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THE J-2 LIQUID HYDROGEN ROCKET ENGINE

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A DIVISION OF
NORTH AMERICAN AVIATION, INC.

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INTRODUCTION

The J-2 high-energy liquid propellant rocket engine (Fig. 1), a large engine producing 200,000 pounds of thrust at altitude conditions, burns liquid hydrogen and liquid oxygen to produce the necessary high specific impulse for practical space use. Rocketdyne, a Division of North American Aviation, Inc., is developing the engine for the George C. Marshall Space Flight Center, NASA. The first use of the engine will be in the upper stages of the Saturn vehicles. Five engines will be used for the second, S-II stage of the Saturn V, and one will power the S-IVB third stage of the Saturn V and S-IVB second stage of the Saturn IB.

The J-2 development program at Rocketdyne was initiated in September 1960. The engine passed rapidly through feasibility firing phases and progressed to daily firings for operational refinement and reliability verification. Encouraging progress was demonstrated by success of the first attempt at a full-duration firing at full thrust. The development program will reach the Preliminary Flight Rating Test milestone this year, and production engine deliveries will commence this summer. Qualification and first flights are scheduled for 1965.

In this paper, the engine system and component design will be discussed, with emphasis upon the newer features whose development has been dictated by the use of liquid hydrogen as the fuel. A brief description of the development program and of the principal specialized test equipment will be given.

BASIC SYSTEM

The J-2 engine is built around the high-altitude thrust chamber, which serves as a mount for all components and is designed for 10-degree

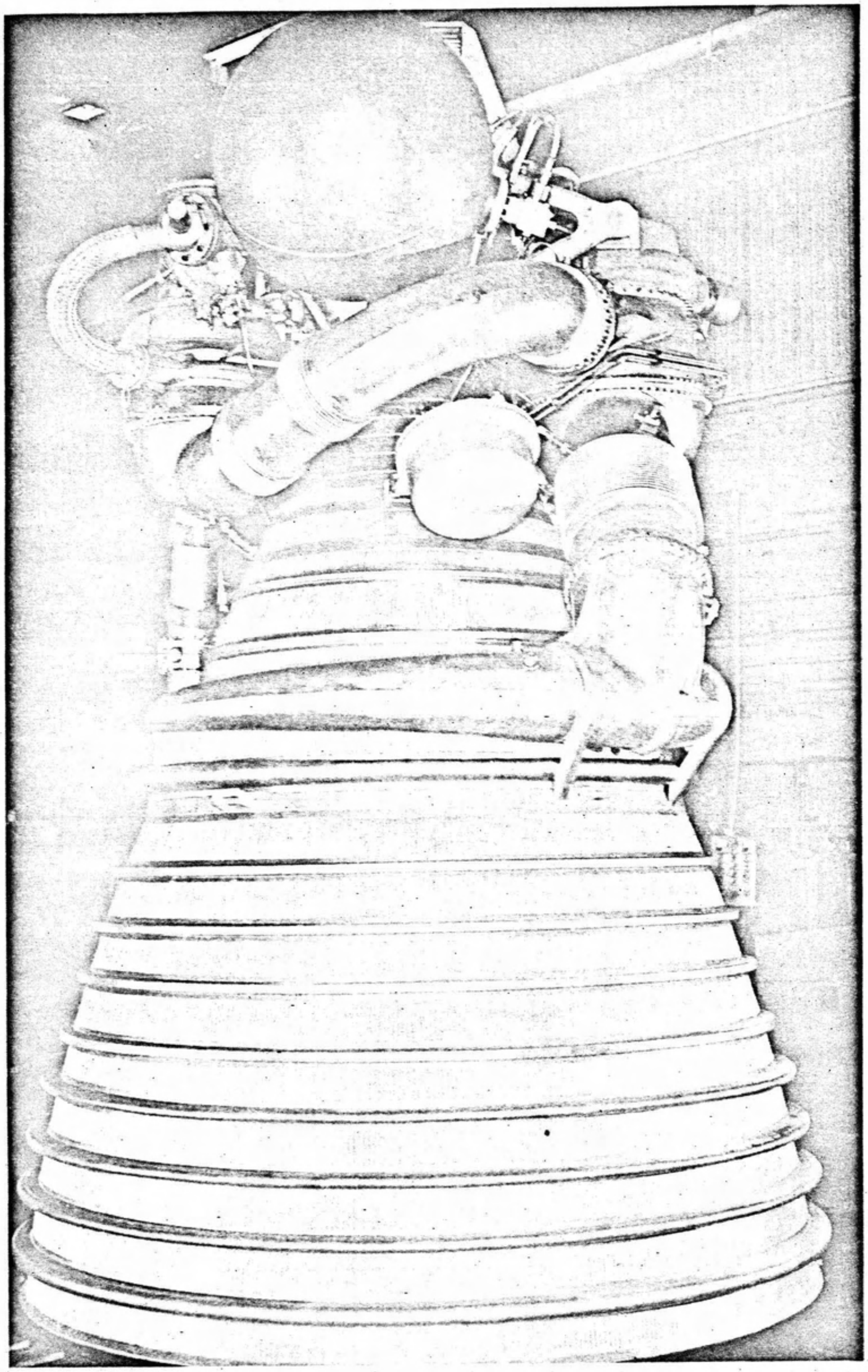

Figure 1. The J-2 Engine

directional control by gimbaling the entire engine. The thrust chamber has an expansion area ratio of 27.5:1, as large as possible for vacuum performance while retaining the desirable feature of sea-level firing capability for stage checkout and reliability development.

The propellants for the engine are delivered to the injector and combustion chamber by two separate turbopumps mounted on either side of the combustion chamber. The liquid hydrogen pump is a seven-stage, axial-flow pump operating efficiently at more than 25,000 rpm. The liquid oxygen pump is a radial pump operating in the 6000-rpm range. Separation of the two pumps avoids the complication of gear sets or efficiency compromise. Each pump is driven by an integrally mounted, two-stage, velocity-compound turbine.

The turbine power cycle is illustrated in Fig. 2. Liquid hydrogen and liquid oxygen are burned in a single gas generator, fuel rich to provide reasonably hot but highly efficient low-molecular-weight gas. This gas passes first through the two stages of the hydrogen pump turbine, and then is directed to the oxygen pump turbine. Finally, as low-pressure exhaust, it is injected into the thrust chamber expansion zone. The two independent pumps are calibrated for the correct engine propellant flow of 5 pounds of oxygen to 1 pound of hydrogen, and operate gas-coupled without controls.

Each propellant pump is equipped with a highly efficient inducer stage to operate with unusually low suction pressures because tank pressure requirements for large space vehicles must be minimal. Net Positive Suction Head (NPSH) for the hydrogen pump is 130 feet (4 psia), and for the oxygen pump is 25 feet (12.5 psia).

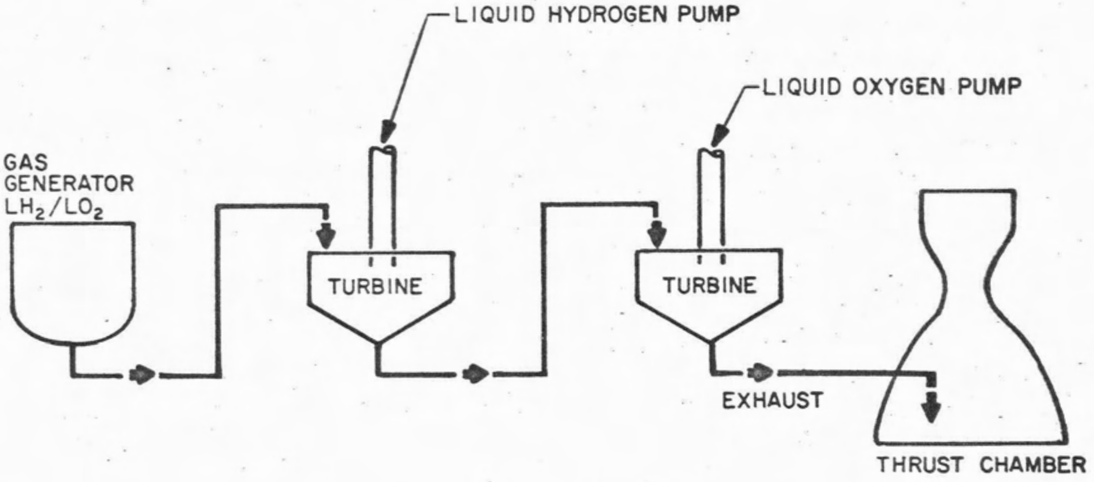

Figure 2. J-2 Engine Power Cycle

The power cycle was originally conceived to provide a start sequence in which the gas generator is started from pressures ordinarily available in the vehicle tanks; its feed pressures and power are then increased by increasing the speed of the turbopump. Although simple, the "tank-head" start proved to be too slow for efficient stage use in the Saturn application. Accordingly, the turbine power system was augmented, as shown in Fig. 3, by a 4-cu ft sphere of compressed hydrogen gas. This gas drives the turbine during the early phase of starting to produce initial rapid pump acceleration. The "gas-spin" start may be repeated any number of times during flight by simply recharging the sphere with hydrogen which has been heated in the chamber tubes during the engine run. The initial starts and restarts are identical, and do not require different control or operating sequences.

The engine system is completed by helium-actuated valves and an electrical control and ignition system. Flight instrumentation, hydrogen and oxygen gases for tank pressurization, and integrated interface connections are included.

COMPONENT DESIGN

Thrust Chamber Assembly

The J-2 thrust chamber and propellant injector designs have made full use of the unique heat-transfer properties of hydrogen. The large chamber is adequately cooled by hydrogen flowing 1-1/2 longitudinal passes in the stainless-steel tubes of which it is constructed. Liquid hydrogen at more than 800 psi enters this cooling cycle and is heated from approximately -423 to approximately -260 F. This temperature and

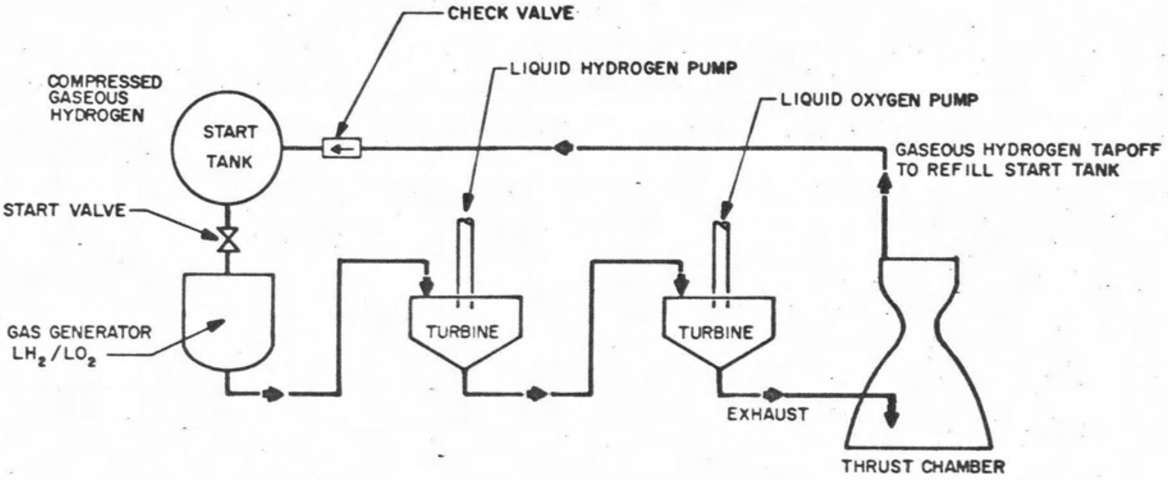

Figure 3. Turbine Power Cycle With "Gas Spin" Start

this pressure are well above the ctitical values, and the hydrogen is to all intents a gas. The hydrogen is pressure-reduced to supply pressurizing gas to the fuel tank, and to recharge the start bottle. The injector is designed for gas/liquid injection, giving unusual freedom to atomize the propellants and to promote stable, controlled burning.

The tubular construction of the thrust chamber was selected not only because it lends itself to good structural strength and known fabrication techniques, but also because of the very thin metal wall demanded by the application. The gas-side heat transfer on each side of the tube wall is so good that the thermal resistance of metal is significant in the series heat transfer from the hydrogen-rich combustion gas, through the tube wall, to the cooling hydrogen flow.

The thrust chamber coolant circuit is illustrated in Fig. 4. Coolant velocity varies from 60 ft/sec to 1000 ft/sec at the throat. The wide variations in heat flux, hydrogen flowrate, and corresponding large density changes, require radical variations in tube cross section. An iterative computer program which solves the general energy equation, momentum equation, continuity equation, equation of state, and heat balance equation across tube walls provides design tube cross section shapes for the specified wall temperature profile. The resulting design of a tapered, formed tube has demonstrated conformance to the analytical model.

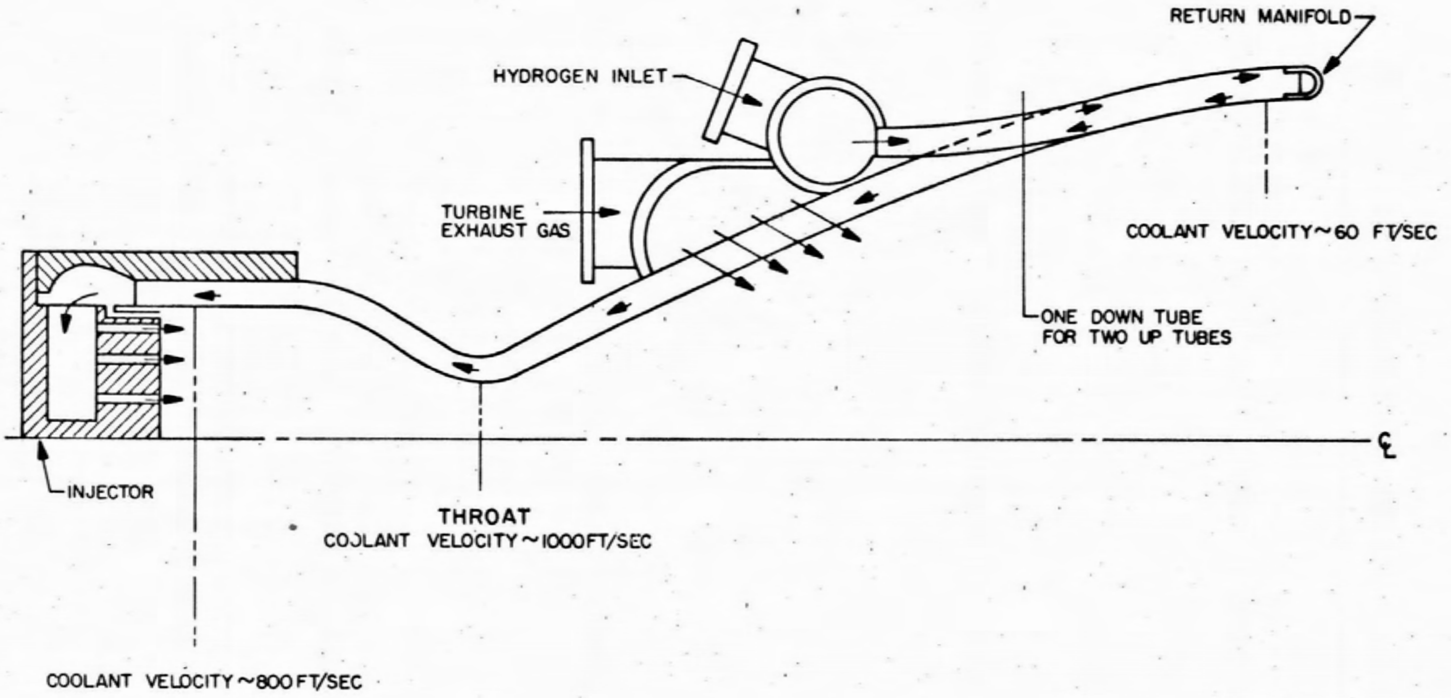

Figure 4. Thrust Chamber Coolant Circuit

The "1-1/2 pass" cooling circuit, illustrated in Fig. 4 and 5, was selected to reduce the size of the fuel inlet manifold and to facilitate the tubular construction to a high nozzle expansion ratio. The liquid hydrogen enters a manifold at a chamber expansion area ratio of 12:1, and flows down to the exit end in 180 tubes. This flow is divided in a return manifold between two long return tubes which carry it to the injector end. There are 360 return tubes. This 1-1/2 pass system provides a natural passage for injecting the turbine exhaust gas into the chamber at the discontinuity between the down and up tubes. A manifold distributes the exhaust gas to the 180 triangular holes available for this purpose.

Turbopumps

The J-2 turbopumps are both single-shaft units, each with its own two-stage velocity-compound turbine. A one-stage centrifugal liquid oxygen pump (Fig. 6) and a seven-stage axial-flow liquid hydrogen pump (Fig. 7) are employed. Speed ratio of the turbopumps is preadjusted by a calibrated orifice downstream of the liquid oxygen pump turbine. This permits operation of both units at their respective optimum speed and at the same time eliminates the need for high-power gearing.

A major simplification of the turbopumps was made possible by the development of propellant-lubricated ball bearings for each unit. The oxygen turbopump bearings are lubricated by an internal bypass flow of 20 gpm of liquid oxygen which passes through the two bearings in series. In the hydrogen turbopump, an internal liquid hydrogen flow of 10 gpm is provided for each of two bearings. The hydrogen turbopump bearings operate at a D-N (bore diameter in millimeters by speed in rpm) of

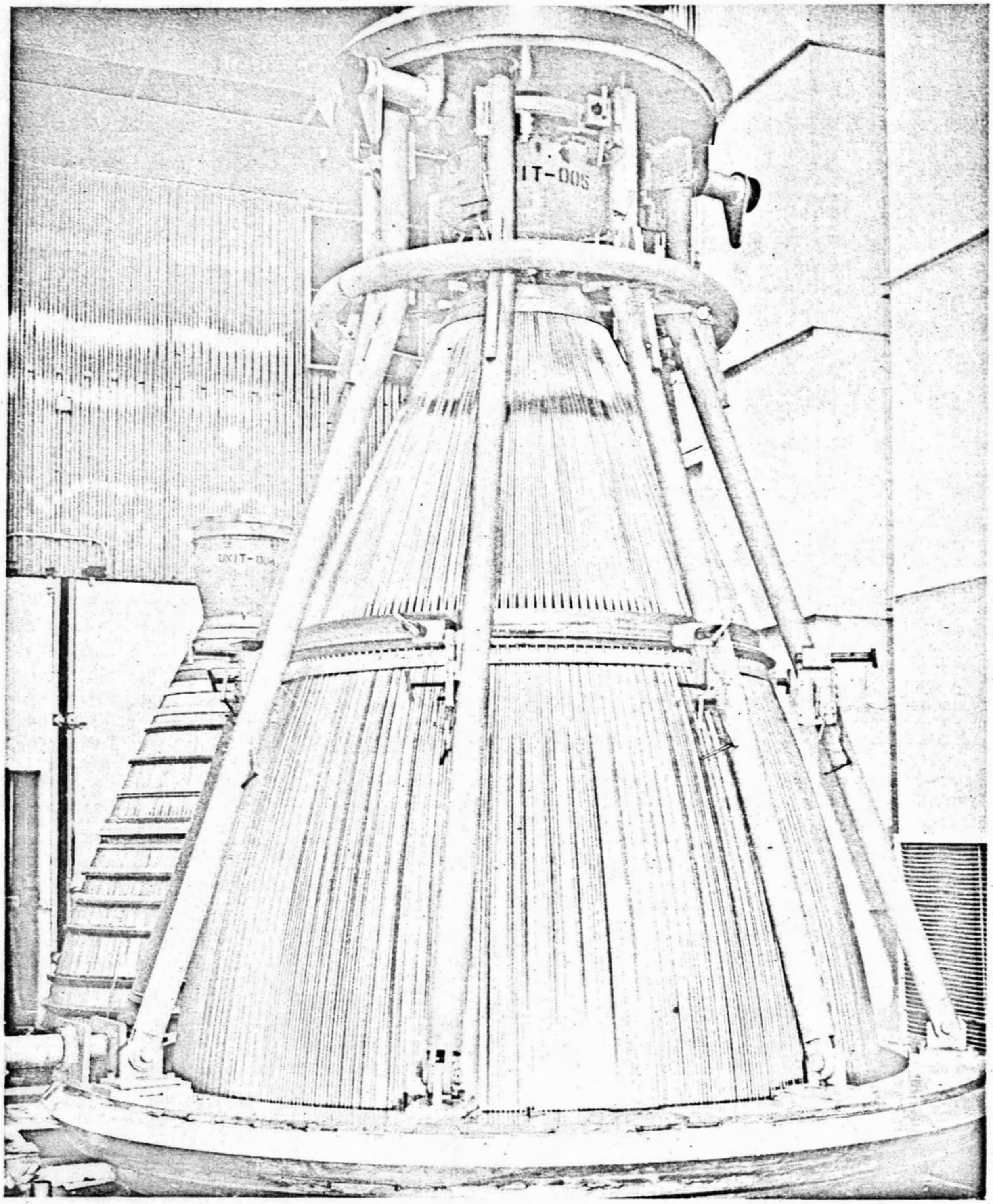

Figure 5. Thrust Chamber Tube Stack, Prior to Braze Operation

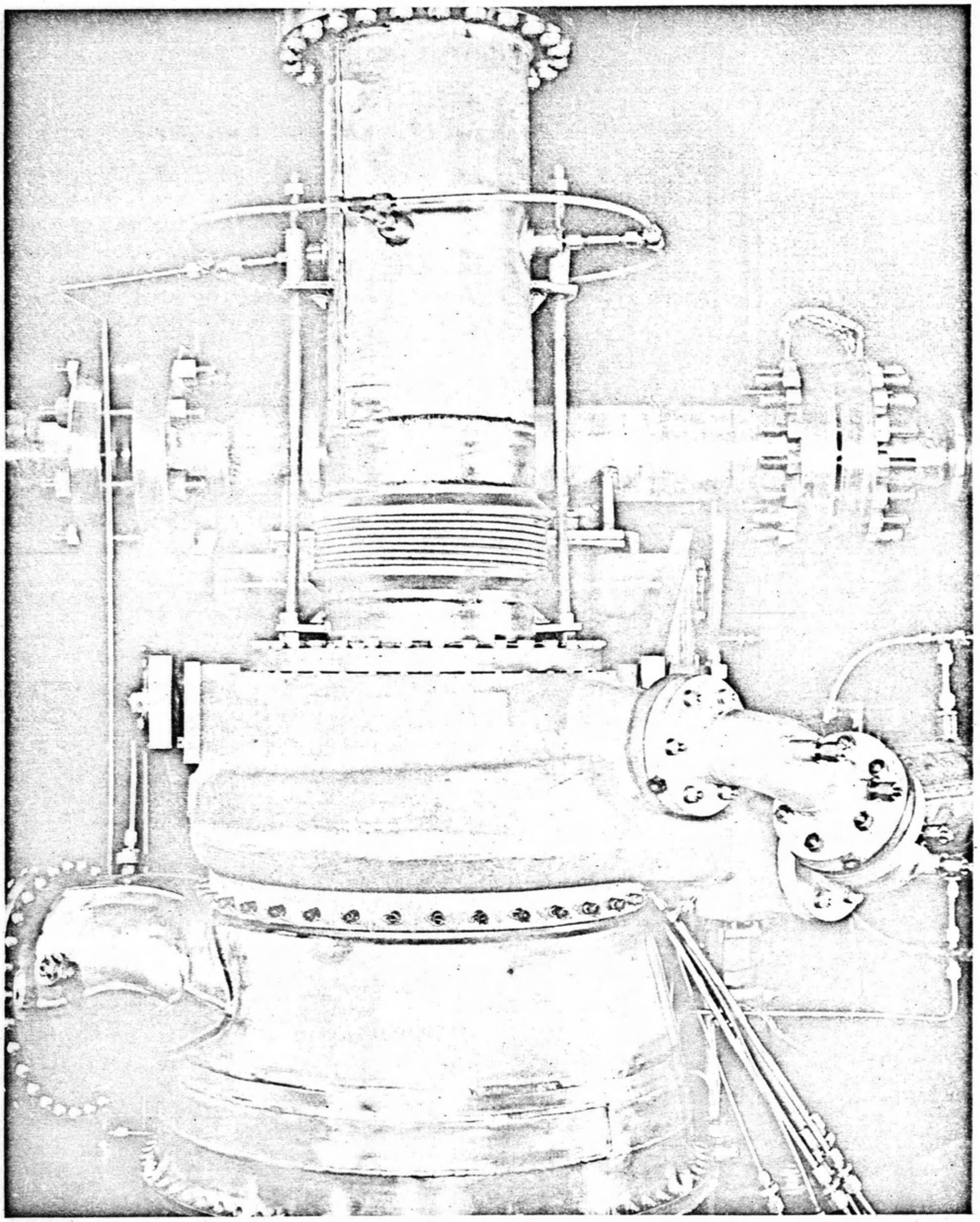

Figure 6. Liquid Oxygen Turbopump, Component Test Setup

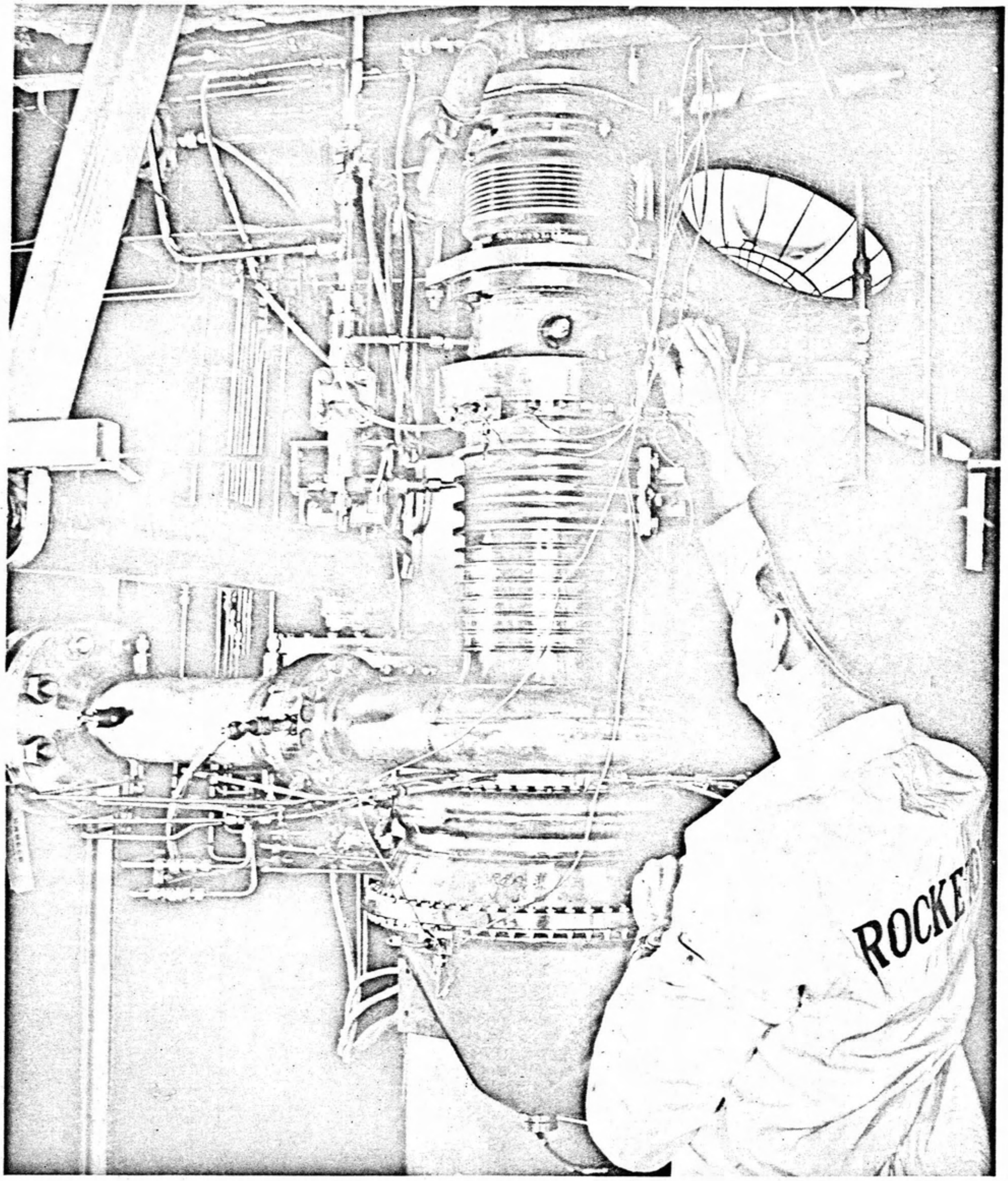

Figure 7. Liquid Hydrogen Turbopump, Component Test Setup

1,800,000. Testing to date has demonstrated the adequacy of both designs. In addition to its basic simplicity, this lubrication method avoids the use of lubricating oils which would prove troublesome because of the cryogenic operating temperatures. Internal bypass propellant flow is also utilized in each turbopump to provide thrust balance, and thus to prevent axial loading of the bearings.

Electrical System

The programming, safety, instrumentation, and ignition circuits of the J-2 engine are composed of electric components and circuits of advanced design. To avoid the necessity of heated electrical containers, a specification of operability through a temperature range of -300 to 140 F was added to the other severe conditions for rocket engine use. These conditions include extreme vibration and moisture resistance, stringent radio frequency interference, high circuit stability, and exceptionally high reliability. A satisfactory electrical and electronic design for these conditions is a unique achievement of the J-2 engine design. Component selection at extreme conditions, particularly -300 F in combination with vibration, and circuit overdesign, have resulted in an electrical system of demonstrated reliability and performance. For illustrative purposes, Fig. 8 is appended from another source,* and shows the temperature performance of two silicon NPN transistors. Note that even the better transistor has wide performance variation, which must be allowed for in circuit design.

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*Clinger, E. C.: "Cryogenic Testing of Electric Components," American Rocket Society, Paper No. 2636-62, 13 November 1963.

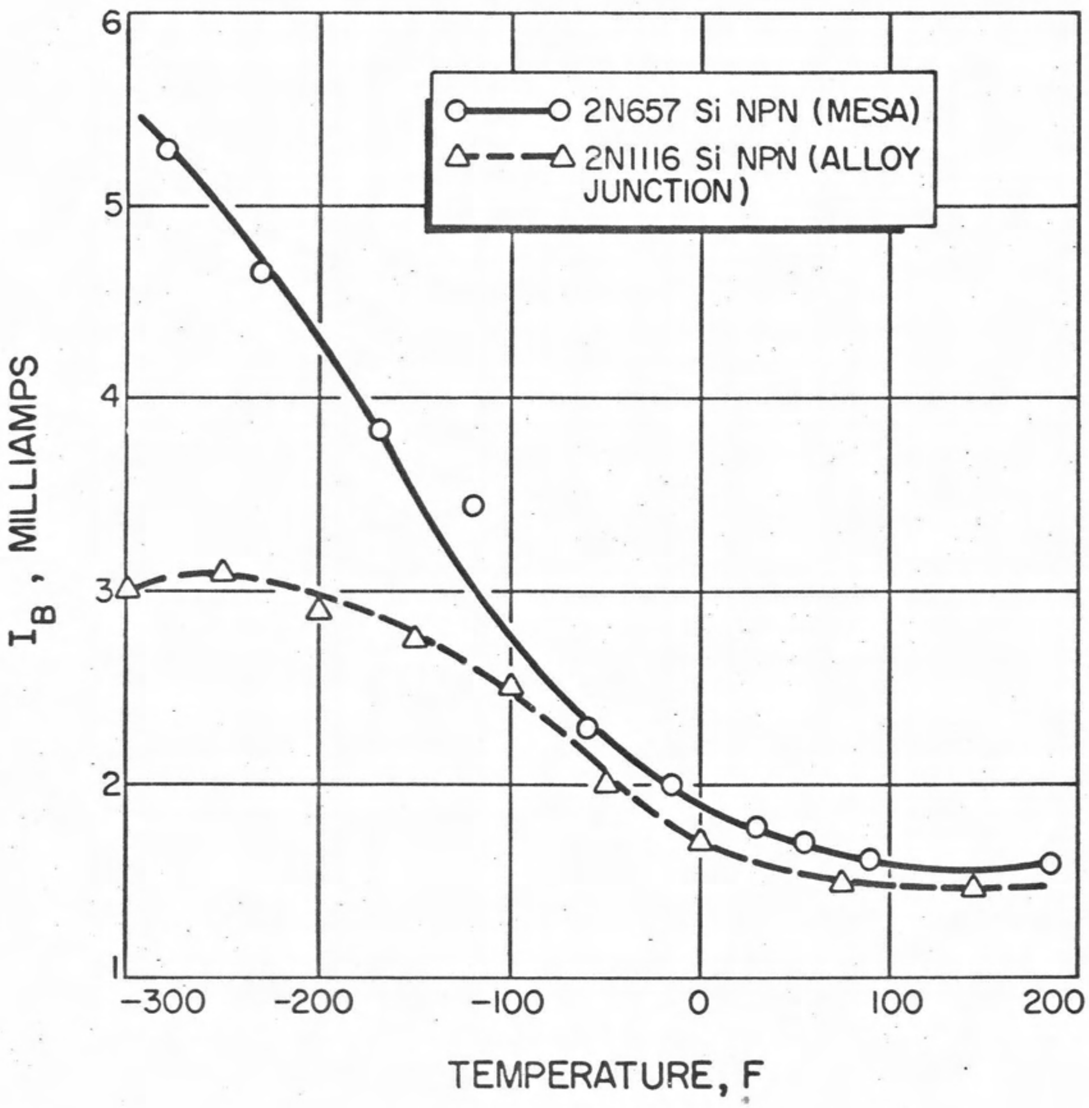

Figure 8. Comparison of Two Silicon NPN Transistors: Base Current Required for Collector Current of 50 ma vs Temperature

The J-2 engine electrical design employs approximately 75 transistors, 350 diodes, 50 Zener diodes, 140 capacitors, 400 resistors, and 25 inductors, all of which are assembled and sealed together. Connections from the electrical container to engine control components and to the stage are carried in high-temperature-resistant (1500 F) cabling. As an indication of the importance of these components in the over-all engine design, it has recently been determined that the electrical system contributes 15 percent of the total cost of the engine hardware.

Vacuum Jackets

Cryogenic component design in rocket engines using liquid oxygen has long profited from the fact that bare metal containing liquid oxygen forms a coating of frost from the atmosphere which is a surprisingly good insulation against heat. Accordingly, it has been common practice to design such components with no deliberately added insulation. In contrast, bare metal containing liquid hydrogen is so much colder (-423 F) that frost does not form, but air liquifies on the surface. The resulting streams of liquid air constitute a serious heat leak as well as being an unacceptable annoyance. It is therefore necessary to provide insulation for most engine components containing liquid hydrogen. This is conveniently accomplished for the hydrogen ducts and pump by either good, moisture-sealed insulation, or by vacuum jackets. Current models of the J-2 engine employ vacuum jackets for these parts. The most difficult design problem in this regard is the liquid hydrogen inlet duct, which must take the motion incident to 10-1/2 degree gimbaling of the engine. The bellows construction of this duct is shown in Fig. 9, in which a duct is undergoing life test. Compression and extension of ±4.5 inches in the 21-inch duct are required, in addition to

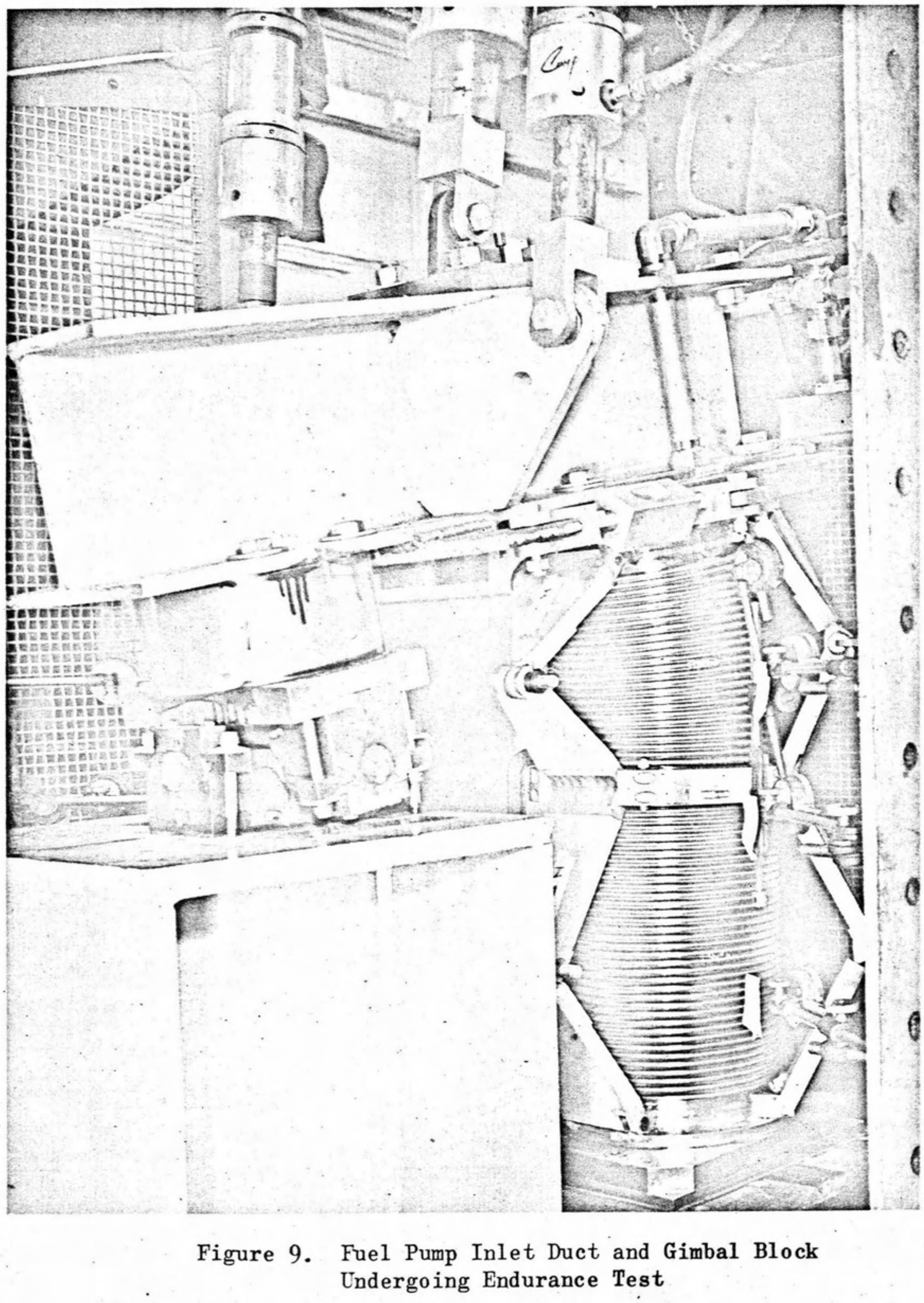

Figure 9. Fuel Pump Inlet Duct and Gimbal Block Undergoing Endurance Test

angulation and twist. In this duct the vacuum jacket is provided by a double bellows and stabilization is provided by scizzors-type external supports. An inlet duct and the engine spherical gimbal bearing are shown in Fig. 9.

Static Seals

The static seals for hydrogen have had particular design attention, not only to prevent loss under vacuum operation, but to prevent hazardous mixing of hydrogen with air during sea-level testing and handling. To alleviate sealing complications, the engine design has concentrated on the elimination of joints requiring sealing by a uniquely complete utilization of welded connections. For example, the injector dome is welded to the injector, and all small tube joints are completely welded. Where welding is not practical, a specification of zero (measurable) leakage has been met by a design using a pressure-actuated combination seal. This seal has such excellent demonstrated performance that it is used throughout the J-2 engine, not only for liquid hydrogen but for liquid oxygen, helium, and generator hot gas. Approximately 112 seals are used in the J-2 engine, the majority being used for instrument connections. The largest is a 19.48-inch seal for the thrust chamber/injector seal.

A further consideration with regard to seals is the specification initial hardware temperature of -250 F, which precludes the use of any soft seal materials such as O-rings. No soft seals are incorporated in the J-2 design, and this restriction has led to the design of a four-way solenoid valve with metal-to-metal seats.

Solenoid Valve

The J-2 pneumatic control valve is a direct-acting, solenoid-operated unit which is pressure-balanced by simultaneously mating pairs of seats and flexible disk seals, thus eliminating the need for dynamic seals. All-metal construction permits operation from -400 to 160 F and, within solenoid limitations, intermittently to 400 F. The solenoid is hermetically sealed and employs thermal compensation windings for low-temperature current control.

The parts of the valve mechanism (Fig. 10) are made of hardened steel, ground and lapped to a 4-microinch finish. Critical surfaces and dimensions are specified to ±50 millionths of an inch tolerance. The disk seals are made from a cobalt-base spring steel which is used as rolled to a 4-microinch finish.

Leakage past the seats, measured under helium pressure, has been held to very low values in a variety of environmental tests.

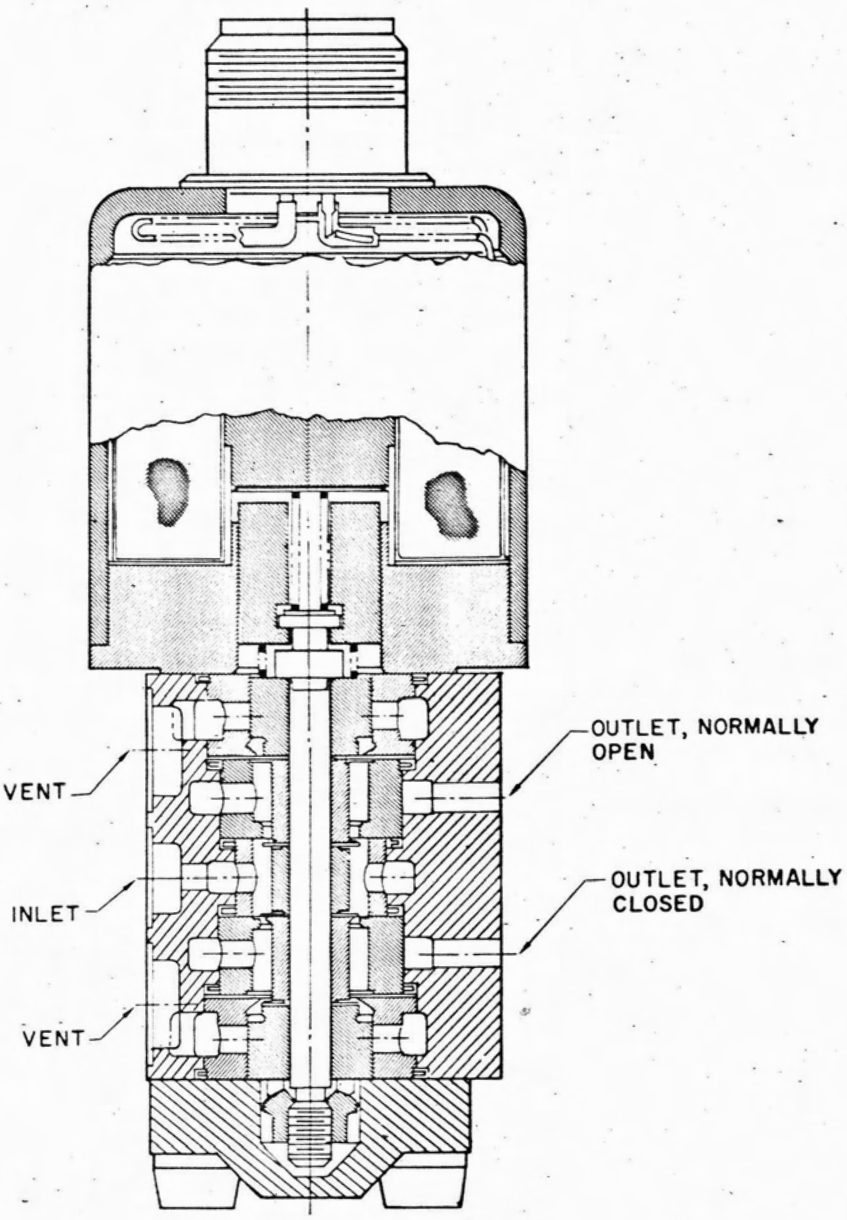

Figure 10. Four-Way Solenoid Control Valve

RELIABILITY VERIFICATION

The intended manned use of the J-2 engine led to a stringent reliability specification requirement at qualification to include performance as well as hardware integrity. Even though this reliability has been approached by liquid propellant missile engines, the reliability goal was accepted as the major design challenge of the J-2 engine. Each component and its subsequent system integration was subjected to an initial series of design and reliability reviews. Subsequent component development programs were conducted to verify the reliability which was demanded of the original design. Anticipated reliability growth of the engine as development progresses is shown in Fig. 11.

TEST EQUIPMENT

Though the J-2 component and engine test equipment was based upon existing operating large engine facilities, the unusual requirements of the upper-stage liquid hydrogen engine have led in some cases to test equipment development programs. The cryogenic temperatures of liquid hydrogen have necessitated the solution of a number of design problems pertaining to hydrogen tanks, transfer lines, and valves. Requirements to test the engine at simulated altitude conditions have led to new concepts in large vacuum test facilities.

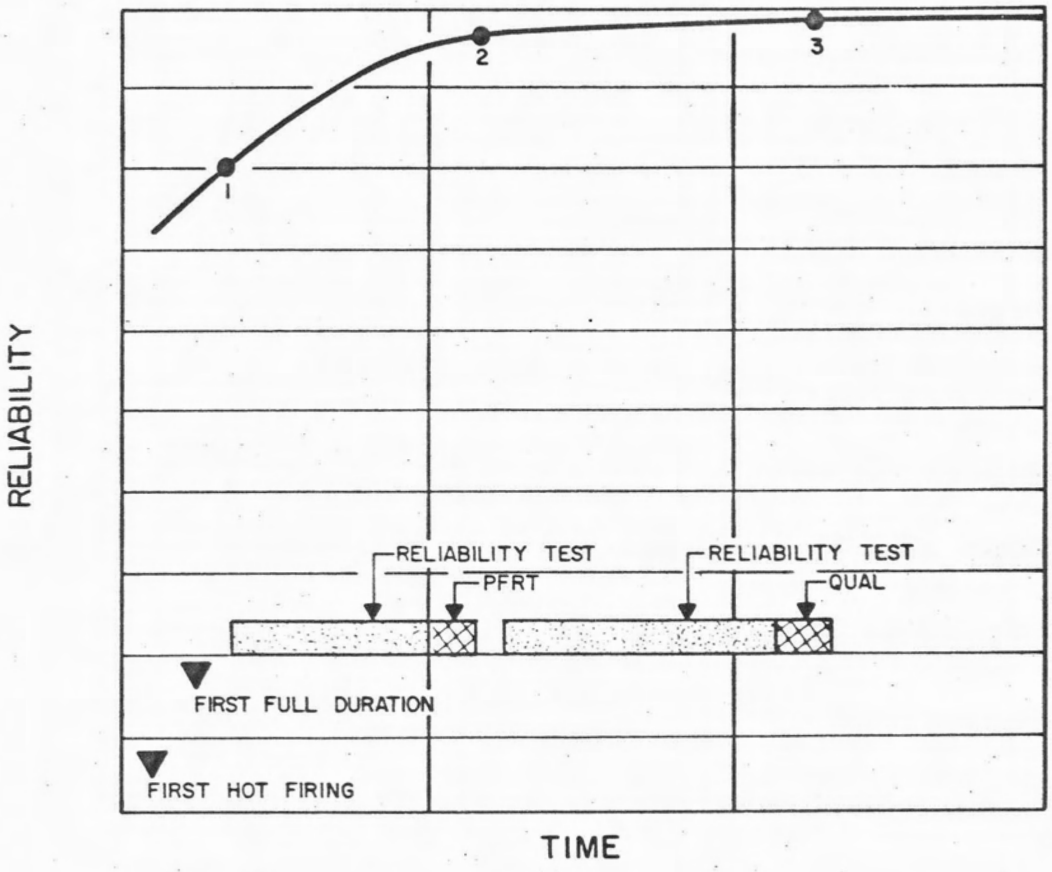

Figure 11. J-2 Engine Reliability Growth

Engine Vacuum Test Equipment

The J-2 engine was designed with sea-level test capability; accordingly, most engine development and all stage engine firings will be accomplished at ambient pressure. To provide altitude performance comparisons and to search for unexpected environmental occurrances, two of the five J-2 engine development test stands are equipped for vacuum simulation. Because the desired performance measurements are concerned primarily with start and stop characteristics, the vacuum stands were designed to maintain the low pressure corresponding to a 60,000-foot altitude in an engine capsule during the entire start, run, stop, coast, and restart cycles.

When the engine is running, self-aspiration through a diffuser is a technique previously reduced to practice. The diffuser illustrated in Fig. 12 was designed and built for this purpose. To provide the vacuum pumping when the engine is starting, stopping, or not running, the basic diffuser was provided with a second throat and an annular steam ejector (Fig. 12). The very high steam flowrate is provided by a 24-inch valved line from a system of steam accumulators, which is in turn heated by a hot-oil circulating system. Characteristics of the steam system are given in Table 1.

The diffuser design was complicated by the added requirement that the walls be capable of dealing with heat from the J-2 engine jet impingement. The supersonic section of the diffuser illustrated was constructed of square-section copper tube, in a manner similar to a rocket thrust chamber. The copper tubes are TIG-welded together to provide a gas-tight seal. The subsonic section is an externally supported mild steel shell cooled by water sprayed on the outside.

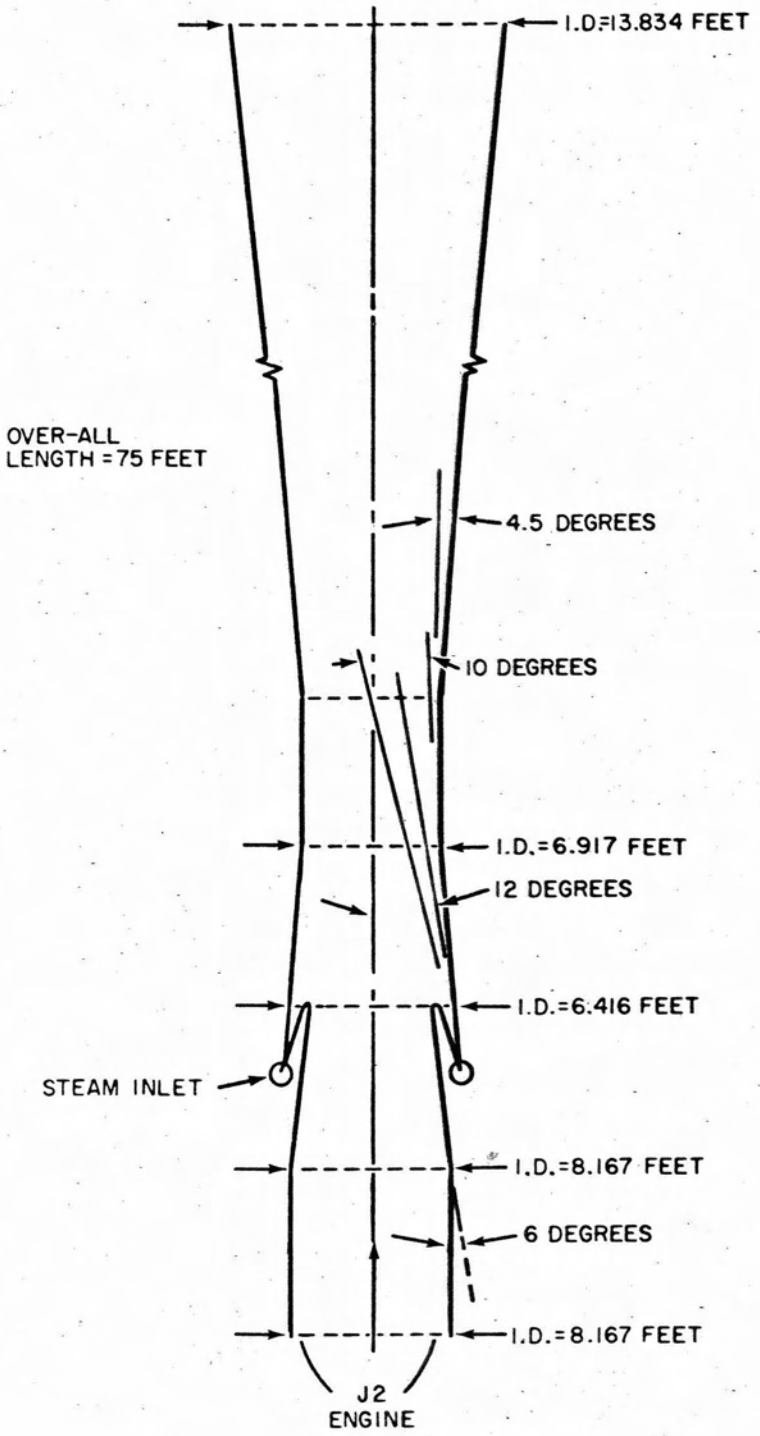

Figure 12. Steam Diffuser-Ejector, Engine Stand VTS-3A

TABLE 1

CHARACTERISTICS OF VACUUM ENVIRONMENTAL EQUIPMENT, J-2 ENGINE TEST STAND VTS-3A

Diffuser:	
Expansion area ratio, engine throat to diffuser throat	27.5:1
Area ratio of mixing section (based on steam nozzle)	27:1
Heat flux, diffuser wall, Btu/sq in.-sec (maximum)	8
(average)	2
Steam Nozzles:	
Nozzle throat area, sq ft	1.4
Expansion area ratio, annular nozzle	15.3:1
Steam flowrate, lb/sec	900
Steam pressure, nominal, psi	300
Steam Accumulator:	
Accumulator working pressure, psi	500 to 340
Steam storage capacity, pounds	18,400

The vacuum equipment described above is currently in operation to provide a simulated altitude for J-2 engine tests. Figure 13 shows the test stand, with the horizontal diffuser. Two steam accumulators are at the right of the stand. A second such system is under construction at another test stand, with an improvement consisting of a more flexible, gas-generator type high-capacity steam generator, the Rocketdyne "Hyperflow" concept, in place of the boiler-accumulator system.

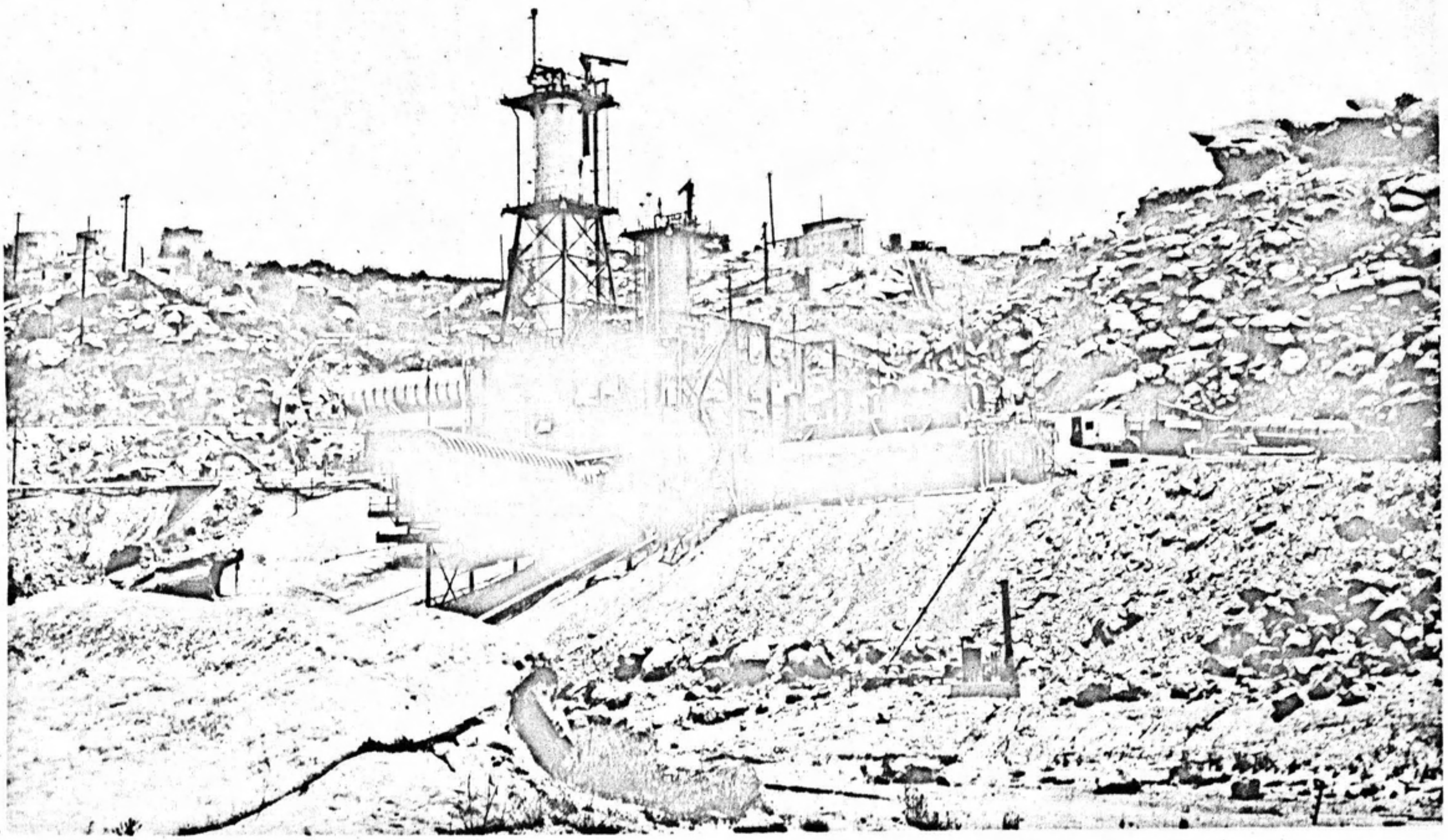

Figure 13. J-2 Engine Test Stand VTS-3 Showing Altitude Simulation Diffuser and Steam System

Vacuum-Jacketed Tanks

The liquid hydrogen run tanks for J-2 engine testing were constructed according to conventional pressure-vessel practice, with the added embellishments of complete vacuum jacketing and unusually large size. Figure 14 illustrates a test stand with a jacketed hydrogen tank of 90,000 gallons capacity under construction. This tank is flanked by two 20,000-gallon bare liquid oxygen tanks.

Invar Transfer Lines

Liquid hydrogen transfer pipe lines in the test areas must be vacuum jacketed for the same reasons which require jacketing of the cryogenic tanks. Although adequate double-wall design has been in use for many years, rather severe maintenance problems are associated with bellows provided for expansion and contraction in the inner pipe. A new approach to the hydrogen piping has been reduced to practice by the use of Invar* low-expansion alloy pipe. Thermal contraction of this alloy is negligible, such that inner pipe runs without expansion provisions may be employed. Invar pipe has been built in the 3- and 4-inch sizes in runs up to 1200 feet; welded pipe as large as 10 inches in diameter is in service. The outer jackets of Invar transfer pipe are usually made of stainless steel, with bellows for thermal movement. Shop welding of longitudinal seams of Invar and field circumferential welds have been developed to good reliability.

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*Invar = Fe 63 percent, Ni 36 percent, other 1 percent

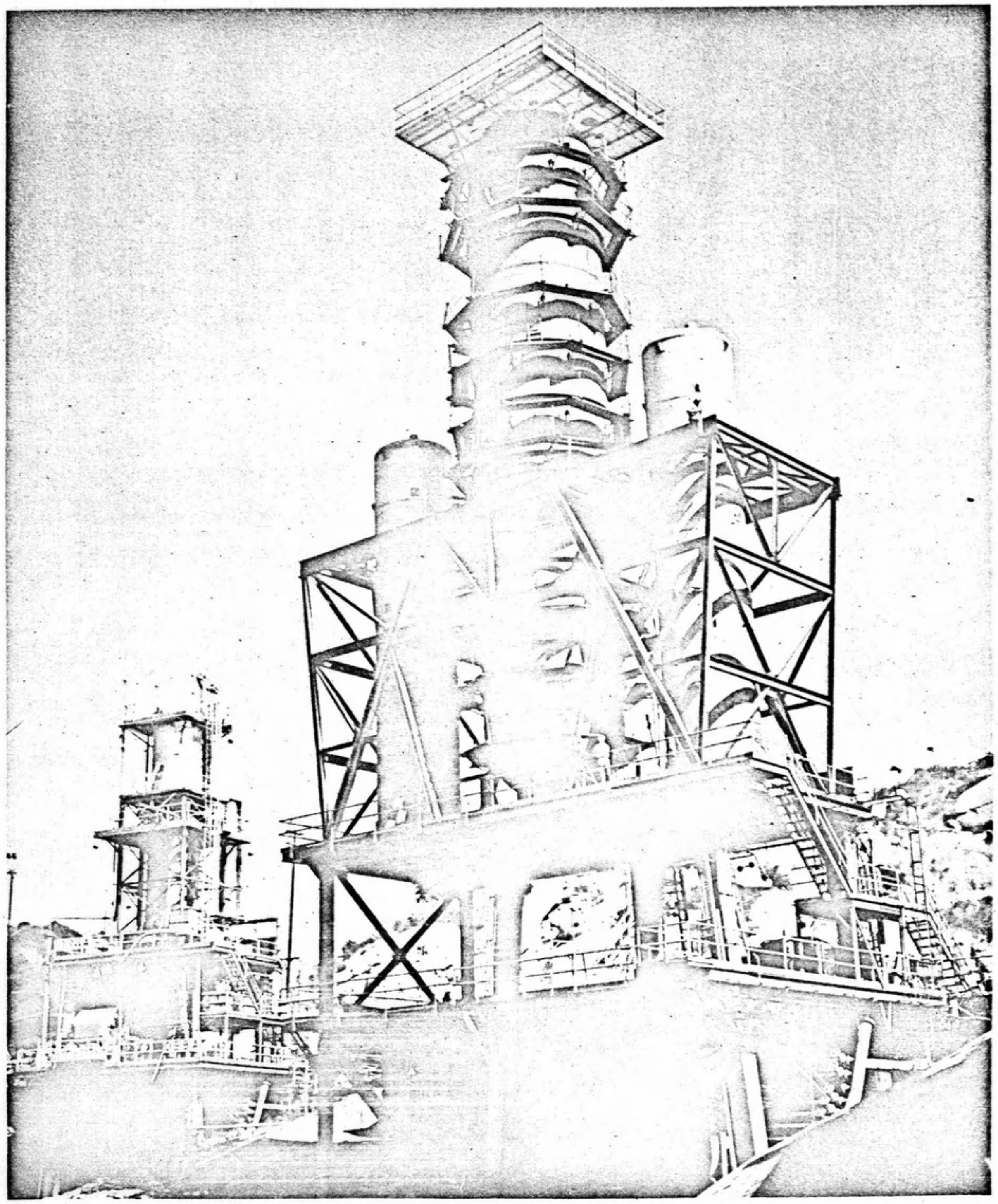

Figure 14. J-2 Engine Test Stand Delta 2 Under Construction

Mechanical Gimbal Actuator

An advanced design mechanical gimbal actuator has been developed for test stand use. This actuator (Fig. 15) employs a ball-bearing screw to give 42,000 pounds of force for actuation. This self-contained unit is fully operable at environmental temperatures down to -300 F, and avoids the heaters, pumps, accumulators, etc., associated with hydraulic actuators. It is anticipated that the advantages of such actuators will be realized eventually for flight use.

SUMMARY

The J-2 engine development program has progressed through design phases, component test, and system verification test to the operating phases concerned with design refinement, reliability verification, and stage coordination. To verify reliability, extensive engine testing, backed up by several thousand component tests, will be completed in the next 2 years. Meanwhile, engine deliveries to initiate stage development firings will commence. It is anticipated that this basic large high-energy engine will be assigned to a variety of tasks in the United States space program.

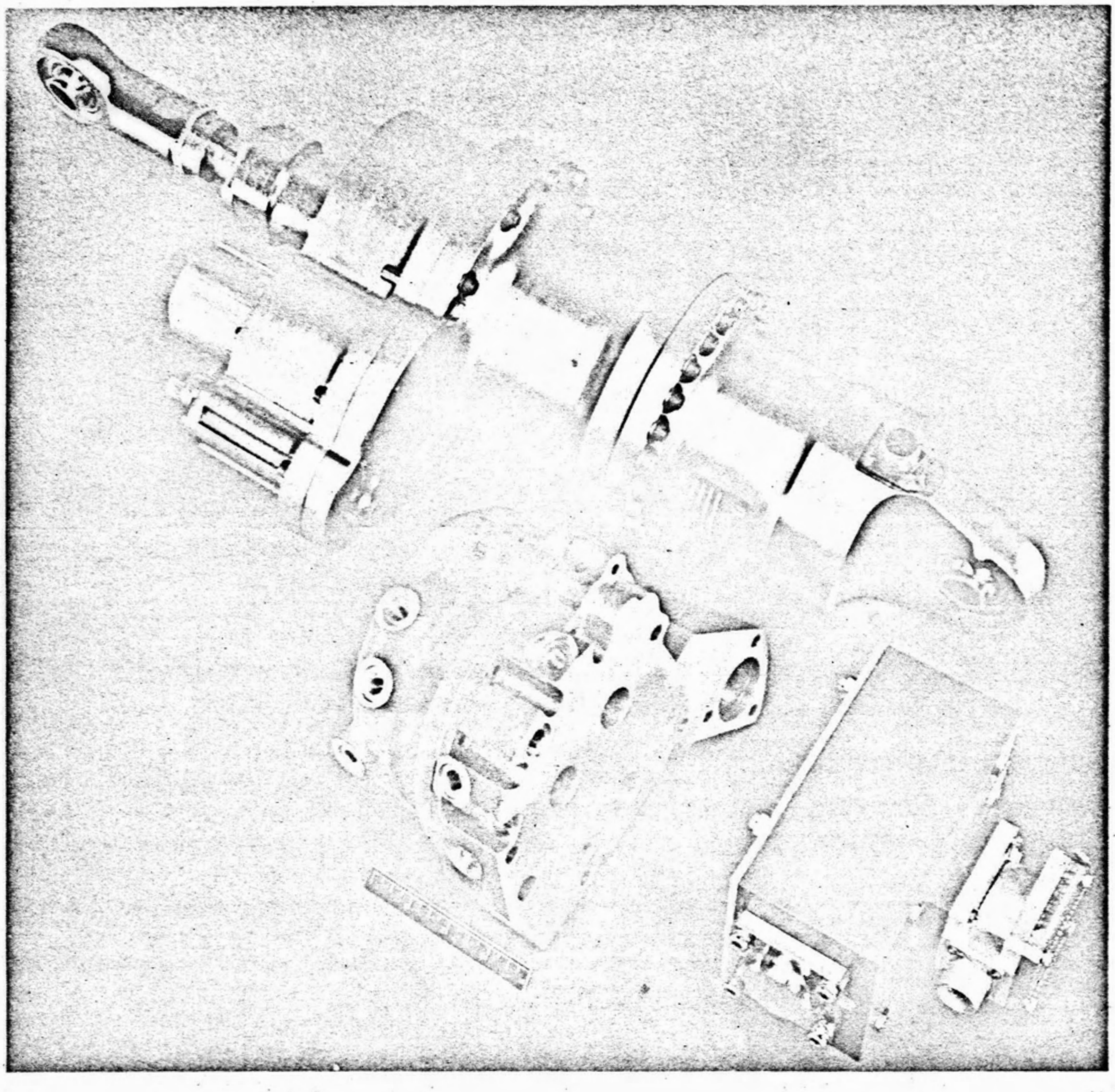

Figure 15. Mechanical Gimbal Actuator