminum tubing with machine-flared joints and standard aircraft fittings.

Engine Modifications

The basic engine modifications for use of hydrogen fuel are shown in figure 15. The JP fuel is normally injected into the engine through 1/4-inch-diameter tubes, which discharge into vaporizer tubes in the engine combustor section. Similar 1/4-inch-diameter tubes were added for the introduction of hydrogen gas. A special $1\frac{1}{4}$-inch-diameter stainless-steel manifold was installed around the engine and connected to the injection tubes by means of standard flexible metal lines. The gaseous hydrogen from the fuel regulator was conducted directly to the manifold. Further details regarding modification of the engine are given in reference 10.

Helium System

The fuel system required a supply of helium for valve operation and purge of the hydrogen tank and lines. This helium supply was carried in 24 Fiberglas spheres each with a volume of 880 cubic inches, which were charged to a pressure of 3000 pounds per square inch and mounted in a modified tank suspended from the right wingtip. A photograph of the tank mounted on the wingtip of the airplane is shown in figure 16. This installation also provided aerodynamic symmetry for the hydrogen fuel tank mounted on the left wingtip. Two of the 24 spheres were isolated from the common manifold for emergency use and could be made available by operation of explosively actuated valves (valves 17, fig. 3).

The pressure-regulating system (fig. 3) reduced the supply pressure through appropriate pressure-reducing valves (valves 15 and 16) for purging and pressurization. A rupture disk was installed in the supply line (pressure, 150 lb/sq in.) to protect against overpressure due to possible malfunctioning of the pressure regulators, and a relief valve (valve 14) was also incorporated in series with the rupture disk to prevent total loss of helium should the supply return to normal after bursting the disk.

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FUEL-SYSTEM OPERATION

Fuel Loading

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In preparation for loading the wingtip tank with liquid hydrogen, the aircraft was moved to an area where the vent at the rear tip of the tank could be connected to a special ground vent system. This vent system exhausted in an open area well separated from the airplane site and was located so that the gas would be vented in a safe direction.

The vacuum-jacketed transfer line from the portable ground supply Dewar tank was attached to the tank filling connection located at the rear of the pylon (figs. 3 and 8). With the transfer line connected, the entire system, including the transfer line, the wingtip tank, and the ground vent lines, was purged with helium gas by pressurization of the tank and exhausting of the gas through the ground vent system. The liquid was then transferred from the Dewar tank to the wingtip tank. During this filling period the vent remained open to exhaust the boiloff gas well away from the airplane as the tank cooled and thus maintain essentially atmospheric pressure in the tank. Figure 17 shows the arrangement of equipment during the filling procedure. Continuous leak checks of the pylon area were made during the filling process with a portable combustible-gas analyzer.

When the tank was filled with hydrogen, the transfer line and portable Dewar tank were removed. The tank was allowed to vent at atmospheric pressure until the engines were started with JP fuel and the aircraft was ready for taxi. At that time, the vent valve was closed to allow pressurization of the tank to begin, and the ground vent system was detached from the rear tip of the tank. A previous fuel-tank investigation (ref. 11) had shown that venting of gas from the tank would not be required until the airplane was airborne. This procedure of filling and storing the fuel eliminated the necessity for venting hydrogen gas near the airplane except during the flight condition when sufficient airflow was available to prevent direct hydrogen contact with possible ignition sources on the airplane.

During climb the flight engineer vented the tank as it approached maximum pressure by manually operating the vent valve. In this way safe tank pressures were maintained.

Transition from JP Fuel to Hydrogen 4603

When the airplane had reached the cruise altitude of approximately 50,000 feet, transition from engine operation with JP fuel to hydrogen was accomplished according to the procedure established in previous test-chamber studies (ref. 10). Each step was accomplished in a simple manner by systematic advancement of the master switch on the rear cockpit control panel. This switching system was arranged to accomplish the following steps for each successive switch position:

(1) Hydrogen fuel-line and tank pressurization with helium

(2) Helium purge of hydrogen fuel line

(3) Change to dual fuel operation (JP fuel and hydrogen)

(4) Complete operation on hydrogen

When cruise on hydrogen was complete, transition to JP fuel operation was accomplished in the following steps:

(5) Change to JP fuel operation and hydrogen-line purge with helium

(6) Closing of hydrogen fuel line

(7) Dumping of residual fuel in tank

(8) Pressurization of hydrogen tank with helium

Obviously, to accomplish these transition steps, multiple-valve operations were required for most of the master-switch positions. In order to ensure that each valve in the system was functioning properly for each sequence position, an indicating light was installed above the master switch for each critical valve (fig. 5). The electric circuit was arranged so that for each master switch position the light was "on" when the valve represented by it was in the correct opened or closed position. These valve lights were actuated directly from the microswitches mounted on valve stems, as described in the section "Valving and plumbing", so that the light indications represented actual mechanical movements of the valves.

Fuel tank and line pressurization. - The master switch was advanced to position 1. The line purge valve (valve 18, figs. 3 and 8) was thereby opened, and then the pressure was adjusted (valve 13) to 5 pounds per square inch above the compressor-discharge pressure. The tank was pressurized with helium gas to 50 pounds per square inch by merely adjusting the tank purge pressure reducer (valve 11) to the proper pressure.

Purge of hydrogen fuel line. - By advancing the master switch to position 2, with the engine operating on JP fuel, the hydrogen manifold valve (valve 3) was opened to allow a flow of helium gas through the hydrogen fuel line and directly into the engine. The helium pressure was then increased (valve 13) to 50 pounds per square inch for approximately $1\frac{1}{2}$ minutes, which was considered sufficient time to purge all air from the hydrogen fuel system.

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Dual fuel operation. - After the hydrogen fuel line was purged with helium gas, the master control switch was advanced to the next position to accomplish the following simultaneously:

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(1) Close the hydrogen-fuel-line purge valve (valve 18)

(2) Open the hydrogen-fuel-supply valve (valve 5)

(3) Open the JP fuel valve to the hydrogen regulator (valve 2)

This valve action simultaneously provided initial hydrogen flow to the engine and provided JP fuel flow through the hydrogen fuel regulator in addition to the normal JP fuel flow to the engine. This condition of dual fuel operation was maintained until the hydrogen fuel system had cooled to a stabilized temperature.

Operation on hydrogen fuel. - When operation had stabilized at the dual fuel condition, the next step merely closed the JP fuel manifold valve (valve 1) and thus terminated the JP fuel flow to the engine. Under this condition of operation, the entire JP fuel flow from the engine-speed control passes through the hydrogen regulator back to the main JP fuel tank and serves to regulate engine speed by controlling the quantity of gaseous hydrogen passing through the regulator to the engine.

Change from hydrogen to JP fuel. - To change back to JP fuel the previously described process was reversed, except that the two-step operation required to change to hydrogen fuel (to attain stabilization after cool down) could be accomplished in one step. Thus, the next advancement of the master control switch simultaneously

(1) Shut off JP fuel flow to the hydrogen regulator (valve 2)

(2) Opened JP fuel flow to the engine (valve 1)

(3) Closed the hydrogen supply (valve 5)

(4) Opened the hydrogen-fuel-line helium purge (valve 18)

After the hydrogen fuel line was adequately purged, the hydrogen manifold valve was closed (valve 3).

Securing the fuel tank. - To maintain as safe a system as possible before landing, the fuel tank was emptied and thoroughly purged. Any remaining liquid hydrogen was jettisoned through the vent tube by opening the dump valve (valve 6). A small amount of liquid in the bottom of the tank could not be jettisoned, since the dip tube extended to within only 1/4 inch of the tank bottom. Therefore, the final helium purge during flight was delayed as long as feasible to allow as much time as possible for the last remaining liquid to evaporate. During the tank-purging process care was exercised to close the vent at a pressure well above atmospheric to prevent possible backflow of air into the tank. The tank was kept closed during the landing and taxi period. The airplane was returned to the fuel loading area, where the ground vent system was attached and additional helium purges were accomplished. 4603

SAFETY CONSIDERATIONS

During these initial flight studies a number of safety measures were taken that experience may show to be unnecessary. However, in these early flights an extremely cautious approach was used to ensure, insofar as possible, a safe operation.

Some of the safety precautions were incorporated into the basic fuel-system design. These included the remote wingtip location for the fuel tank and the provision for dropping the tank. The only major connection between the tank and the pylon was the single dip-tube opening. This opening was sealed by means of a large metal bellows, which would rupture upon separation of the tank from the wing and allow the tank to drop free of the dip tube which would remain with the pylon.

A combustible-gas-alarm system was installed to monitor continuously four selected critical areas during the entire ground and flight procedure. A simple schematic drawing of this system is shown in figure 18. Samples were continuously drawn from the wingtip area, from each of the two ventilation louvers in the gun bays adjacent to the ammunition bay, and from the engine compartment above the hydrogen-manifold connections. These samples were then cyclically passed through the gas alarm located in the cockpit. The cycling function of the system was indicated to the flight engineer by the zone lights on the control panel (fig. 5), and any sample containing a hydrogen concentration higher than 40 percent of the lower explosive limit would be indicated by the combustible-gas-alarm light on the panel.

In general, nearly all electrical sources of ignition were eliminated from the wing area. Exceptions to this were the electrical leads from the microswitches used for valve-position indication and the electrical system used for fuel-tank liquid-level measurement. In both cases the electrical connections were made within an enclosed container which was then inerted with low-pressure helium gas.

All of the valves in the pylon and wing area were pneumatically operated using helium gas as the operating medium.

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The fuel-supply line extending from the tank to the engine was constructed with a minimum number of joints. The fuel-line joints were designed with a double O-ring seal and a bleed tube from the annulus between them, specifically as a safety measure (fig. 14). In addition, the two joints in the liquid portion of the fuel line which were located in the wing cavity were further protected by the installation of a ventilation hood over each joint. A tube was connected from the top of the hood to a low-pressure area overboard to create continuous circulation away from the joint area during flight. This system would not protect against complete joint failure, but would prevent accumulation of gas in the wing cavity due to a small leak caused possibly by relative movement of the wing structure and the fuel line.

Positive ventilation was also created in the general wing and pylon areas by the addition of louvers on the external skin. The ventilation louvers on the pylon are shown in figure 4. A high volume of purge air was supplied to the area where the heat exchanger and fuel regulator were mounted by opening the ammunition-bay ram-air door at the wing leading edge.

The multiple purging procedures for the fuel tank discussed under FUEL-SYSTEM OPERATION might well be considered impractical for a design incorporating a large fuselage tank. However, this purging was deemed advisable at the present stage of development.

Before and after each flight the entire hydrogen fuel system was checked for leaks to ensure tightness of all joints and connections. A mass-spectrometer leak detector was used with the system filled with helium gas at a pressure of 50 pounds per square inch.

INSTRUMENTATION

All the flight measurements were recorded on a multichannel tape recorder mounted on the rotary-type bomb-bay door. Figure 19 shows the installation of the tape recorder with its associated electronic amplifiers, oscillators, and power supplies. Continuous records or point records of the measurements could be made using a remote control located in the cockpit. The recorder carried sufficient tape to operate continuously for 48 minutes.

The flight measurements included:

(1) Engine speed

(2) Engine JP-fuel flow

(3) Bypass JP-fuel flow

(4) Hydrogen-fuel-tank pressure

(5) Hydrogen Venturi-inlet total and static pressure 4603

(6) Heat-exchanger air-scoop-inlet total and static pressure

(7) Air-pressure drop across heat-exchanger core

(8) Hydrogen liquid temperature in tank at six levels

(9) Hydrogen fuel temperature at Venturi inlet

(10) Air-temperature drop across heat-exchanger core

The measurements were directly transduced into analog electrical signals, which were amplified, filtered, and impressed on magnetic tape. After the flight, the process was essentially reversed by playing back the tape through electronic equipment, which transcribed the measurements onto a continuously recording oscillograph. Details and operation of this data-recording apparatus are given in the appendix.

Carbon resistors were used to sense the temperature of the liquid and gaseous hydrogen below -150° F. Changes of resistance in the carbon provided more signal sensitivity than conventional thermocouples would at these low temperatures.

The pressure transducers used for measuring hydrogen pressures were connected with a minimum of 24 inches of stainless-steel tubing to allow warming of the gas, since the cold-gas temperature seriously affects the transducer calibration.

PRELIMINARY INVESTIGATIONS

Several operational problems with the wingtip tank and fuel system were studied prior to flight engine operation with hydrogen fuel in order to ensure a minimum of operational difficulties during flight. The effect of the hydrogen wingtip tank on the airplane handling and wing stability was studied. Also, a wind-tunnel study of the separation characteristics of the tank was made. In addition, comprehensive fuel-flow studies of the complete hydrogen system were made to develop confidence in the system before the final flight phase of the program.

Airplane Handling and Wing Vibration

Several significant differences existed between the hydrogen fuel tank and the JP wingtip tank normally used on the airplane which necessitated aerodynamic studies. The hydrogen wingtip tank was much longer than the tank normally used on the airplane. It was 30 inches in diameter and 23 feet long (outside dimensions), whereas the normal JP-fuel tank is 32 inches in diameter and 14 feet long. The hydrogen tank was suspended from a pylon support, while the conventional tank nestles flush with the bottom surface of the wingtip. The full hydrogen fuel tank, pylon, and
4603 plumbing weighed approximately 1000 pounds as opposed to the conventional full-tank weight of 2300 pounds.

Mockup fuel tanks were substituted on the airplane for the insulated tanks to accomplish the initial aerodynamic flight tests. Figure 20 shows a mockup tank mounted on the airplane wingtip. To preserve symmetry of balance and geometry, identical mockup tanks were mounted on each wingtip. These tanks were ballasted to simulate the weight and moment of inertia of the insulated hydrogen tank filled with fuel.

The airplane was flown with and without the mockup wingtip tanks so that the pilot could compare handling characteristics. After the pilot was satisfied that the wingtip tank installation created no general handling problems, the effect of the mockup tanks and the insulated tank on the wing stability was checked. Accelerometers were mounted on the wingtip and in the fuselage to measure the wing vibrations, and a multichannel tape recorder connected to accelerometer amplifiers continuously recorded each acceleration. The wing vibrations in flight were excited by abruptly moving the elevator controls. Although the pilot experienced difficulty in imposing great enough change in acceleration to excite the wing into a free oscillation by this method, enough data points were obtained to show a stability criterion within the proposed range of flight conditions. The results indicated that for the range of flight conditions considered for this airplane there was no critical wing flutter.

Tank Separation

A calculation of the forces on the tank in its normal position on the wing, based on estimated aerodynamic coefficients, indicated that upon separation the nose of the tank would yaw out and pitch up and that the tank would translate outward away from the wingtip.

A tank separation study was conducted in a 6- by 9-foot wind tunnel with a 1/6-scale model to verify these calculations. A semispan of the airplane wing was cantilevered from one side of the tunnel wall so that the tank model was located approximately on the centerline of the tunnel test section. The tank was constructed of wood and steel to simulate the correct scaled weight and moment of inertia.

Tank separations were made for several flight conditions covering the full-scale range of airspeeds and associated angles of attack proposed for the hydrogen flight investigation.

The wind-tunnel results corroborated the estimated motion of the tank and for none of the simulated flight conditions did the tank strike any part of the pylon or wing during separation. From these results it was concluded that it would not be necessary to put stabilizing fins on the tank. 4603

Preliminary Fuel-System Flow Studies

Prior to installation in the airplane, the complete fuel system was assembled in a laboratory facility and used to operate the flight engine under simulated altitude conditions. Nearly all the operational design features were perfected during these operations. The changeover from JP fuel to hydrogen was made many times to ensure reliability in the operational technique. The results of this work are reported in detail in reference 10.

Subsequent to the laboratory functional tests the fuel system was installed in the research airplane. The airplane was flown several times on JP fuel only, after which a nonburning flow check was conducted on the ground to verify that the system was leak proof and that the flow regulator operated satisfactorily. The fuel tank was filled with hydrogen and pressurized with helium gas as would be done during flight. Using the master control switch, the operator duplicated the flight procedure to change from JP fuel to hydrogen. The flow of hydrogen through the system merely bypassed the engine and was exhausted as a gas from the ground vent system well away from the airplane. The proper JP fuel flow through the regulator was established without engine operation, and the response of the regulator for proper control of hydrogen flow was satisfactorily established. During the operational period with hydrogen, the entire system was checked for leaks.

The first flights using the system consisted of dry runs without hydrogen fuel. The purpose was to check the operation of the components at the altitude and flight conditions for which they were expected to operate and to test operation of the JP fuel bypass system. The fuel tank was filled with helium gas instead of hydrogen fuel. The flight engineer duplicated the exact changeover procedure that would be used for hydrogen fuel. Thus, when the system was switched to the dual fuel position (as described under FUEL-SYSTEM OPERATION) engine speed dropped to idle, since fuel from the hydrogen system was not available to the engine. Of course, when the system was switched to full hydrogen operation, the engine flamed out, but operation of valves in the system could be established by this procedure.

These flights did reveal a problem not previously discovered. The low temperature at high altitudes presented a difficulty with the helium-pressure-regulator valves in the tank-pressurizing system. The existing rubber diaphragms in the valve became too stiff to operate at the tank pressure of 55 pounds per square inch. They were replaced with 0.020-inch-thick neoprene-impregnated nylon-cloth diaphragms, which were extensively tested in the laboratory at dry-ice temperatures.

Leak checks were conducted on the entire system after each flight
4603 using helium gas in the system to ensure that gross wing flexure and
vibration did not create leaks.

FLIGHT PROCEDURE WITH HYDROGEN FUEL

The fuel system designed for this flight investigation was to supply one airplane turbojet engine with enough hydrogen fuel to operate for 20 to 30 minutes at 98 percent of rated speed at an altitude of 50,000 feet and a flight Mach number of 0.72. In order to satisfy this requirement, the wingtip fuel tank was constructed to contain about 200 pounds of hy-
CA-3 drogen fuel at takeoff. The airplane took off and climbed on JP fuel to 50,000 feet, where the pilot shifted one engine over to hydrogen fuel. The taxi, takeoff, and climb periods combined averaged about 55 minutes, which then constituted the storage time of the hydrogen fuel on the airplane from the completion of fueling to use in the engine.

The climb and operation of the engine on hydrogen was conducted over Lake Erie. A "chase" airplane flew beside the research airplane to obtain motion pictures and report visual observations during the operation on hydrogen fuel. These comments were received by both a ground station and the research airplane. The conversations between the airplanes and the ground station were recorded on a tape recorder on the ground. The comments of the crew in the research airplane were also recorded on the data tape recorder in the airplane.

DISCUSSION OF RESULTS

Three flights were made on which the whole supply of hydrogen fuel was burned and the system functioned in a completely satisfactory manner. Data were obtained to show the effects of the hydrogen fuel on engine operation and on the performance of the major system components. Data were taken during changeover from JP fuel to hydrogen and also during steady-state operation and throttle transients. In addition, comparisons of fuel-storage data and heat-exchanger performance with ground facility results were obtained.

Fuel Venting

As described under FUEL-SYSTEM OPERATION, the wingtip tank was closed after the liquid-hydrogen filling procedure was completed and the airplane was ready for taxi. When the design pressure was reached, the tank vent was opened and hydrogen gas escaped out the vent tube; this resulted in a loss of available fuel. Thus, the rate of pressure increase directly affected the time the fuel could be stored before venting was required (no-loss time). The results presented in reference 12 describe the effect of agitation of the liquid on reducing the rate of pressure buildup. The 4603
data obtained during the flight investigation indicate that motion of the airplane during flight and particularly during the taxi period caused enough agitation to reduce the rate of pressure increase in the tank substantially. The data presented in figure 21 compare tank pressure-time histories while the airplane was stationary and while it was taxiing. The vent was closed at zero time. The sharp changes in slope of the pressure-rise plot during taxi are caused by varying degrees of fuel agitation. During the $5\frac{1}{2}$-minute taxiing period, which started immediately after closing of the vent, the pressure reached 30 pounds per square inch absolute. By comparison, for the same period of time the stationary tank reached 50 pounds per square inch absolute, or nearly the design pressure. It is interesting to note the sharp pressure rises while the airplane was parked prior to takeoff and immediately upon being airborne. The slope of the pressure-rise plot during these periods approximately matches the slope of the stationary-tank curve.

The pressure-time history of the entire no-loss period, which is the time beginning when the vent was initially closed until the tank was first vented during climb, is shown in figure 22. In addition to the change in rate of pressure rise during taxi described in figure 21, the effect of air turbulence and possibly, to a lesser extent, the effect of mild airplane maneuvering are apparent on the airborne portion of the plot. For this flight the no-loss period was $17\frac{1}{2}$ minutes.

A time history of the tank pressure for the complete climb period during another flight is shown in figure 23. These data show that eight ventings were required during the 55 minutes of climb to 50,000 feet. The pressure at which the vent was opened and closed was arbitrarily selected by the flight engineer and obviously differed each time the tank was vented. The sharp pressure reduction after the first venting was caused by a moderate turbulence of the air and not by venting. This turbulence reduced the tank pressure from 42 to 37 pounds per square inch absolute. These results indicate the importance of the effect of agitation of the liquid on the no-loss period and consequently on fuel loss.

The fact that agitation of the fuel tank causes significant reduction in the rate of pressure rise indicates that the liquid is not in equilibrium. The data presented in figures 21 to 23 illustrate that varying degrees of agitation correspondingly affect the pressure rise. Reference 12 describes this effect in detail and shows that violent agitation of liquid hydrogen in a tank results in the pressure rise following very closely the calculated equilibrium pressure-temperature curve. During the flight investigation measurements were made of variation in temperature of the liquid between the bottom of the tank and the surface. Figure 24 presents these temperature measurements plotted against pressure compared to the calculated equilibrium curve. At the lower tank pressures (25 to 30 lb/sq in.) the measured values approximate the theoretical values, but near the maximum tank pressure (55 lb/sq in.) the measured temperatures are nearly 5° R below the equilibrium temperature. It is believed that at the surface of the liquid pressure and temperature are in full equilibrium, but that the equilibrium layer is very thin. Thus, measurement of the liquid temperature in the controlling surface would be extremely difficult, especially during flight, when the liquid is in motion.

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A continuous record of the quantity of fuel in the tank was made throughout the flight by use of the capacitance-type level indicator incorporated with the dip tube. A time history of the fuel quantity is shown in figure 25. When the vent was initially closed the tank contained 207 pounds of fuel. When the airplane was at cruise altitude and the engine started to operate on hydrogen, the tank contained 174 pounds of fuel. The venting losses amounted to 33 pounds, or 16 percent of the initial quantity. Data during the climb period are not shown because the airplane angle of attack caused the liquid to change level at the dip tube and introduced a large error.

Engine Speed and Tailpipe Temperature

Figure 26 shows the effect of the fuel transition to hydrogen on engine speed and tailpipe temperature. During the first $1\frac{1}{3}$ minutes the fuel tank was pressurized with helium gas. Next the fuel line was purged with helium gas. At this point the engine speed and tailpipe temperature increased momentarily. This was caused by injection of a small amount of JP fuel, which flowed back from the vaporizer tubes into the hydrogen system during JP-fuel operation. The helium purge then forced this JP fuel into the combustor, where it enriched the mixture. During this period the tailpipe temperature momentarily increased to 650° C. This is well below the established limit of 800° C for a momentary peak temperature.

The fuel line was purged for approximately $1\frac{1}{2}$ minutes, after which the engine was shifted to dual fuel operation to burn both JP fuel and hydrogen. To accomplish this change, the JP-fuel flow was split (as described under FUEL-SYSTEM OPERATION) causing a momentary loss of JP fuel to the combustor. This resulted in a slight loss in engine speed because hydrogen was not yet available to the engine. The throttle control suddenly received an increased-demand JP flow to maintain the set speed. Operation with the two fuels allowed the hydrogen system to cool down to an equilibrium temperature prior to the complete shift to hydrogen fuel. This transition period was arbitrarily established to last 2 minutes; however, the engine would operate satisfactorily for an indefinite period using both fuels.

The switch to complete hydrogen operation was made with no appreciable change in engine speed or tailpipe temperature, and the engine functioned entirely satisfactorily until the fuel supply was exhausted (for 21 min). 4603
When this became apparent to the flight engineer, he switched directly back to JP fuel without incident. As the engine lost speed when the hydrogen supply was depleted, the flight engineer retarded the throttle before shifting back to JP fuel; then the engine accelerated normally on JP fuel to the original speed.

Engine Response to Throttle Setting

On two of the flights the engine throttle was varied during operation on hydrogen to determine the engine response. Figure 27 shows the effect of throttle change on engine speed and tailpipe temperature. As the throttle was sharply retarded, the engine speed dropped smoothly from 94 to 84.5 percent rated with a corresponding drop in tailpipe temperature. The reduction in speed was limited at the cruise altitude, since idle speed was approximately 78 percent. The throttle advance was made in two steps to avoid compressor stall. The data presented in figure 27 along with other similar data which were obtained during several throttle changes with operation on hydrogen fuel indicated that the hydrogen fuel regulator responded very satisfactorily. Some throttle changes resulted in slight speed oscillations, which were believed to be associated with the dynamic characteristics of other fuel-system components. Additional data regarding this condition are reported and discussed in reference 10.

Heat-Exchanger Performance

The heat exchanger was designed to vaporize 520 pounds of hydrogen per hour utilizing a ram-air flow of 1.75 pounds per second. The aircraft system used approximately 495 pounds per hour, and therefore this design allowed for very little superheating. Some concern existed that the heat exchanger would accumulate sufficient ice (or frost) on the ram-air side of the finned tubes to cause appreciable pressure drop and reduction of heat-exchanger effectiveness. The available moisture for icing on the heat-exchanger tubes is very small at the altitude conditions of operation; however, cumulative icing could be significant. Although the pressure-drop measurements did not indicate blocking during the time hydrogen was passing through the heat exchanger, no visual data were obtained during these flights to verify the absence of ice or frost on the tubes.

Figure 28 shows a comparison of the ram-air-temperature drop with hydrogen fuel flow between the flight data and the laboratory facility data. The flight data indicate higher air-temperature drops or improved heat-exchanger effectiveness than the laboratory data for the same airflow. This may be due to lower heat-leak losses in the flight installation.

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Condensation Trails

The photographs in figure 29 show the tailpipe exhausts from the two engines during flight when the left engine was using hydrogen fuel and the right engine was using JP fuel. The hydrogen-burning engine developed a very dense and peristent condensation trail, while the other engine did not produce a contrail. The hydrogen contrail extended rearward as far as could be observed by the chase airplane.

Fuel Jettisoning

Two flights were conducted during which the shift was satisfactorily made to hydrogen fuel, but a flow restriction of hydrogen fuel prevented engine acceleration to high speed. In those flights the entire fuel supply was jettisoned through the vent tube on the fuel tank. Jettisoning of the fuel was believed to be generally less hazardous and less of an operational problem than landing with hydrogen fuel in the wingtip tank. Figure 30 shows a photograph of the airplane while the fuel was being jettisoned. The entire quantity of approximately 200 pounds was emptied in about $2\frac{1}{2}$ minutes. The fuel formed a dense cloud, which disappeared about 20 feet rearward of the vent-tube exhaust. This procedure was carried out without incident on both occasions.

SUMMARY OF RESULTS

Three completely successful flights were made using a specially installed hydrogen fuel system for one engine of a twin-engine aircraft. The climb and descent portions of the flight were made using JP fuel only. The hydrogen-burning portion of each flight at an altitude of approximately 50,000 feet lasted nearly 21 minutes and exhausted the available fuel supply. Transitions to hydrogen fuel and back to JP fuel were made very satisfactorily without serious effects on the engine. Operation on hydrogen fuel was excellent. Throttle changes were made in a normal fashion.

Heavy condensation trails were observed from the hydrogen-burning engine, whereas there were none from the engine burning JP fuel.

On two additional flights, liquid hydrogen was jettisoned from the fuel tank without incident. Also, hydrogen vapor resulting from fuel boiloff in the tank was vented periodically from the tank. Pressure and temperature data taken in the fuel tank show that agitation of the liquid during flight and particularly during taxi substantially reduced the rate of fuel-tank pressure rise from the rate previously observed for the tank in a stationary position. Heat-exchanger data showed good agreement with simulated altitude data for ram-air pressure drop and general heat-exchanger effectiveness. 4603

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, July 5, 1957

APPENDIX - FLIGHT INSTRUMENTATION FOR

LIQUID-HYDROGEN FUEL SYSTEM

By Scott H. Simpkinson and Jacob C. Moser

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The instrumentation used for the flight investigation consisted for the most part of modified standard equipment. In addition to the special data-recording system, several of the modifications served a purpose particularly unique to the hydrogen system. These consisted of a fuel-level indicator for the tank, a special fuel-tank low-level indicator to inform the flight engineer when the fuel was nearly exhausted (fig. 5), a fuel-exhausted indicator to show when all the liquid was gasified so that tank purging could be completed, and a heat-exchanger fuel-exhaust-temperature indicator to determine when the fuel system had cooled down to a stabilized temperature during initial operation.

Fuel-Tank Liquid-Level Indicator

The fuel-tank liquid-level indicator operated by means of capacitance measurements using multiple tubes of the dip tube as the sensing device. Two concentric steel tubes electrically insulated from a third outer tube formed the plates of the condenser. The liquid and gaseous hydrogen between the tubes provided the variable dielectric. Thus, as the fuel level changed, the capacitance indication on the flight engineer's control panel reflected this change. The range of a standard aircraft-type capacitance liquid-level-measuring indicator was set to utilize the dip-tube signal.

Fuel-Tank Low-Level Indicator

A carbon resistor was installed near the bottom of the dip tube (3/4 in. from the bottom of the tank) to indicate when the fuel was nearly exhausted. The resistor sensed the change in temperature between the liquid and the warm gas as the liquid surface passed this point. The indicator used with the carbon resistor was a sensitive millivoltmeter connected across a bridge circuit containing the carbon resistance. The bridge values were selected to give a gross noticeable deflection when the liquid level passed the carbon resistor.

Fuel-Exhausted Indicator

In order to determine when all the residual liquid in the tank had gasified so that tank purging could be completed, a copper-constantan thermocouple was spot-welded to the external surface of the bottom of the inner tank shell to sense a change in temperature when all the liquid was exhausted. During laboratory fuel-tank experiments it had been found that a single thermocouple measurement would reflect the existance or absence of hydrogen liquid on the opposite side of the metal surface. The thermocouple was referenced to a cold junction in an ice-water bath. A sensitive millivoltmeter was used as the temperature indicator.

Heat-Exchanger Fuel-Exhaust-Temperature Indicator

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The temperature of the fuel in the downstream manifold of the heat exchanger was used as a criterion to indicate stabilized cool down of the system when hydrogen flow was first started. A carbon resistor similar to the fuel-tank low-level indicator was used for this purpose. These two resistors were placed in the same bridge circuit so that the two resistances were compared on the millivolt indicator for purposes of determining a minimum stabilized exhaust temperature from the heat exchanger. The bridge resistances were adjusted to indicate a maximum full-scale reading of about 100° R.

Pressure Measurements

Pressure measurements were obtained by means of strain gages actuated by metal diaphragms connected to the pressure source. The strain gages were connected to form a bridge circuit having an input voltage of 1400 cycles per second. Pressure on the diaphragm unbalanced the bridge and thus created a bridge output directly related in amplitude and phase to the pressure applied to the diaphragm. The output voltage was amplified and adjusted for plus or minus pressure by phase comparison to a reference voltage. Rectifiers and filters then converted the resulting signal to an analog voltage with a magnitude corresponding to the pressure. This voltage was then applied to the grid of a frequency-modulated oscillator to obtain a frequency output for the tape recorder.

Temperature Measurements

For temperature measurement, analog voltages for the frequency-modulated oscillators were obtained from both thermocouple output voltages and resistance changes of wire-wound or carbon resistors.

Thermocouple output voltages were amplified by chopper-stabilized direct-current amplifiers and then applied to the frequency-modulated oscillators. A reference junction was maintained at 80° F in a thermostatically controlled oven with Fiberglas insulation.

The resistance change of the resistors was converted to an analog voltage by electrically connecting the pickup in one leg of a resistance bridge. The output voltage was treated in the same manner as the output from the pressure-sensing bridge. For temperatures warmer than -150° F, standard air-temperature probes (AN-5525) were used, and for temperatures colder than -150° F special carbon resistors were used. The standard probes consist of a coil of wire encased in a 4-inch-long metal tube. Air temperatures at the heat exchanger were measured by exposing the tubes to the air flowing into and out of it.

The special pickups were small 1/8-watt carbon resistors mounted in perforated metal tubes or on standoff insulators. These resistors exhibit a very strong sensitivity to temperatures in the 0° to 150° R range. Temperature can be accurately determined from the following equation:

$$T = \frac{K_1 R_n}{K_2 R_T - R_n}$$

where

T temperature, °R or °K

K_1, K_2 constants which apply to all resistors

R_n room-temperature resistance

R_T resistance at temperature T

These resistors operated very satisfactorily, especially in the region of 50° R, but some precautions had to be taken. The current through the resistor was limited to less than 2 milliamperes to minimize internal heating. Room-temperature resistance of many of them was found to vary up to about 2 percent until they had been exposed for 1 or 2 hours to temperatures in the 50° to 150° R region or cycled several times to these temperatures. Results indicate that ordinary data reduction yields errors not in excess of 2° at 50° R (about 1 percent of full-scale range), including all system errors, which could account for half of this value. Special data treatment such as careful zero-shift correction reduced this error to 1° R or less.

Data-Recording Equipment

Continuous records of engine performance and fuel-system operation were obtained with a 14-track tape recorder carried in the bomb bay. At a tape speed of 15 inches per second, 48 minutes of record could be obtained. The frequency of the oscillators used for pressure and temperature measurements was centered at 3500 cycles per second and varied ±15 percent by full-scale changes in pressure and temperature. Reference data or zero levels to obtain absolute values were established by calibration. The fuel flow and engine speed were measured by variable-frequency generators. The frequency of the output voltage was varied by changes in the measured quantity.

One track of the tape recorder was set aside to record the voices of the pilot, the flight engineer, and the ground-station operator for purposes of adding to the data and timing events, which could not otherwise be accomplished.

This recorder provided excellent reproduction of signals, all errors being less than 2 percent of full-scale range. Noise superimposed on signals and tape-speed variations were negligible.

Each frequency-modulated oscillator was provided with a reference frequency, which was used during preflights as an index of the oscillator's serviceability. The reference frequency was provided by removing the 1400-cycle-per-second exciting voltage from the temperature or pressure pickup. This was equivalent to having a balanced electrical bridge and, when used in flight, provided the zero-shift compensation data that were used in the processing procedure. This reference calibration was actuated by the flight engineer every 15 minutes in flight.

All pressure transducers were calibrated by direct application of pressure, which was plotted against the corresponding frequency of its associated oscillator. Temperature-controlled oscillators were calibrated by substitution of known resistors for the resistance probes. For wire-resistor temperature probes the resistance-temperature relation was determined by cooling the resistors at boiling-hydrogen and boiling-nitrogen temperatures.

After a flight the tape was played back through a companion data reproducer. The frequency-modulated signals were amplified, filtered (if multiplexed), and converted to analog voltages, which were recorded by an oscillograph.

In general, traceable errors did not exceed 1 percent of full-scale range of the instruments. The frequency response of the reproduced data was limited to 11 cycles per second by the oscillograph galvanometer elements.

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CS-13429

Figure 1. - Airplane used for liquid-hydrogen flight investigation.

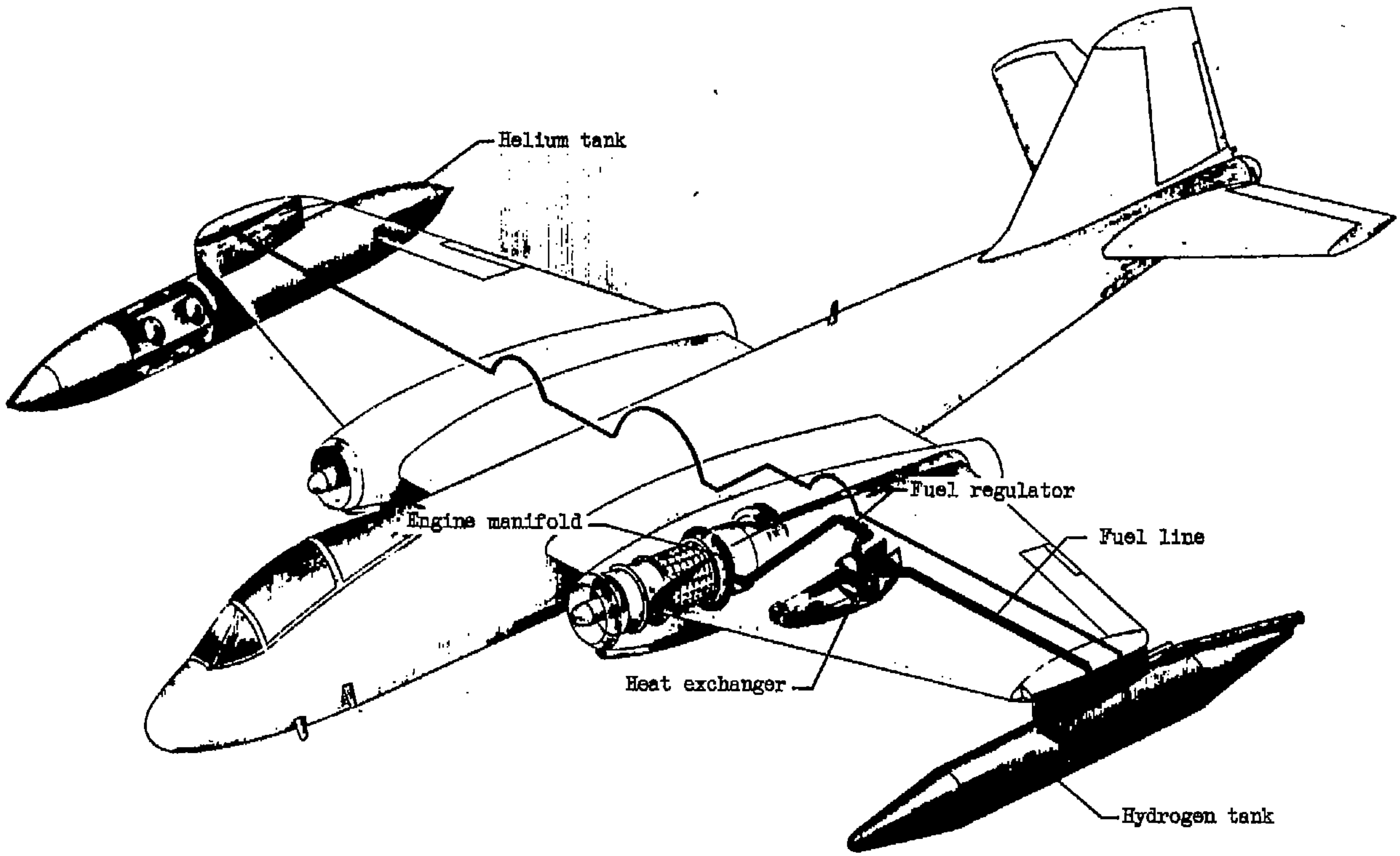

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Figure 2. - General arrangement of liquid-hydrogen fuel system on airplane.

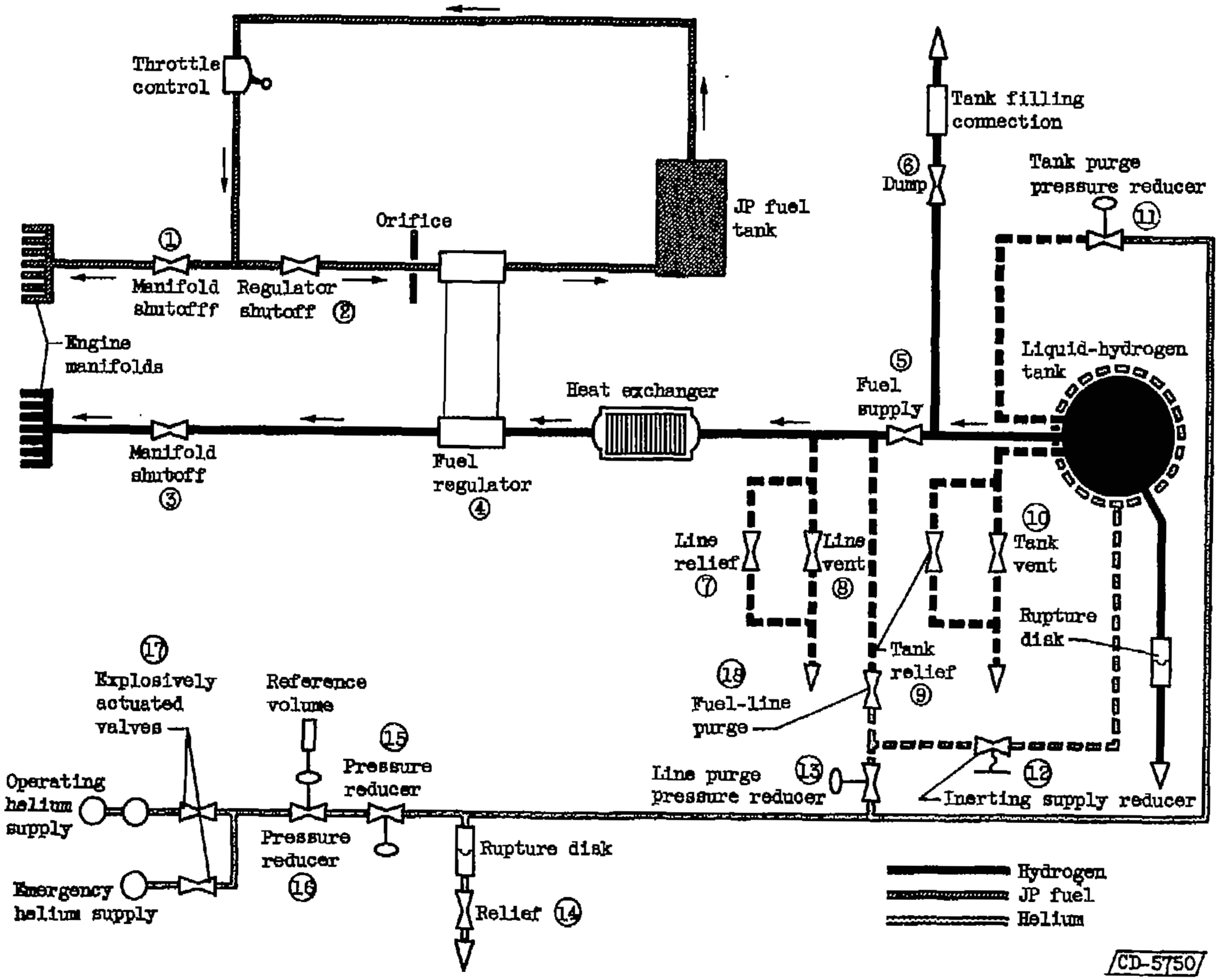

Figure 3. - Schematic diagram of aircraft hydrogen fuel system.

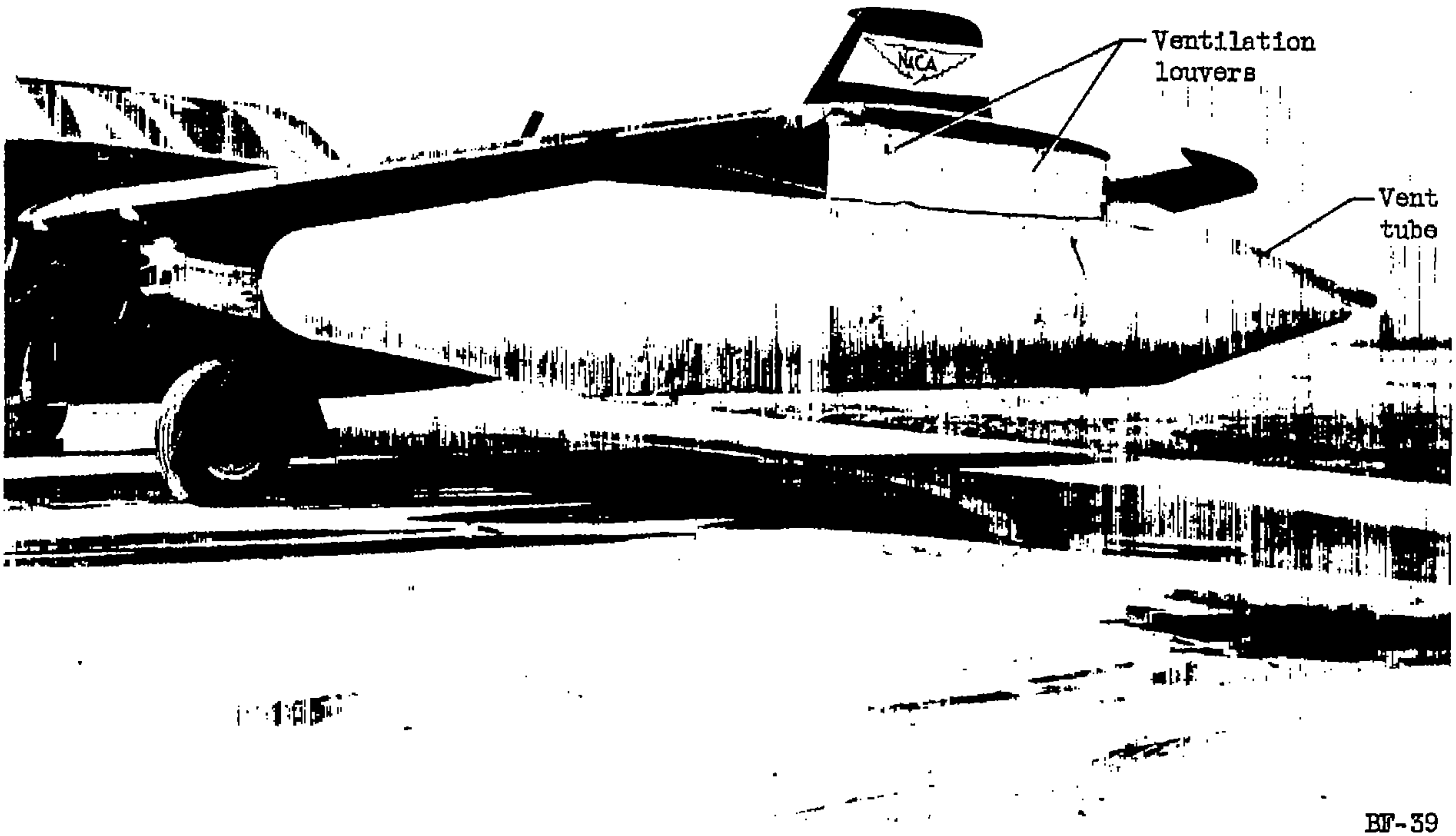

Figure 4. - Liquid-hydrogen fuel tank installed on airplane wingtip.

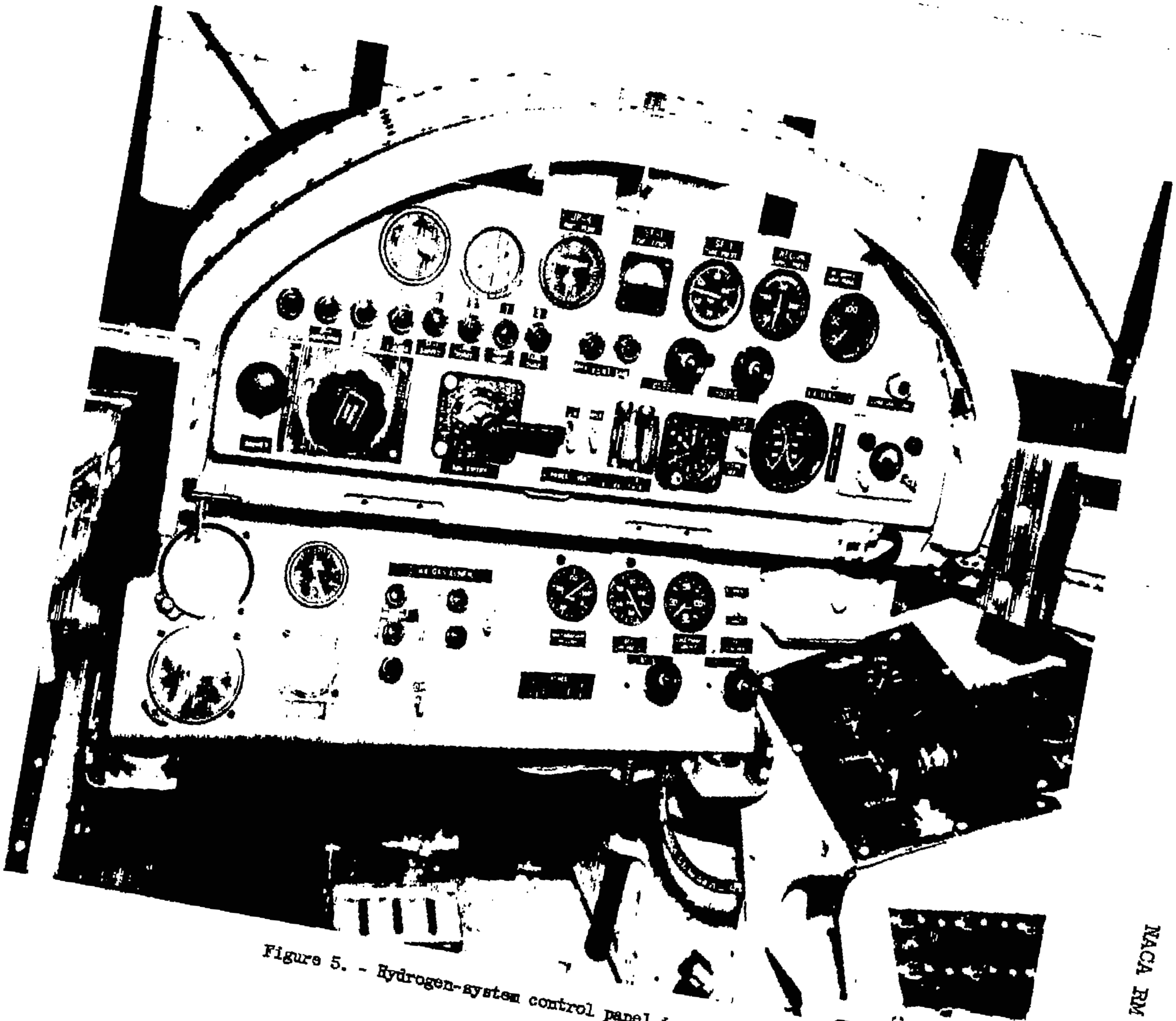

Figure 5. - Hydrogen-system control panel in airplane.

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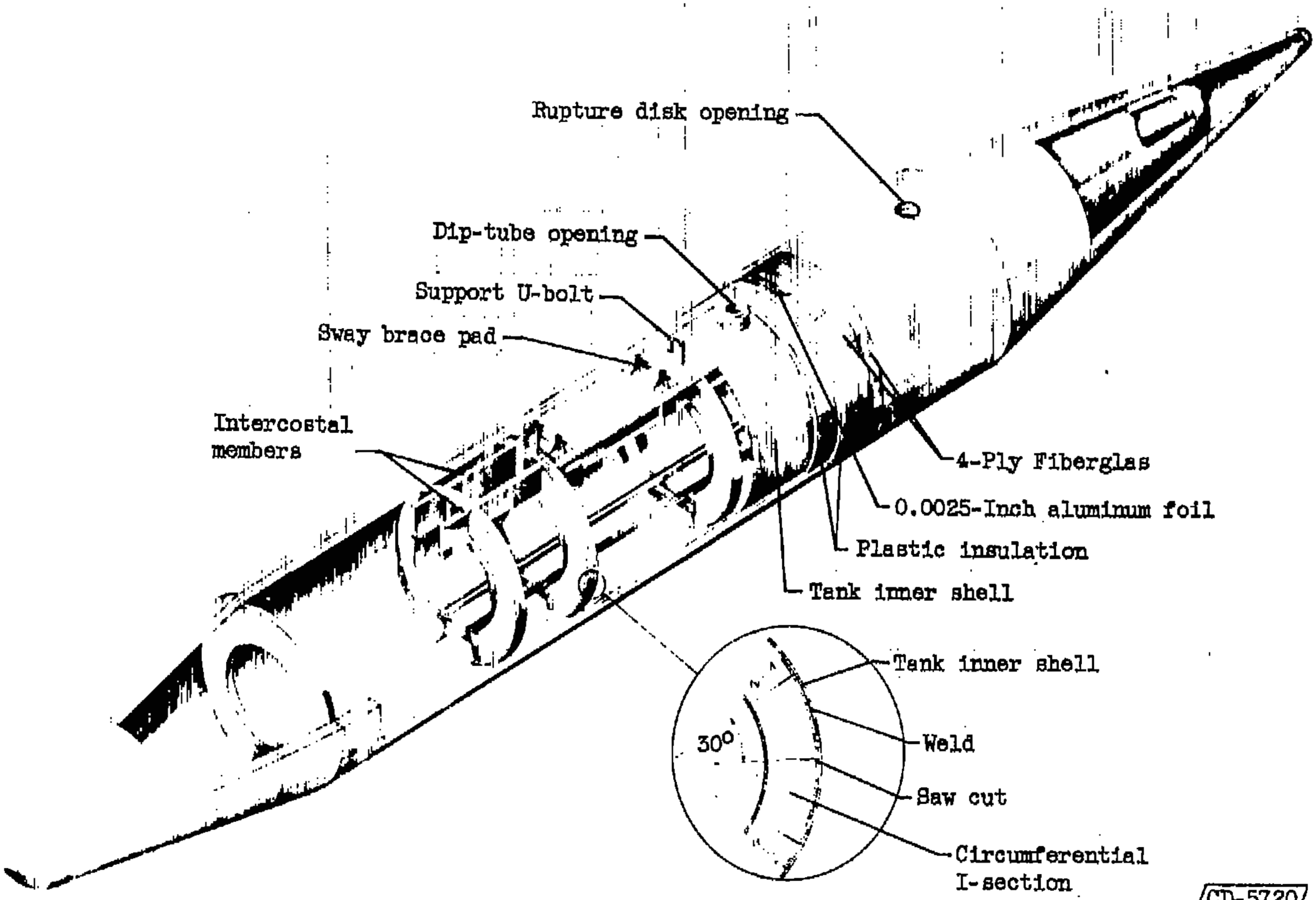

Figure 6. - Details of liquid-hydrogen-tank construction.

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Figure 7. - Fuel-tank pylon on airplane with insulation around hydrogen plumbing.

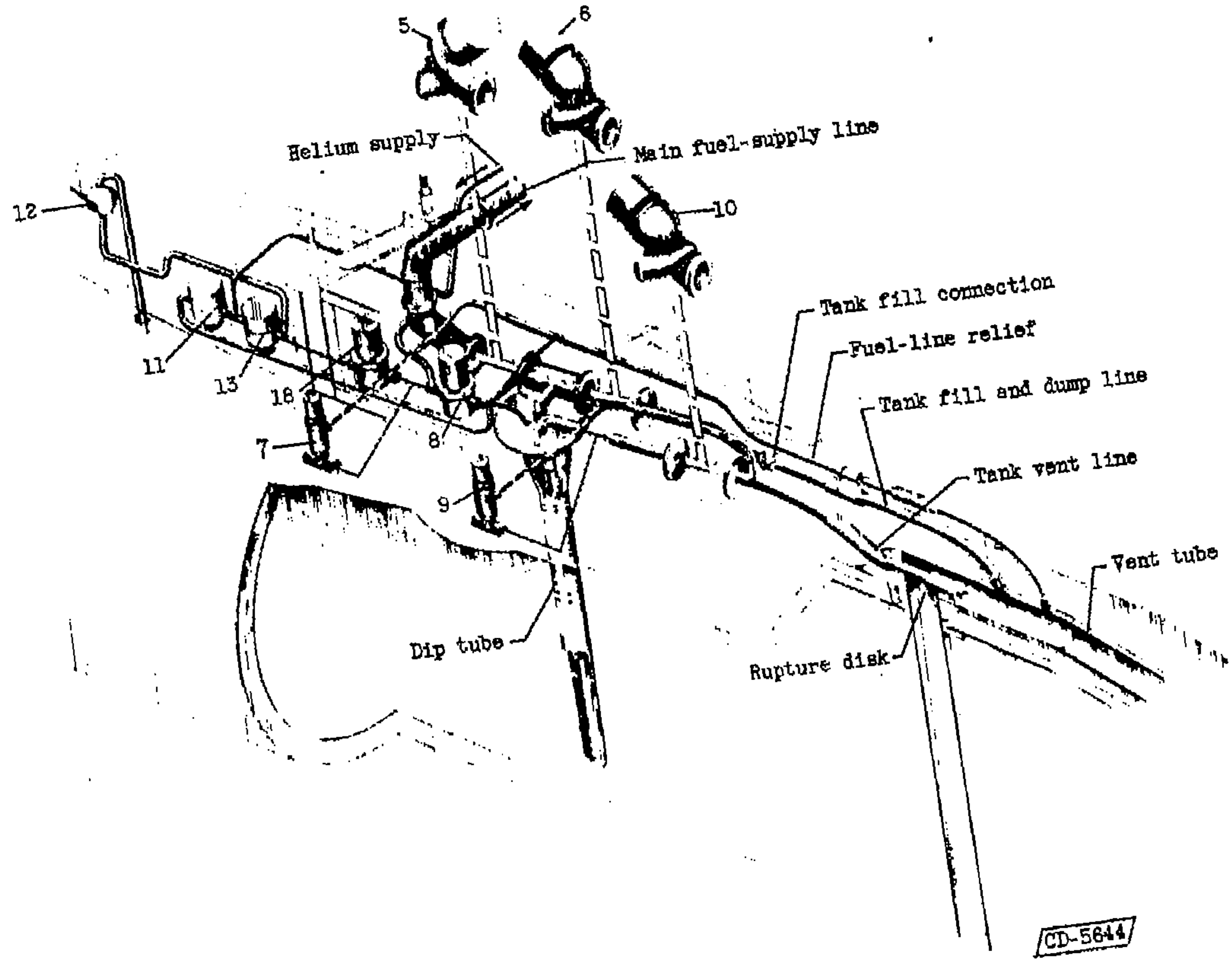

Figure 8. - Hydrogen system in fuel-tank pylon.

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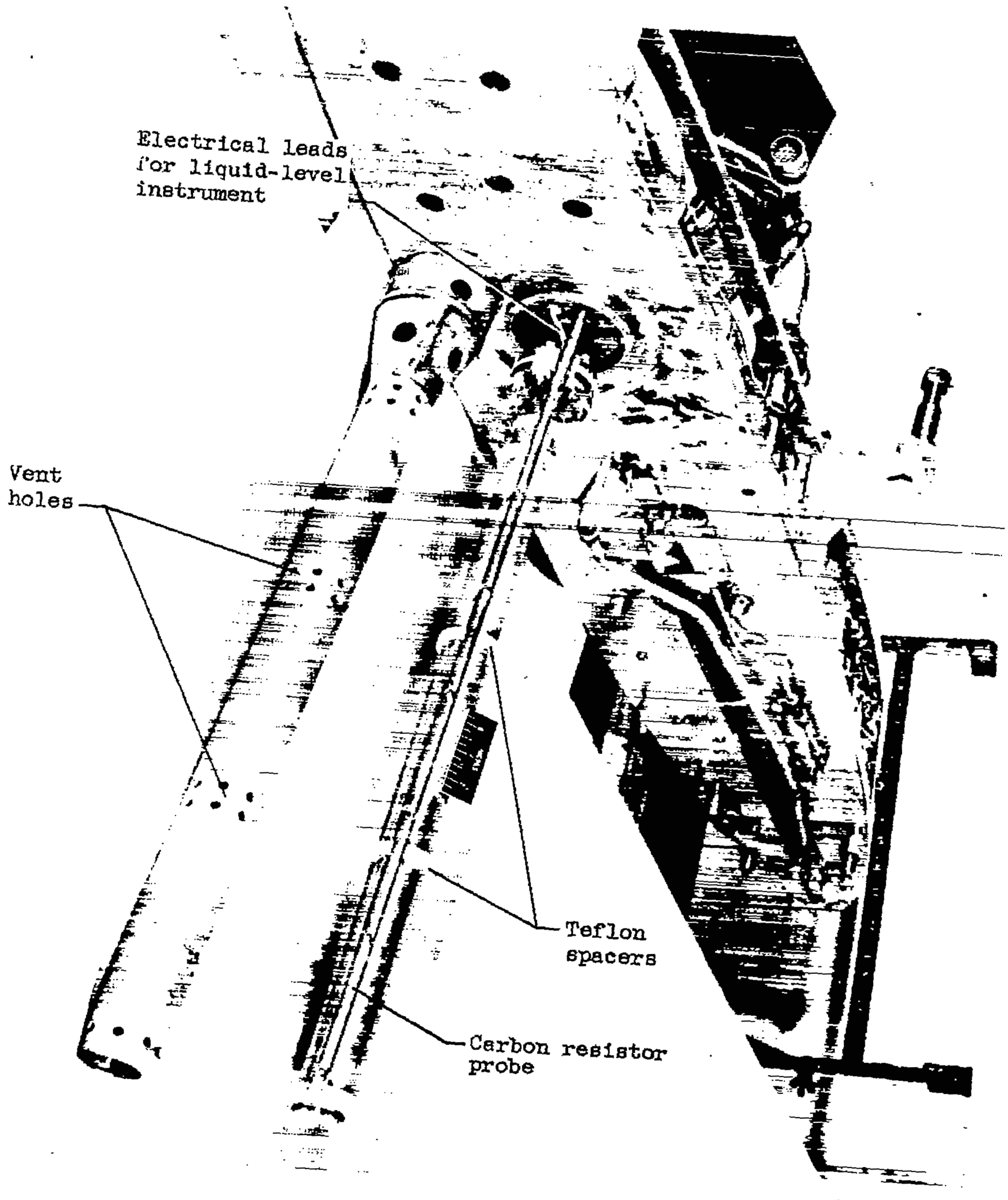

Figure 9. - Hydrogen-fuel-tank dip tube.

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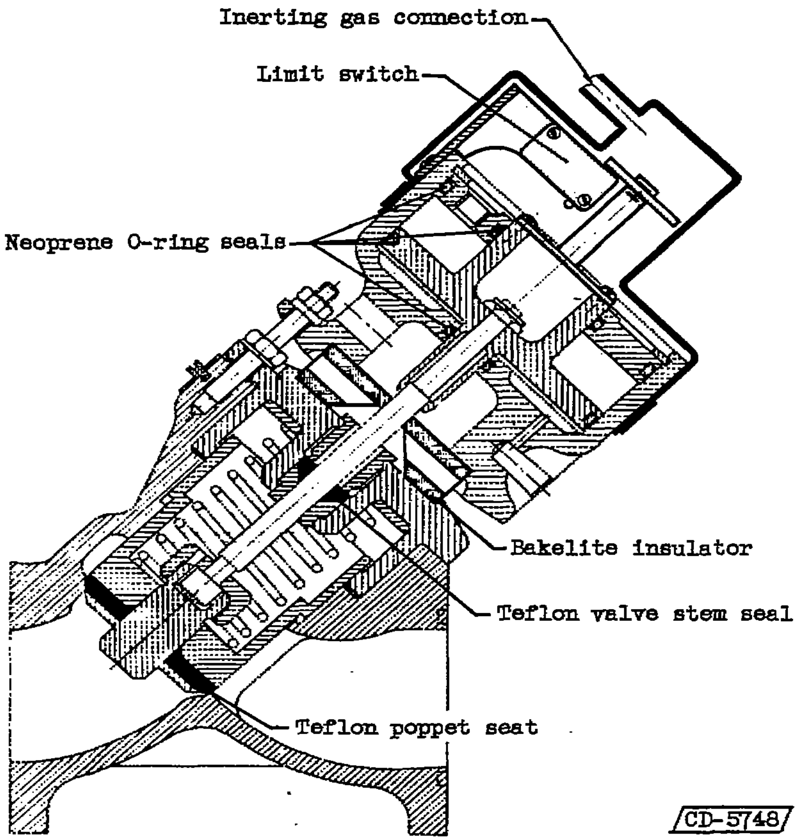
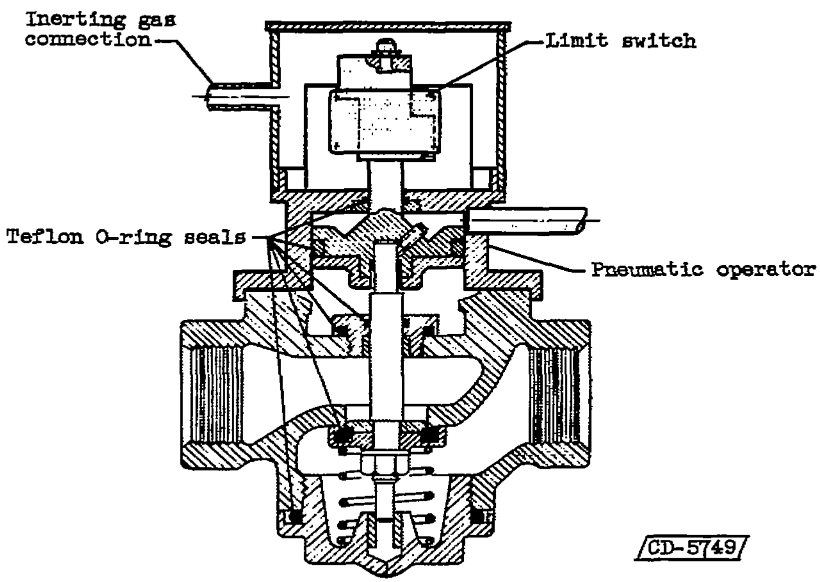


(a) Valve for liquid hydrogen.



(b) Valve for fuel-line vent and purge.

Figure 10. - Modification of valves used in liquid-hydrogen fuel system.

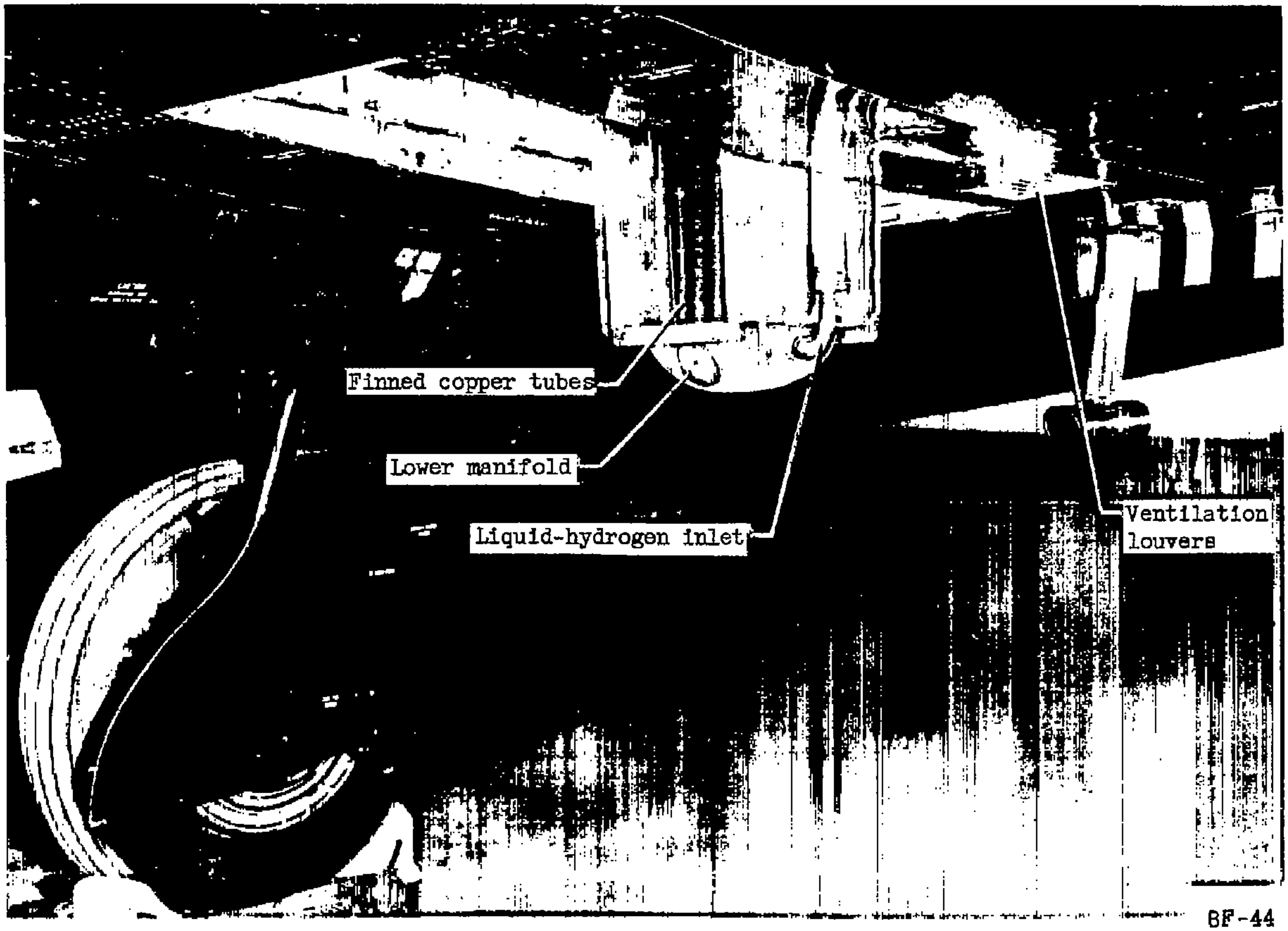


Figure 11. - Hydrogen heat exchanger mounted in airplane ammunition bay.

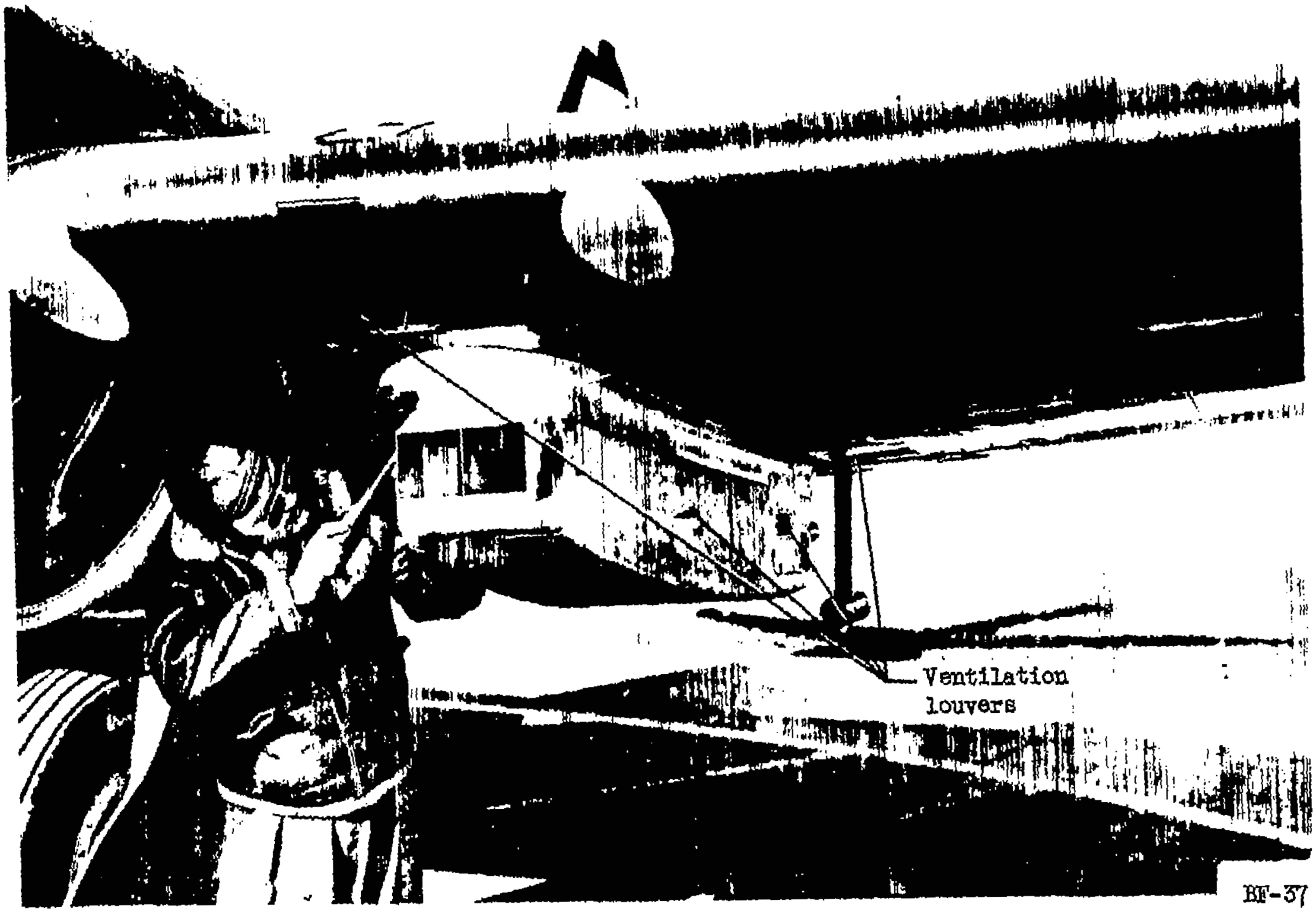


Figure 12. - Ram-air scoop for liquid-hydrogen heat exchanger.

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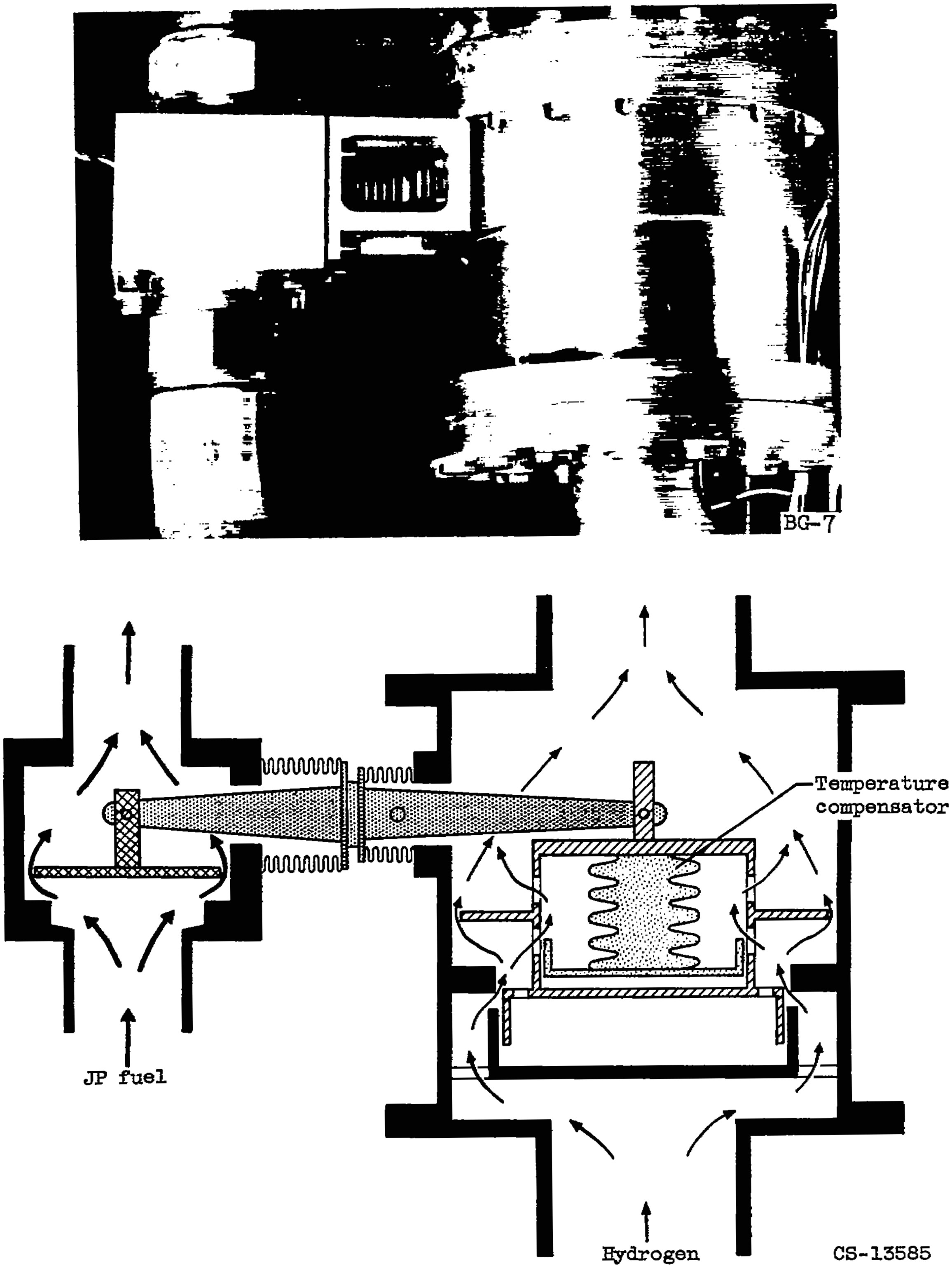

Figure 13. - Hydrogen-fuel-supply regulator for aircraft system.

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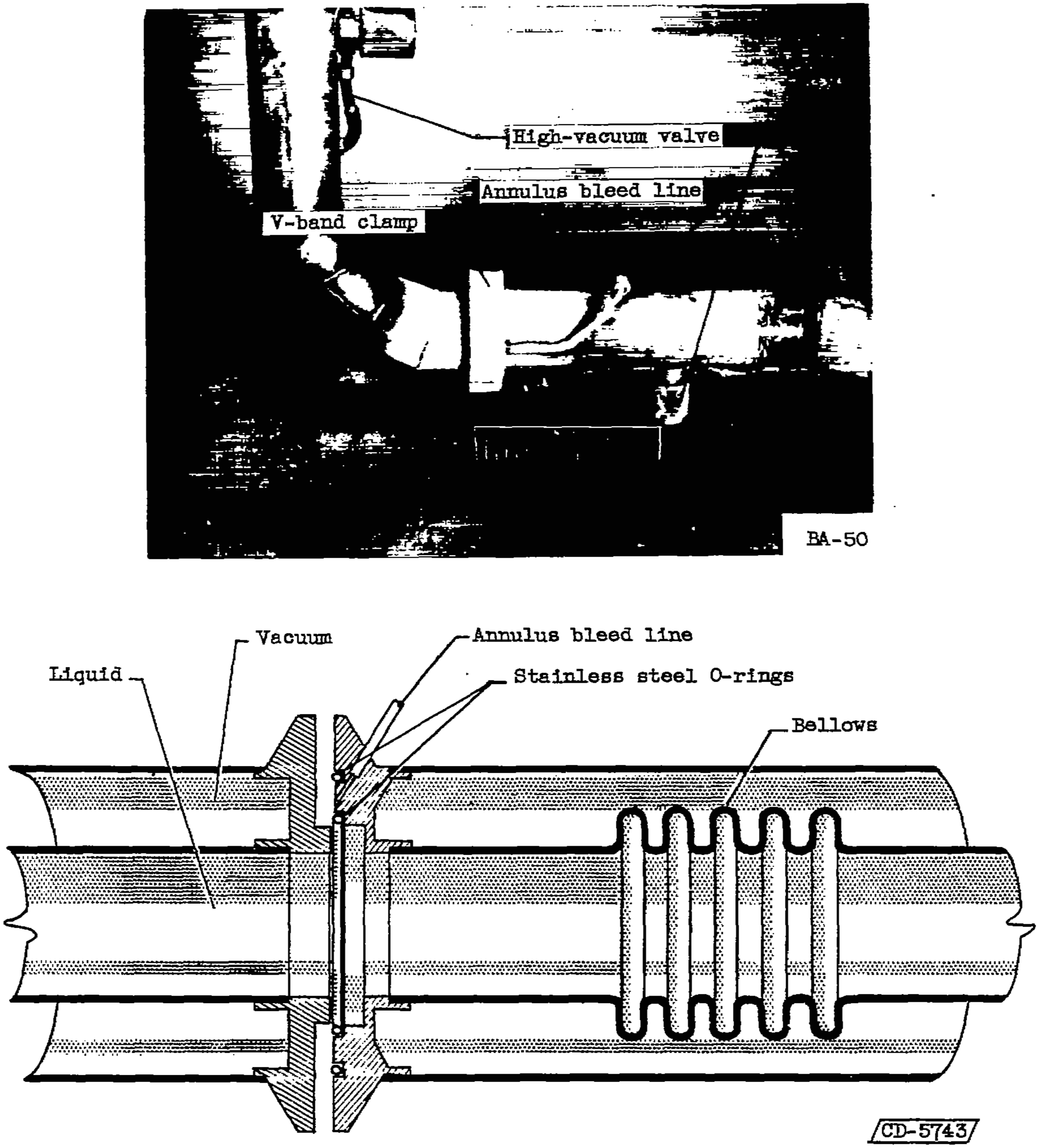

Figure 14. - Vacuum-jacketed liquid-hydrogen fuel line and joint construction used for airplane installation.

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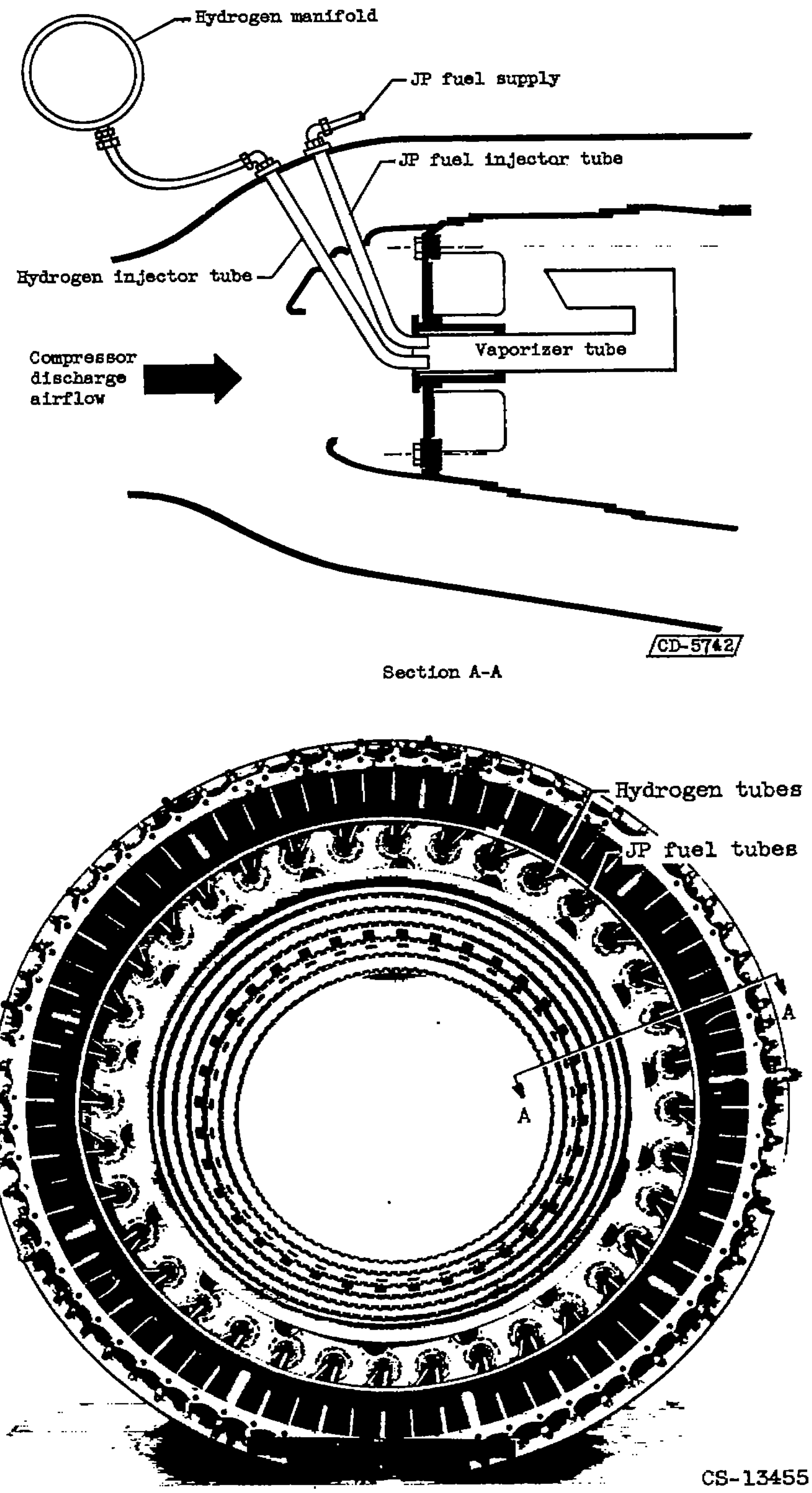

Figure 15. - Modification of turbojet engine for airplane hydrogen fuel system.

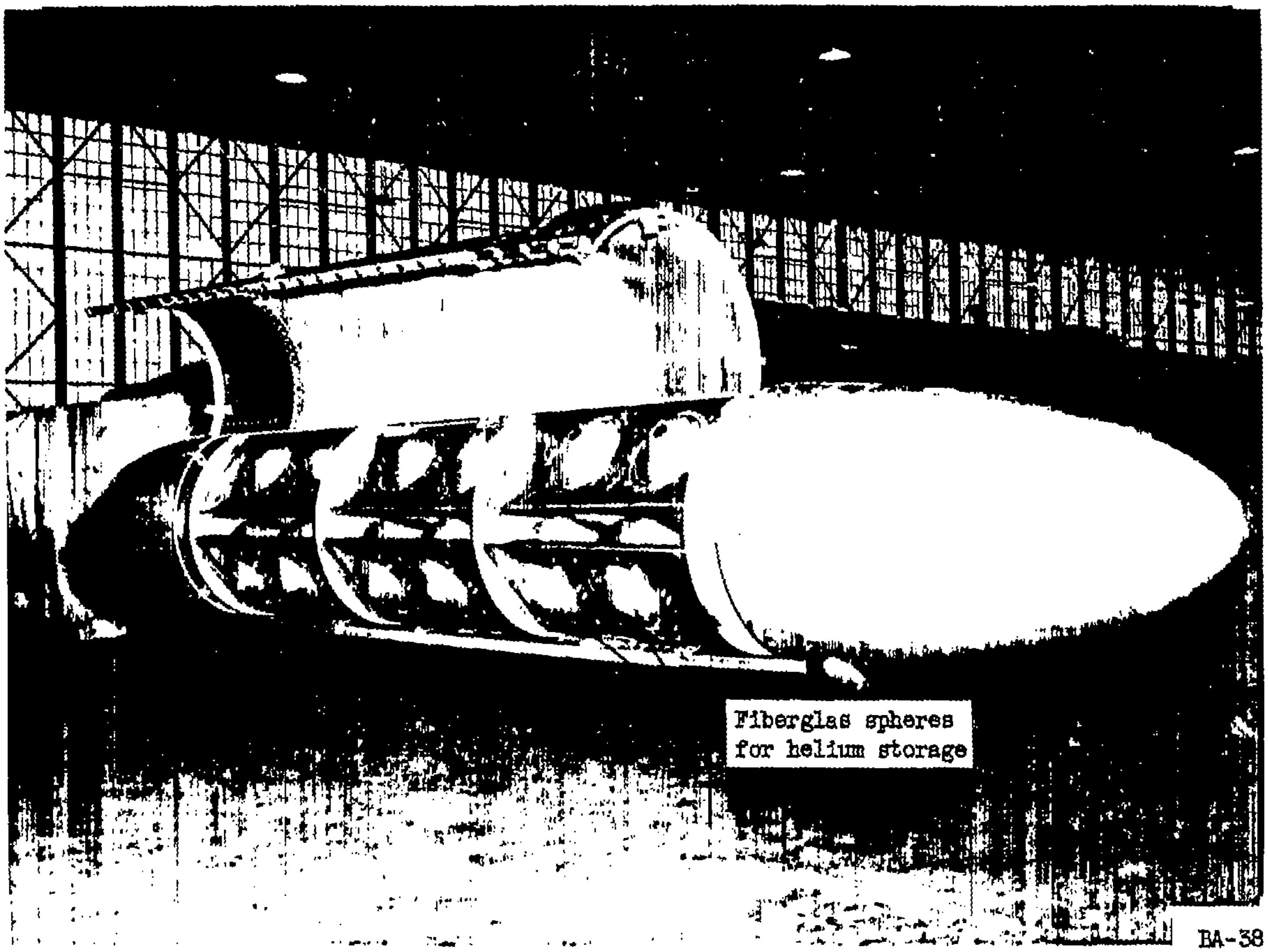

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Figure 16. - Helium supply tank used for airplane hydrogen fuel system.

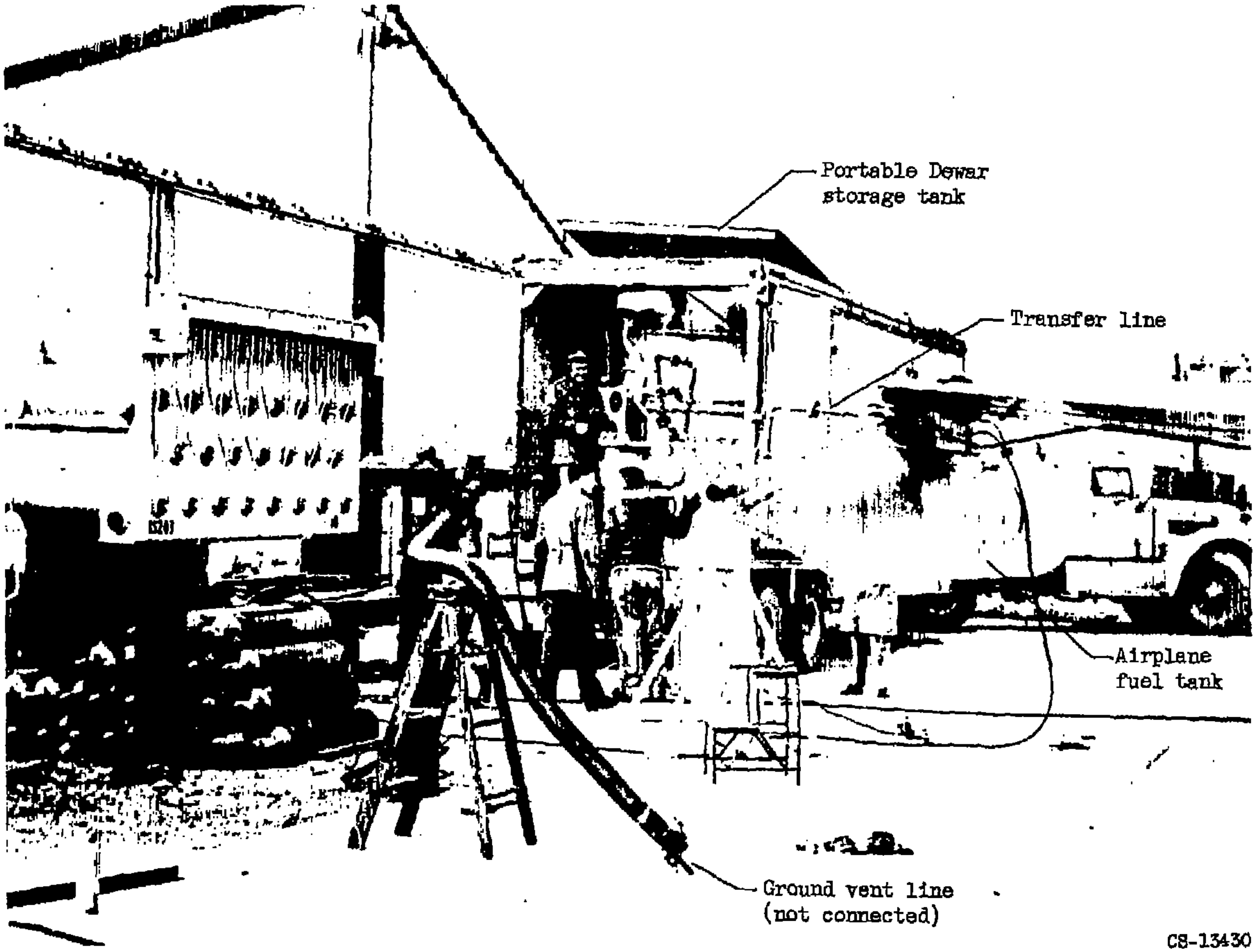

Figure 17. - Arrangement of equipment for loading of liquid-hydrogen fuel into airplane wingtip tank.

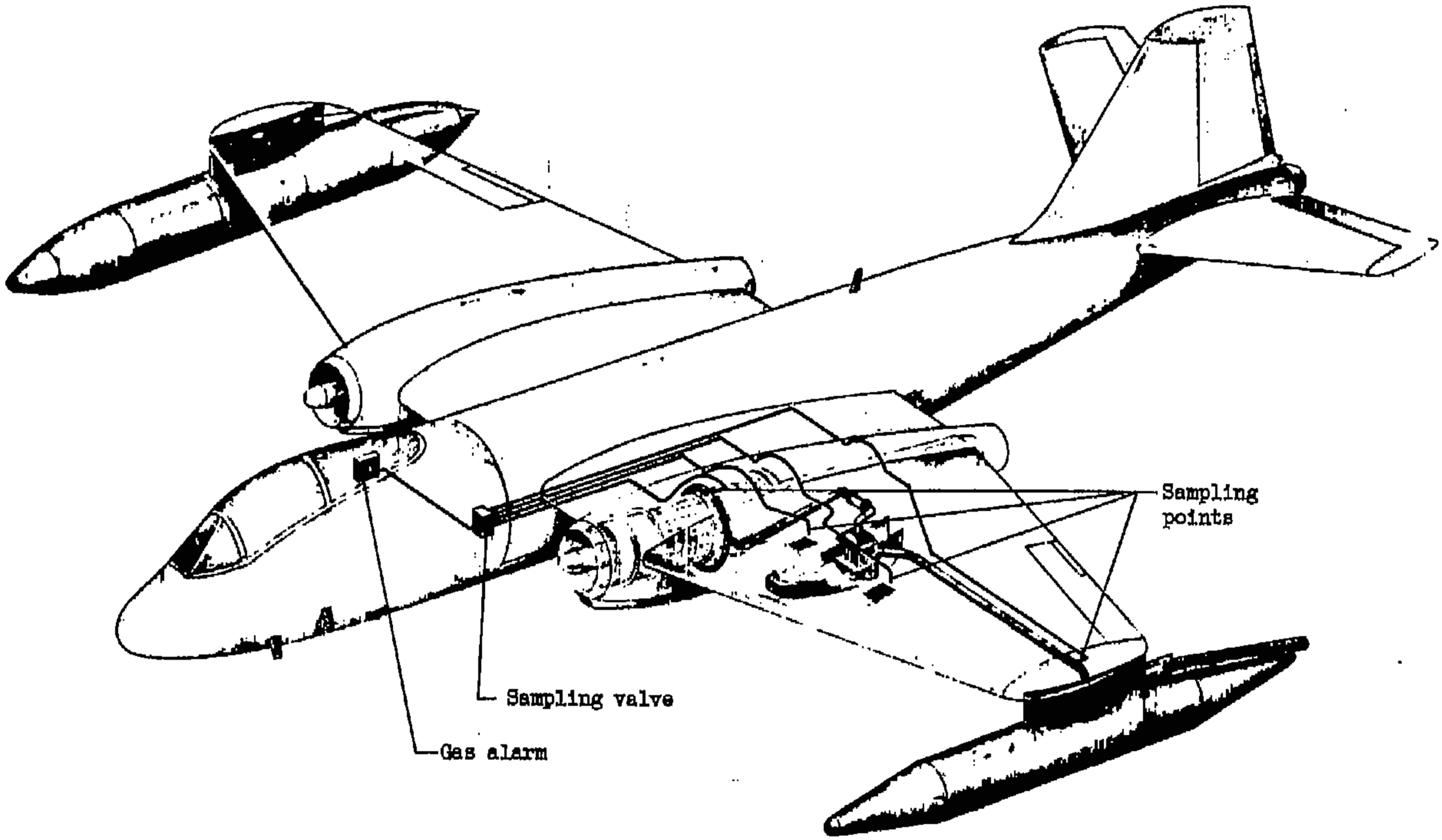

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Figure 18. - Arrangement of combustible gas-alarm equipment for airplane hydrogen system.

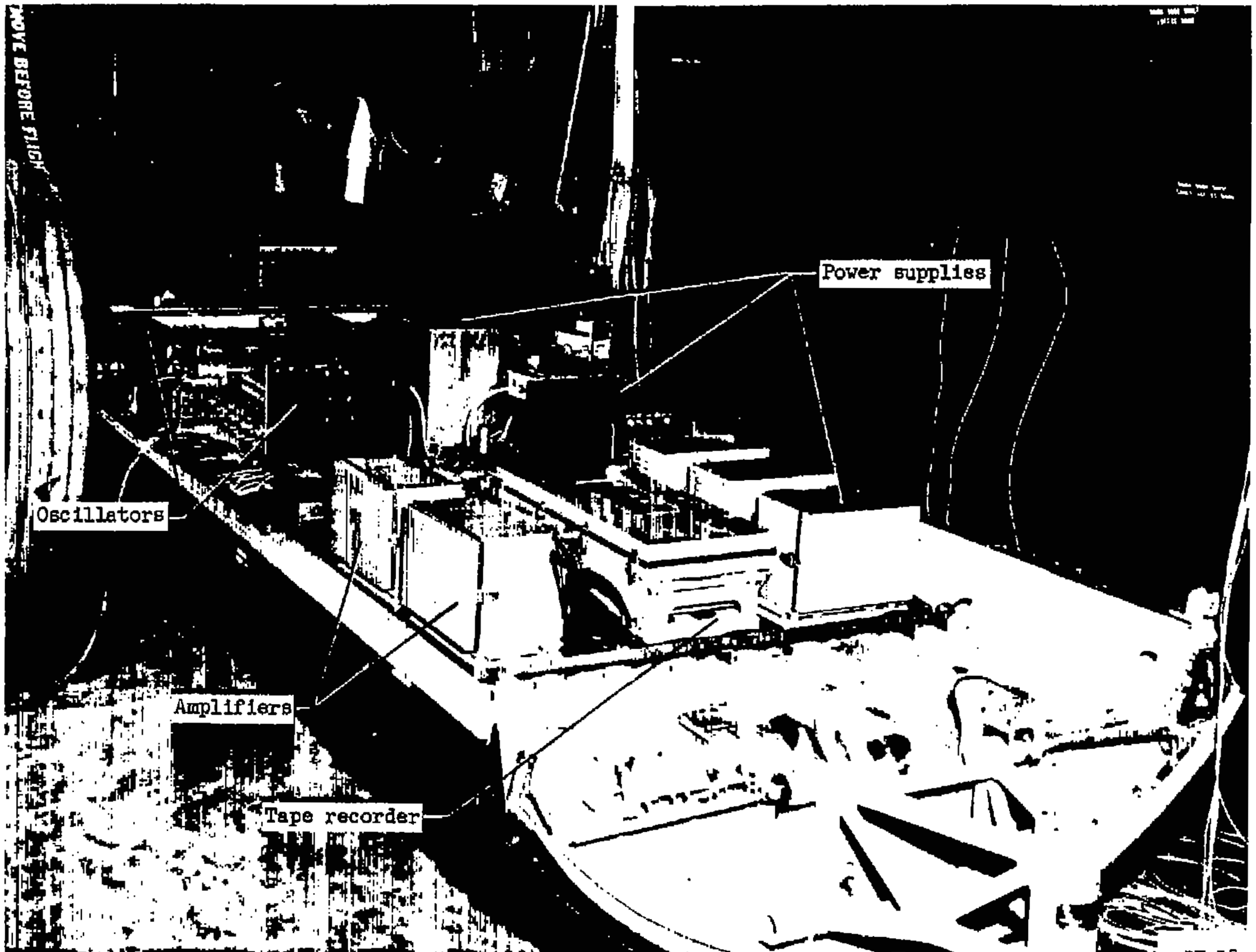

Figure 19. - Multichannel data-recording system mounted on bomb-bay door of airplane.

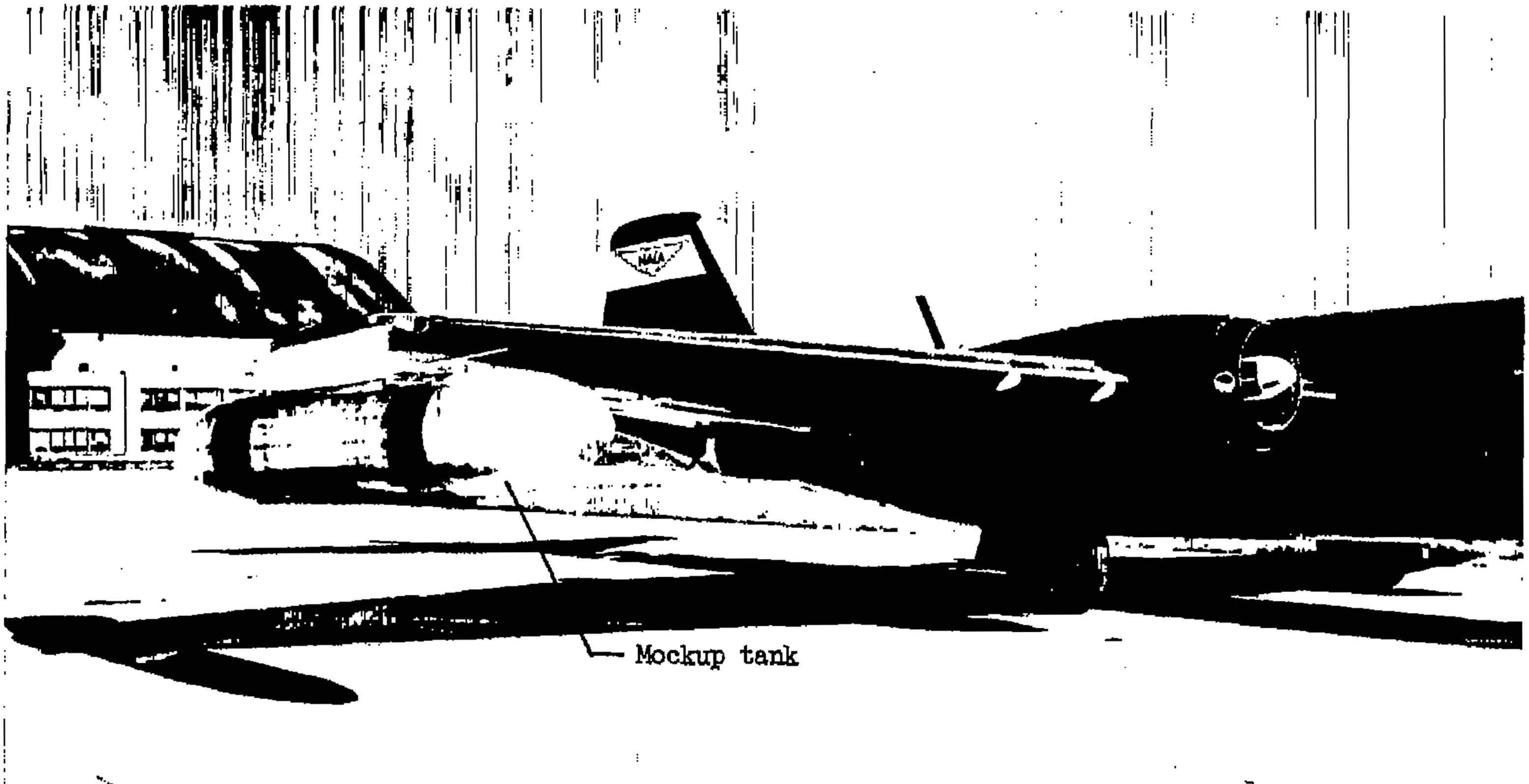

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Figure 20. - Mockup wingtip tank used for preliminary flights of aircraft hydrogen-fuel system.

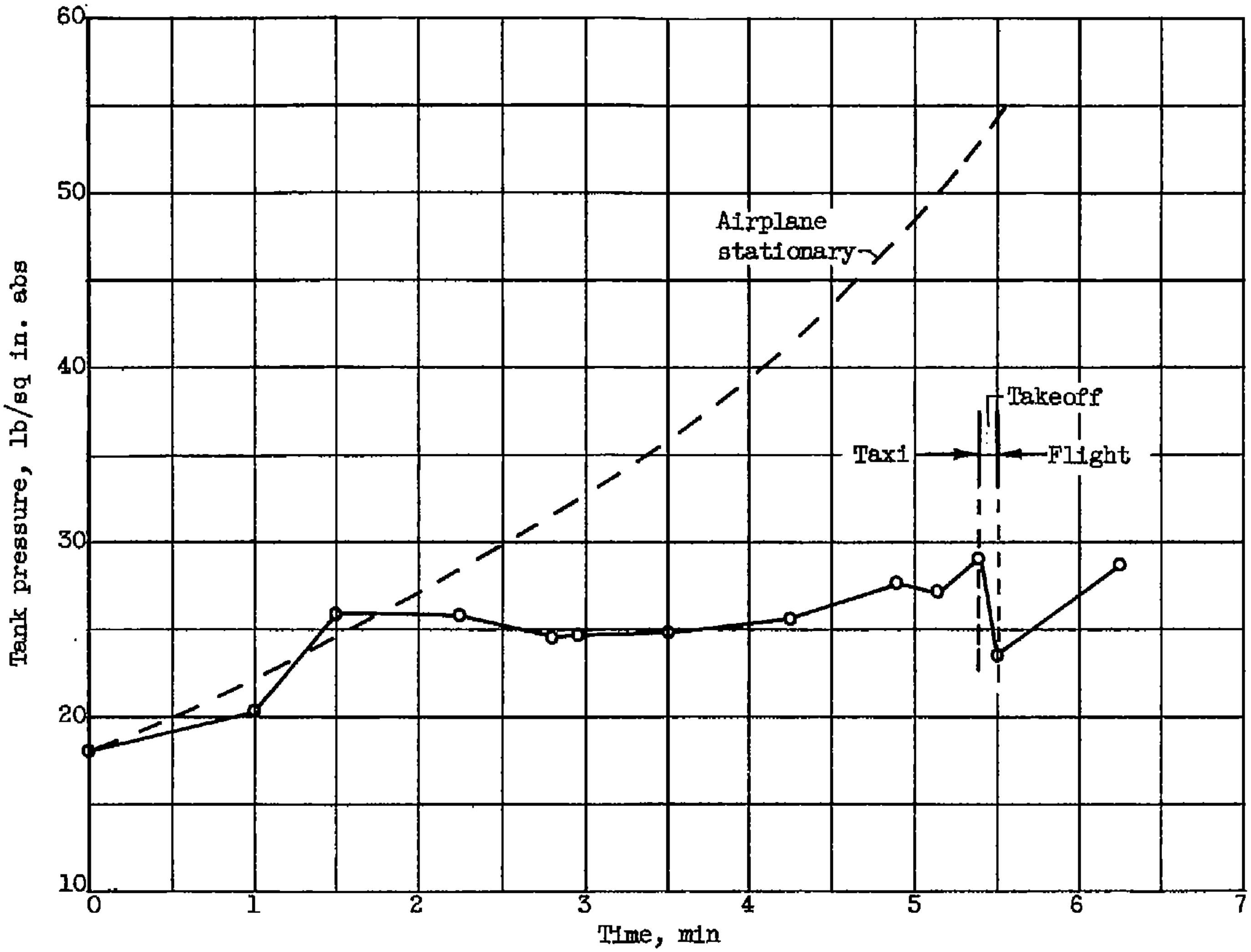

Figure 21. - Comparison of pressure rise in aircraft hydrogen-fuel tank before and during taxi.

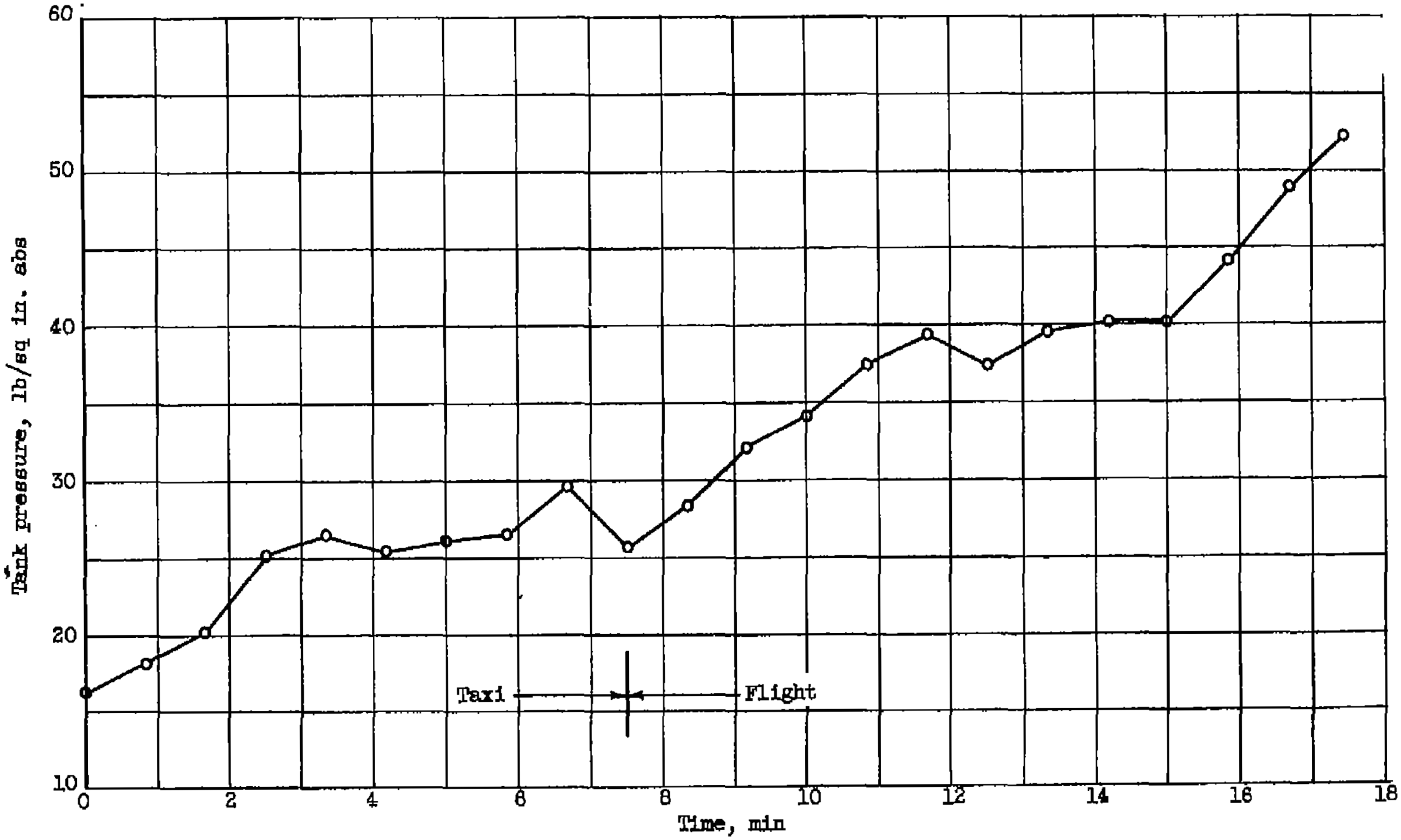

Figure 22. - Time history of hydrogen-fuel-tank pressure rise during taxi and initial period of climb preceding first tank venting.

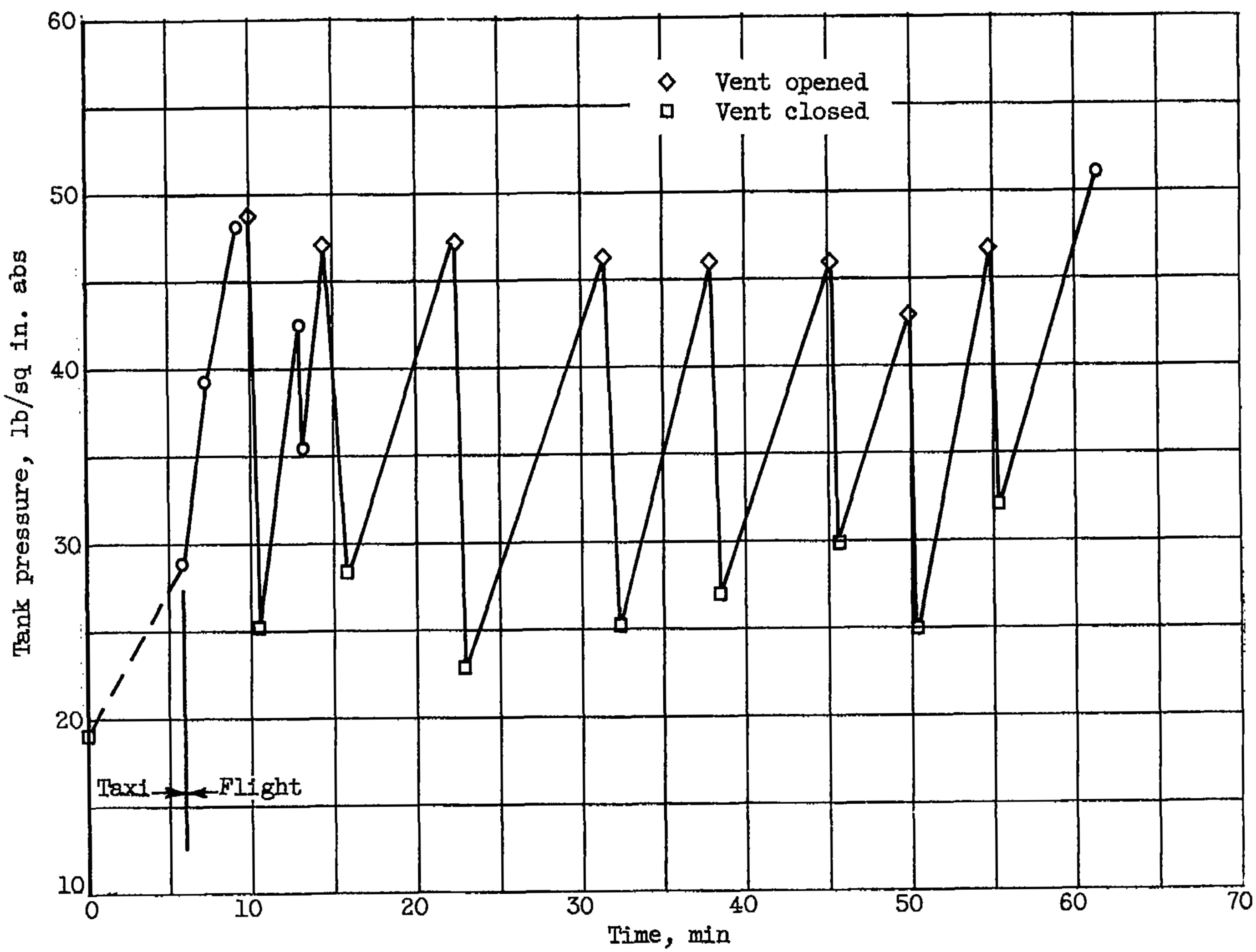

Figure 23. - Pressure changes in hydrogen fuel tank during climb to cruise altitude.

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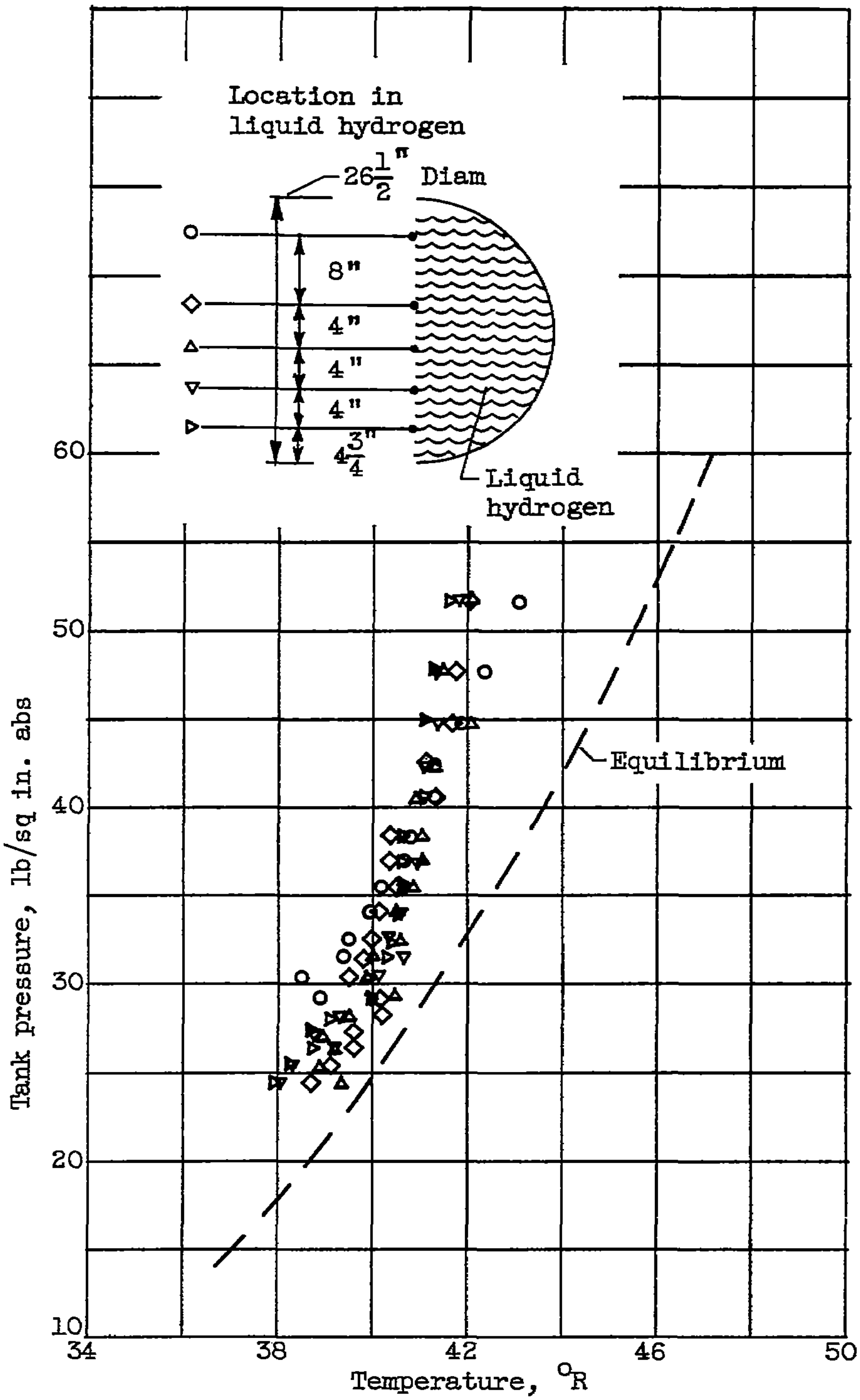

Figure 24. - Comparison of liquid-hydrogen temperature and pressure in fuel tank with equilibrium curve.

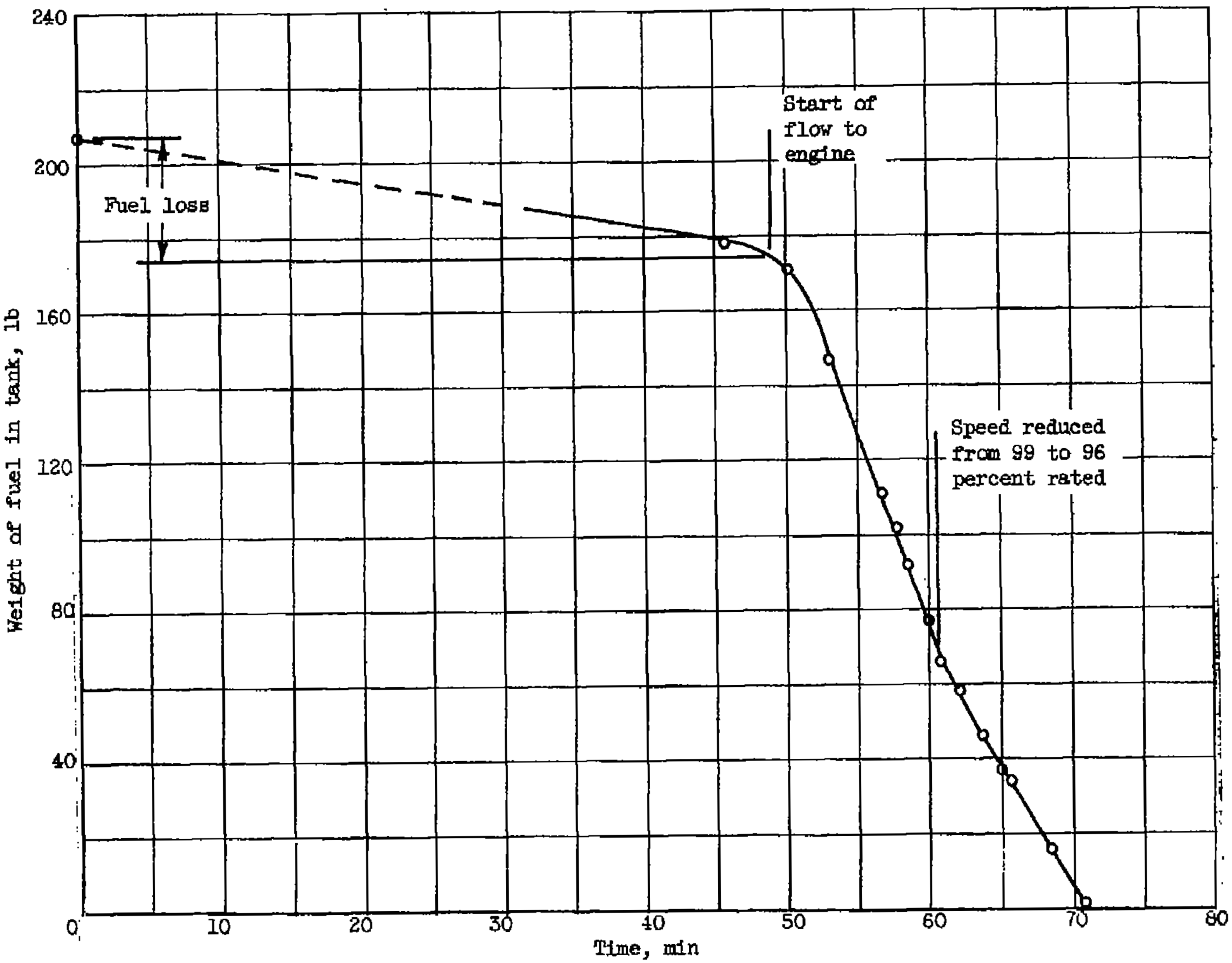

Figure 25. - Time history of fuel weight in hydrogen tank.

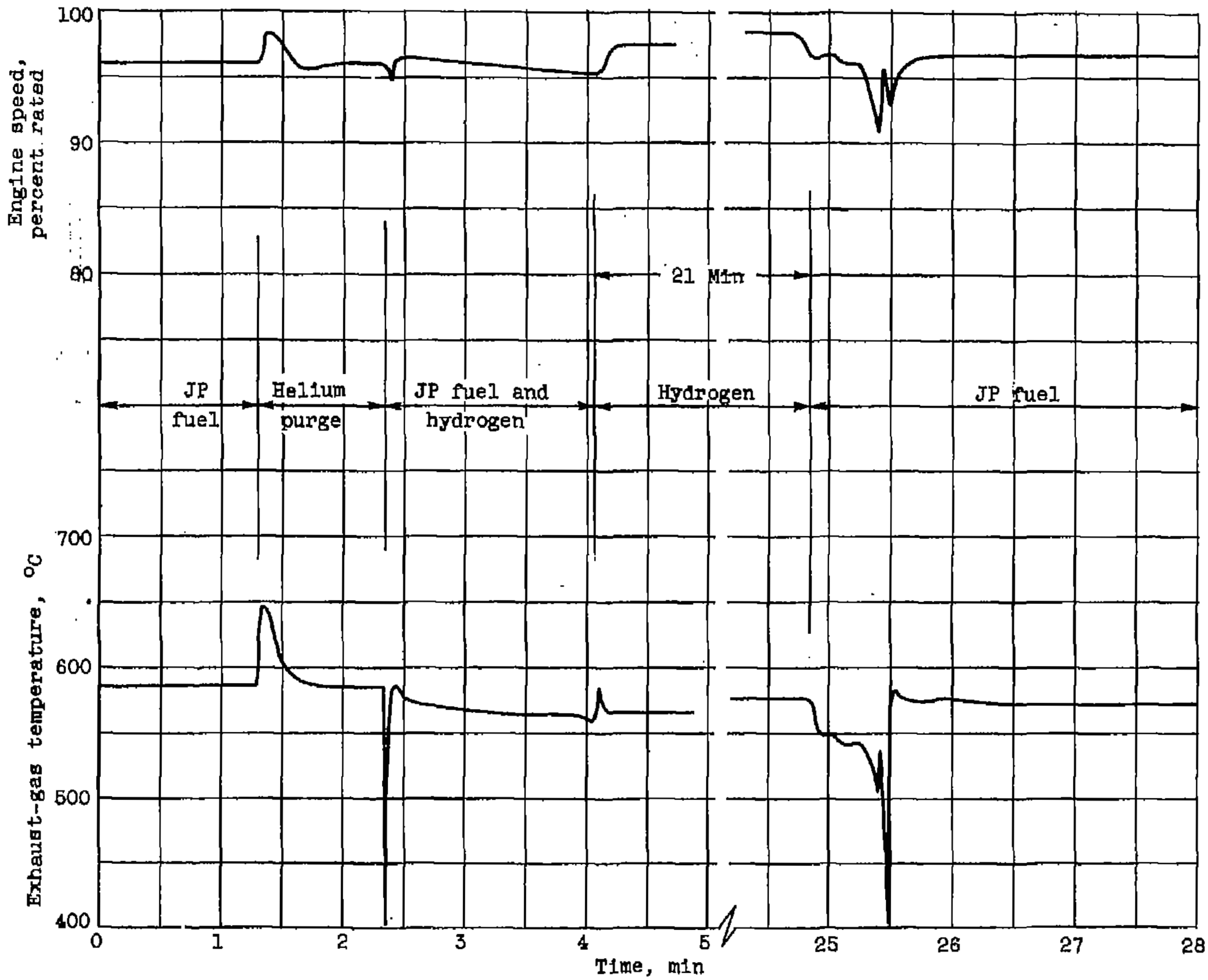

Figure 28. - Engine speed and exhaust-gas temperature during transition from JP fuel to hydrogen during flight.

[redacted]

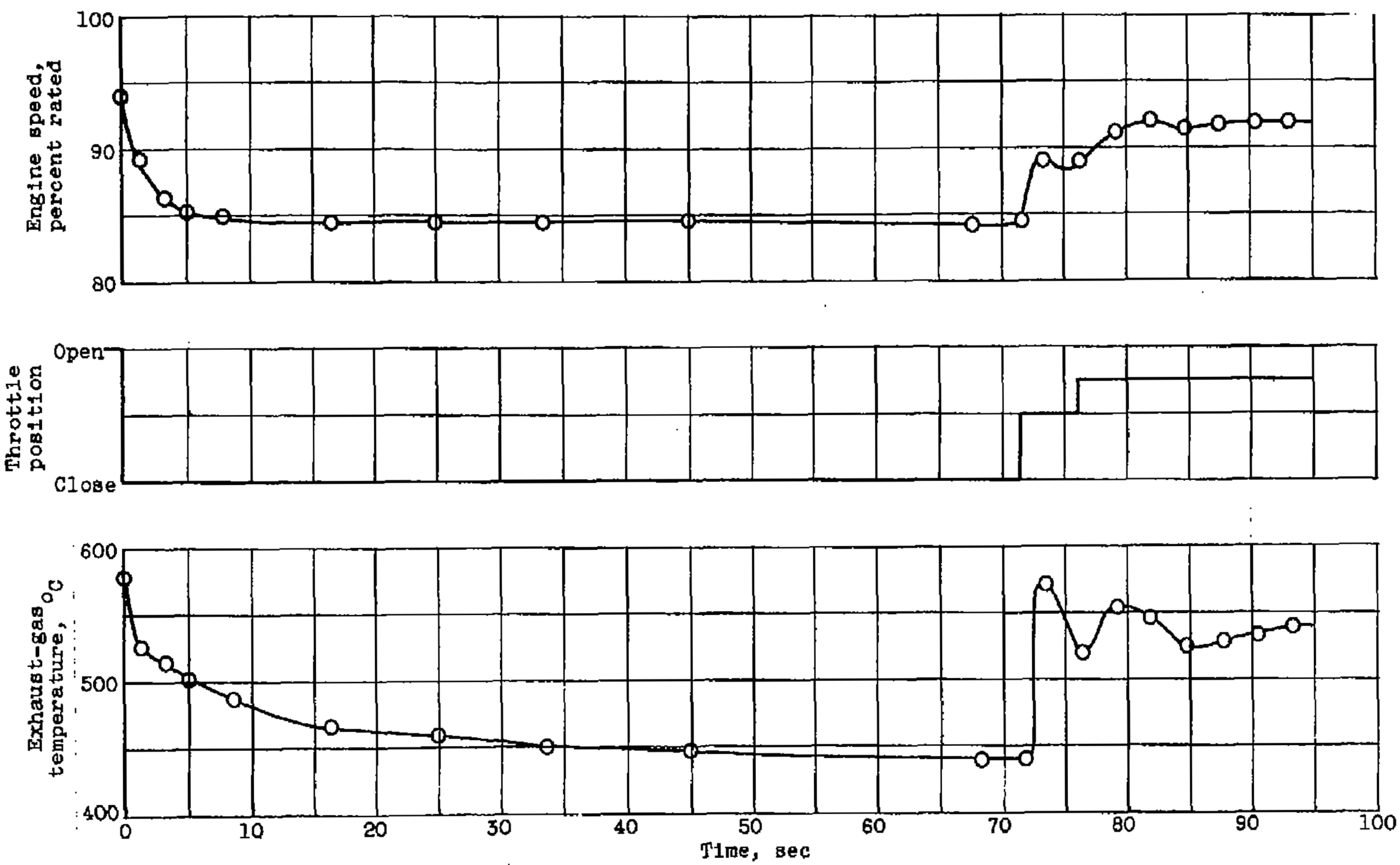

Figure 27. - Response of tailpipe temperature and engine speed to change in throttle position during operation on hydrogen fuel.

[redacted]

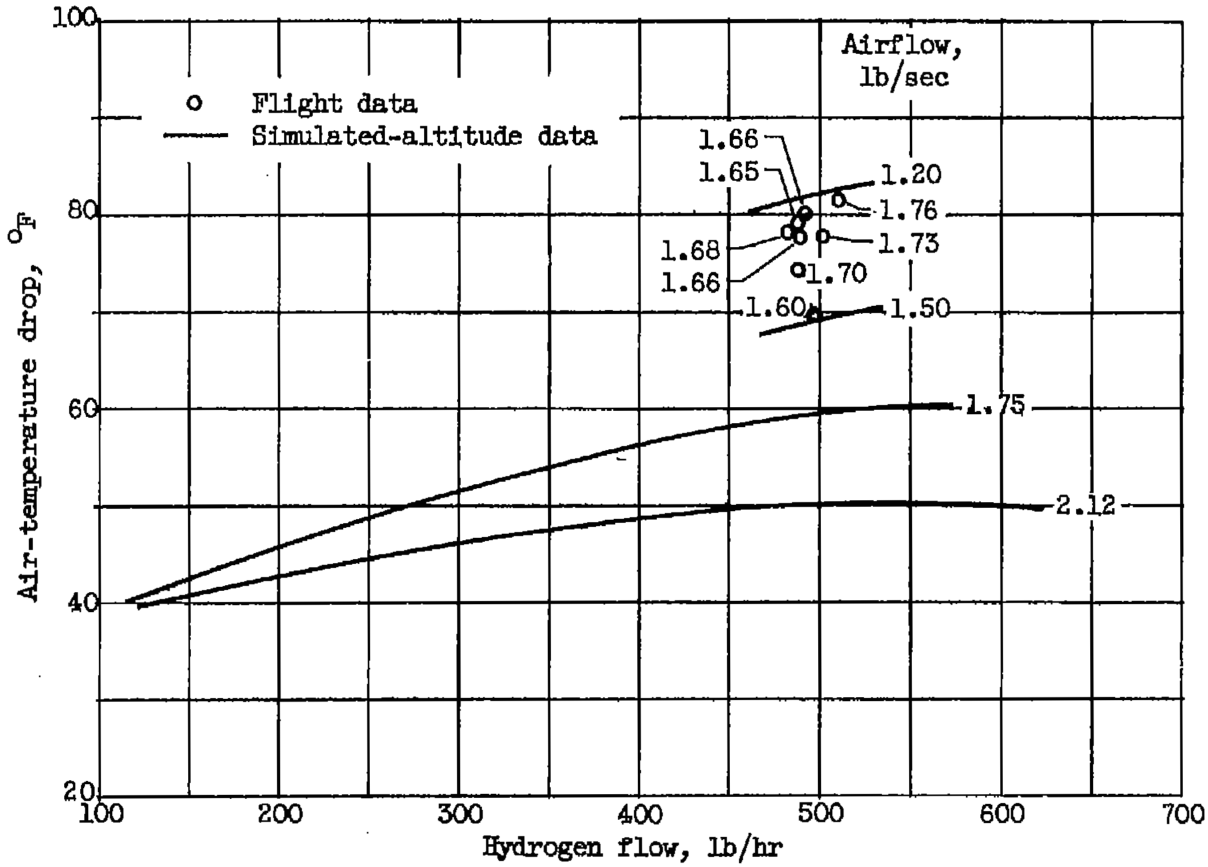

Figure 28. - Comparison of performance of hydrogen-vaporizing heat exchanger during flight with performance in altitude facility.

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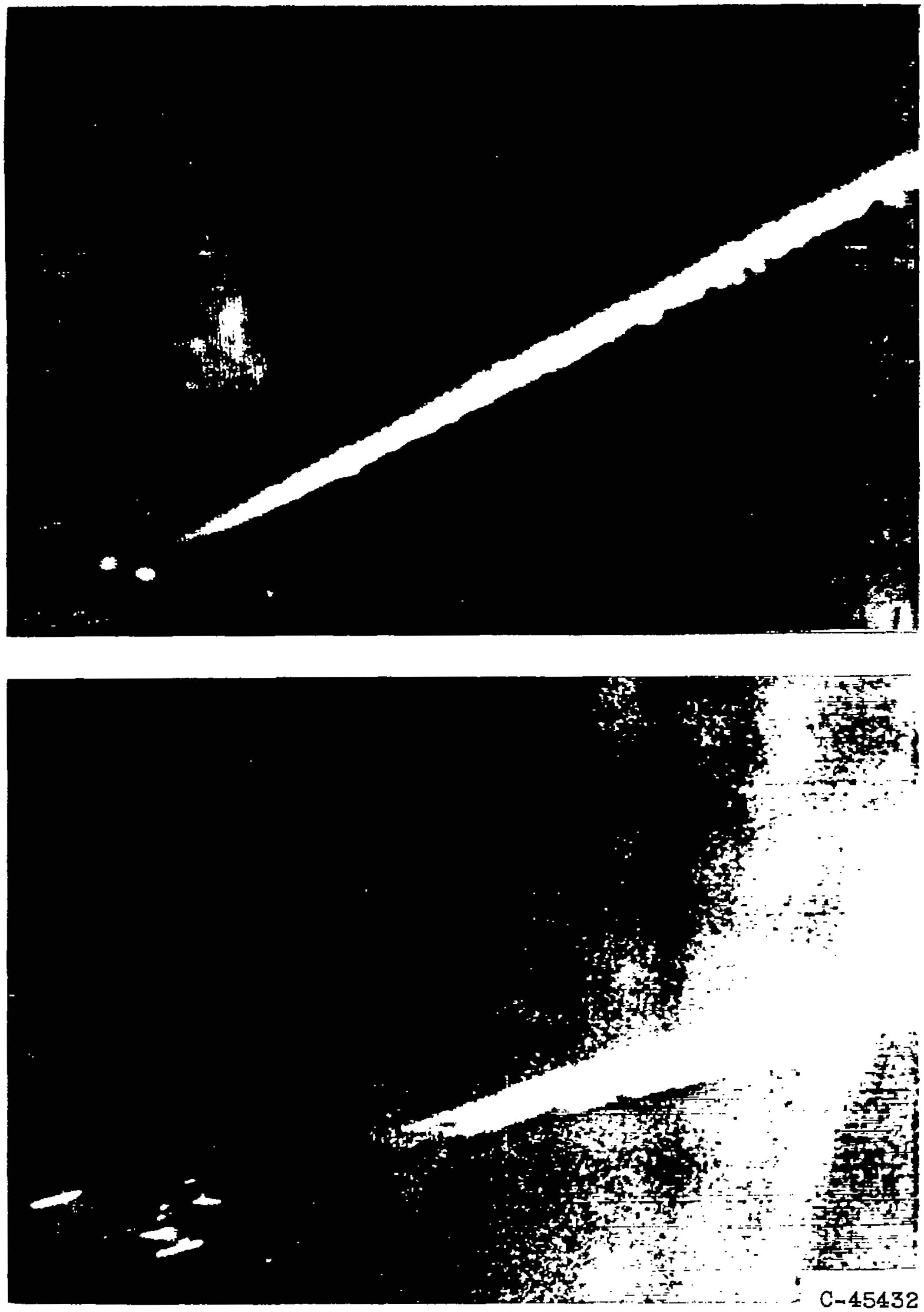

C-45432

Figure 29. - Contrails from engine operating on hydrogen fuel. Altitude, 48,000 feet; Mach number, 0.70.

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Figure 30. - Jettison of liquid hydrogen from fuel tank. Altitude, 44,000 feet; Mach number, 0.70.

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