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NASA PROGRAM APOLLO WORKING PAPER NO. 1195

APOLLO SPACECRAFT LIQUID PRIMARY PROPULSION SYSTEMS

NASA

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
MANNED SPACECRAFT CENTER
HOUSTON, TEXAS
FEBRUARY 7, 1966

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CONTENTS

FIGURES

APOLLO SPACECRAFT LIQUID PRIMARY PROPULSION SYSTEMS

By Propulsion Analysis Section

GENERAL

The purpose of this document is to provide a general familiarization with the Apollo spacecraft liquid primary propulsion systems. A brief discussion of the mission, engine history, and design philosophy is presented for the three primary Apollo spacecraft engines, including the specifications and geometry of each.

Mission Requirements

The Apollo mission will place three men into lunar orbit, land two of these men on the lunar surface, and return the three men to earth. The entire mission will take approximately 8 days and is shown in detail in figures 1 through 3. The Apollo spacecraft (fig. 4), consisting of the service module, the command module, and the two-stage lunar excursion module, contains three primary propulsion systems, which are the subject of this report.

The service module contains the service propulsion system (SPS) (fig. 5). The service module engine (fig. 6) has a nominal thrust of 21 500 pounds and is used for midcourse correction during the translunar phase, lunar orbit insertion, transearth injection, and midcourse correction during the transearth phase.

The lunar excursion module (LEM) (figs. 7 through 10) contains the descent and ascent propulsion systems (DPS and APS). The LEM descent engine (fig. 11) has a variable thrust capability between 10 500 and 1 050 pounds and provides the thrust for retrofire from lunar orbit and lunar descent, hover, and landing.

The LEM ascent engine (fig. 12) has a nominal thrust of 3500 pounds and provides the thrust to place the ascent stage of the LEM into lunar orbit for rendezvous with the orbiting command and service module.

Design

Philosophy.- One of the predominant requirements which dictated the designs of the Apollo engines is crew safety, and, therefore, propulsion system reliability. To achieve the desired system reliability, the following design features were incorporated in all three Apollo primary propulsion systems.

1. The propellants are storable at ambient temperature, eliminating the problems associated with long term storage and venting of cryogenic propellants in space under zero gravity conditions.

2. The combustion chambers are ablatively cooled because of the rugged nature of ablatives and their high resistance to sudden failure.

3. The engines are pressure-fed to eliminate complexities associated with pump fed engines.

4. Redundant components are used for all moving parts in the engine pressurization and propellant feed systems. This provides for mission completion or a safe mission abort if a malfunction occurs in one leg of a redundant component or in a number of redundant components in the propulsion system.

Basic features.- The design philosophy and mission requirements of Apollo have dictated a number of design features which are common to the three primary spacecraft propulsion systems. All three primary propulsion systems (figs. 13, 14 and 15) use ablative thrust chambers, have redundant valves, and are pressure fed. Optimum performance and minimum weight are basic requirements because of the nature of the Apollo mission. Large expansion ratio nozzles are used for optimum performance in the vacuum conditions of space. Relatively low chamber pressure and low pressure drops through the propellant feed system and injector are required for optimum vehicle efficiency with the pressurized propellant feed system. The propellants utilized in these systems are earth storable and hypergolic. The fuel is a blended hydrazine (approximately 50 percent unsymmetrical dimethylhydrazine and 50 percent anhydrous hydrazine). The oxidizer is nitrogen tetroxide. These propellants provide the performance necessary to accomplish the Apollo mission and have acceptable handling and material compatibility characteristics.

To minimize engine weight, the service module and descent engines have major portions of their nozzles constructed of high temperature metals (figs. 16 and 17) which are cooled by radiant heat transfer to space. The entire nozzle of the ascent engine (fig. 18) is constructed of ablative material because the required engine mounting location and vehicle heat shield configuration does not provide a sufficient view factor for radiation to space.

The LEM descent engine utilizes a variable area injector and variable area cavitating venturi flow control valves for throttling. The single-injector and single-fuel and oxidizer-flow control valves are exceptions to the rule of redundancy for all moving components. However, the actuation system which controls these components is redundant.

Pressurization and Propellant Feed Systems

Gaseous helium is used for pressurization, with the gas being stored at ambient temperature in the SPS and APS, and at cryogenic temperatures in the DPS. The DPS cryogenic helium storage system takes advantage of the weight savings possible in the helium storage vessel due to increased helium density at reduced temperatures, but results in increased complexity in the pressurization system. In each propulsion system, oxidizer and fuel tanks are fed from a common pressure regulation assembly to guarantee equal ullage pressures in the oxidizer and fuel tanks.

A series-parallel valve arrangement is used on the pressure regulation, check valve, and shutoff valve assemblies of each propulsion system. In the event a valve should fail open, the series arrangement provides a second valve to shut off flow. In the event a valve should fail closed, the parallel arrangement provides a second flow path for continued operation. The oxidizer and fuel engine valves are paired so that each set is mechanically linked and operates from a common actuator assembly to guarantee the proper relative valve timing during operation. Trim orifices are located in the propellant feed systems to trim the propulsion system and to provide the desired mixture ratio and thrust level.

Chamber-Injector Compatibility and Ablation

Chamber-injector compatibility is a major concern when optimum engine efficiency is a design requirement. High performance requires high combustion temperatures which can result in high ablation rates. High ablation results in a reduced nozzle area ratio, a performance reduction, and the requirement for a thicker and heavier ablative chamber. To control ablation, a barrier of low mixture ratio combustion gases is used to isolate the hot core of combustion gas from the chamber wall. The service module engine injector (fig. 19) uses a row of showerhead fuel orifices adjacent to the chamber wall, while the LEM ascent engine injector (fig. 20) uses a low mixture ratio unlike-doublet adjacent to the chamber wall. Because of the unique design of the variable area descent engine injector (fig. 21), no specific portion of the fuel can be considered as the film coolant.

SERVICE PROPULSION SYSTEM

Operation

The helium pressurization supply is contained in two spherical pressure vessels at a nominal pressure of 4000 psia and ambient temperature, isolated from the fuel and oxidizer tanks during engine shutoff by two continuous duty solenoid operated valves (fig. 22). The valves are controlled individually and are energized open and spring-loaded closed. Two dual stage regulators, arranged in parallel, are located downstream of the solenoid valves and provide pressure-regulated helium to the fuel and oxidizer tanks. Two sets of check valve assemblies, arranged in series-parallel configurations, prevent fuel or oxidizer from entering the pressurization system. Pressure relief valves prevent overpressure in the propellant tanks. This relief is provided when the burst diaphragm ruptures and the relief valve opens. The relief valve recloses when the pressure once again reaches a safe level. A burst diaphragm is incorporated in each pressure relief valve to provide a more positive seal than can be obtained with the relief valve alone. Heat exchangers are used in the helium lines to condition the helium to a temperature approximating that of the propellant in the tanks. Fuel and oxidizer are each contained in a set of two cylindrical tanks connected in series. The upstream tank is called the storage tank and the downstream tank is called the sump tank, each sump tank being directly connected to each storage tank by a crossover line and standpipe. Each sump tank outlet contains a zero-gravity retention reservoir which retains propellants over the propellant feed line inlets and reduces the propellant settling time requirements. Thrust from the reaction control motors provides for propellant settling in addition to that maintained by the zero-gravity retention reservoir. An engine shutoff valve assembly (fig. 23) provides control of propellants to the engine injector. The shutoff valves are actuated (fig. 24) by gaseous nitrogen stored at 2800 psia in a vessel mounted on the shutoff valve housing. Only one set of the series paired fuel and oxidizer shutoff valves is actuated at any given time during firing. A spring-loaded, normally-closed prevalve controls gaseous nitrogen flow into the valve actuation system. When this prevalve is opened, prior to an engine start, high pressure gaseous nitrogen is released downstream to a two-stage regulator. Pressure regulated nitrogen is then supplied to the upstream side of two, three-way solenoid control valves which, when energized by a thrust-on signal, allow gaseous nitrogen to enter the shutoff valve actuation chambers. The two actuators produce ball valve rotation allowing propellants to flow into the thrust chamber. At engine shutdown, the two solenoid control valves are deenergized and the pressure in the actuators is vented overboard, allowing the ball valves to rotate closed. A secondary gaseous nitrogen system and shutoff valve package provides redundancy and is identical to the system described above.

DESCENT AND ASCENT PROPULSION SYSTEMS

Descent Propulsion System Operation

Helium for propellant tank pressurization is stored in an insulated vacuum-jacketed, spherical dewar at an initial pressure and temperature of approximately 100 psia and 10° R (fig. 25). Utilizing a combination of heat leak (heat transfer into the storage vessel) and standby time (time from loading until system operation), the stored helium gas achieves an operational pressure and temperature of approximately 1250 psia and 32° R. During the engine start, helium gas is released from the storage tank by an explosive valve simultaneous with the initiation of the propellant flow to the engine. (The propellant tanks are pressurized to operating conditions prior to launch.) The helium is discharged through the primary pass of a two-pass heat exchanger which is located externally to the storage vessel and uses fuel as the heat source. The helium then flows into a second heat exchanger situated inside the helium storage container. This internal heat exchanger serves to heat the helium stored in the container in order to aid in maintaining storage pressure as helium is used. From the internal heat exchanger, the helium flows through the secondary pass of the external heat exchanger, through a filter, and then divides into two flow paths, each of which passes through a normally closed solenoid valve and a dual-stage pressure regulator. Only one of the four regulator stages normally functions at any given time with the others providing redundancy. Downstream of the pressure regulators the helium flows into a manifold and then divides again into two symmetrical paths leading to the fuel and oxidizer tanks. Each path contains a series-parallel check valve assembly through which the helium must flow prior to entering the diffusers located in each propellant tank. Located downstream of the check valve assemblies, a burst disc and pressure relief valve are provided to vent helium overboard in the event of excessive propellant tank pressure. The fuel and oxidizer are each stored in two tanks connected in parallel. Separate crossover lines connect the ullage spaces and the lower portions of each pair of propellant tanks in order to keep the ullage pressures and propellant levels equalized. Each propellant tank contains baffles for slosh control.

Start and shutdown is controlled by a series-parallel propellant shutoff valve assembly (figs. 26 and 27). The shutoff valves are mechanically linked, fuel-actuated ball valves. Fuel for valve actuation is controlled by solenoid operated pilot valves which are opened simultaneously at engine startup. In the open position, the pilot valve poppets seal the vent ports and allow pressurized fuel into the actuators which open the main propellant valves. For engine shutdown, pilot valve solenoids are deenergized allowing the valve springs to close the supply ports and open the vent ports. The pressure in the actuation chamber is relieved and the spring loaded actuators return to the closed position, expelling the fuel from the actuation chamber overboard through the vent lines.

For throttling, a variable area concentric injector is mechanically linked and actuated in conjunction with cavitating venturi type flow control valves (fig. 28). When down throttling (fig. 29), the throttle actuator simultaneously reduces the flow area of the propellant flow control valves and moves the injector orifice area so that the desired injection velocity is maintained as propellant flow is reduced. Below 70 percent thrust, cavitation occurs in the flow control valves which allows the propellant flow to be controlled independent of pressure changes downstream of the control valve. Engine start and shutdown can be accomplished at any engine thrust setting desire.

Ascent Propulsion System Operation

Helium for pressurization is stored in two spherical tanks at ambient temperature and 3500 psia (fig. 30). Each tank is sealed by an explosive shutoff valve and is filled through a separate coupling. Prior to the first engine start, the explosive valves release helium from the storage tanks. The two gas streams flow to a junction and divide into two symmetrical branches, each containing a filter, a latching solenoid shutoff valve, and a pressure regulating valve. Each pressure regulating valve contains two stages, essentially identical except for output pressure settings. Only one of the four independent reducing stages normally functions, the others providing redundancy. After entering a common outlet line, the helium flows via separate paths through series-parallel check valve assemblies to the fuel and oxidizer tanks. A burst disc and a pressure relief valve are located in each line between the check valve and propellant tanks to prevent overpressurizing the tanks. Each propellant is stored in a single spherical tank which includes a helium diffuser, an anti-vortex device, baffles, and a low-level sensor. Each propellant flows from the tank through a trim orifice and filter, and enters the engine through a fuel-actuated series-parallel bipropellant shutoff valve assembly (fig. 31). To start the engine, the pilot valves are energized, admitting pressurized fuel to the valve actuators which rotate the ball valves to the open position. When the pilot valves are deenergized, the fu in the valve actuation chambers is vented overboard allowing the ball valves to rotate to the closed position.

TABLE I.- APOLLO SPACECRAFT ENGINE SPECIFICATIONS

Component	Service module	LEM descent	LEM ascent
Engine			
Manufacturer	Aerojet-general	TRW systems	Bell aerosystems
Thrust, lb	21 500	10 500 to 1050	3500
Mixture ratio	2.0	1.6	1.6
Chamber pressure, psia	100	110 to 11	120
Propellants	Fuel: 50/50 blend of UDMH and hydrazine; oxidizer: N_2O_4		
Chamber and Nozzle	Ablative	Ablative	Ablative
Material	Hi silica/phenolic	Hi silica/phenolic	Hi silica/phenolic
Extension	Radiation cooled from Ae/At = 6 through 62.5	Radiation cooled from Ae/At = 16 through 47.4	Ablative
Material	Columbium from Ae/At = 6 through 40 Titanium from Ae/At = 40 through 62.5	Columbium	Asbestos microballoon
Injector			
Type	Concave/baffled	Coaxial/variable area	Flat/baffled
Material	Aluminum	Inconel	Aluminum
Pattern	Unlike doublet	Fuel sheet/radial oxidizer	Triplet - 2 fuel, 1 oxidizer
Film cooling	7 percent of $\dot{W}_{fuel}$	None	20 percent of $\dot{W}_{total}$
Type	Showerhead	NA	Unlike doublet
System pressures			
Tanks, psia	175	225	190
Interface, psia	165	210	165
Injector drop	Oxidizer 44; fuel 47 psia	Variable	28
Chamber, psia	100	110 to 11	120

TABLE I.- APOLLO SPACECRAFT ENGINE SPECIFICATIONS - Concluded

Component	Service module	LEM descent	LEM ascent
Lunar mission			
Total burn time, sec	500	1030	465
Number starts	8	2	2
Approximate dimensions			
Overall length, in.	153	85	51
Dry weight, lb	650	350	210
L*-char. length	34	36	24
Contour, percent bell	70	67	72
Ae/At	62	47	46
Maximum chamber diameter, in.	18	14	8
Throat diameter, in.	12	8	5
Exit diameter, in.	98	58	31
Throat area, in.^{2}	122	54	16
Exit area, in.^{2}	7595	2664	750
Thrust vector control	Gimballed ±8.5° pitch; ±6° yaw	Gimballed ±6° pitch; ±6° yaw	None

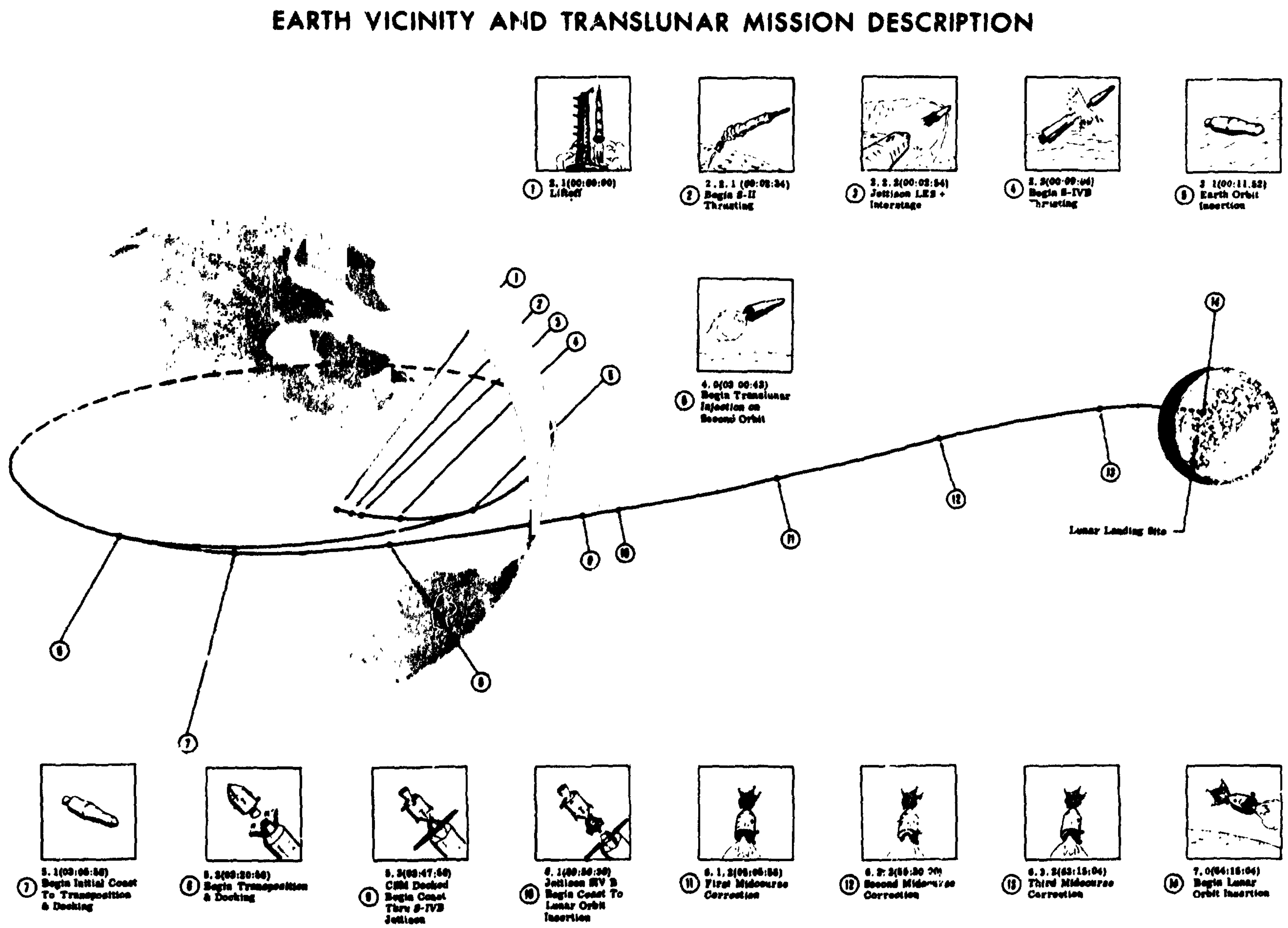


Figure 1.- Earth vicinity and translunar mission

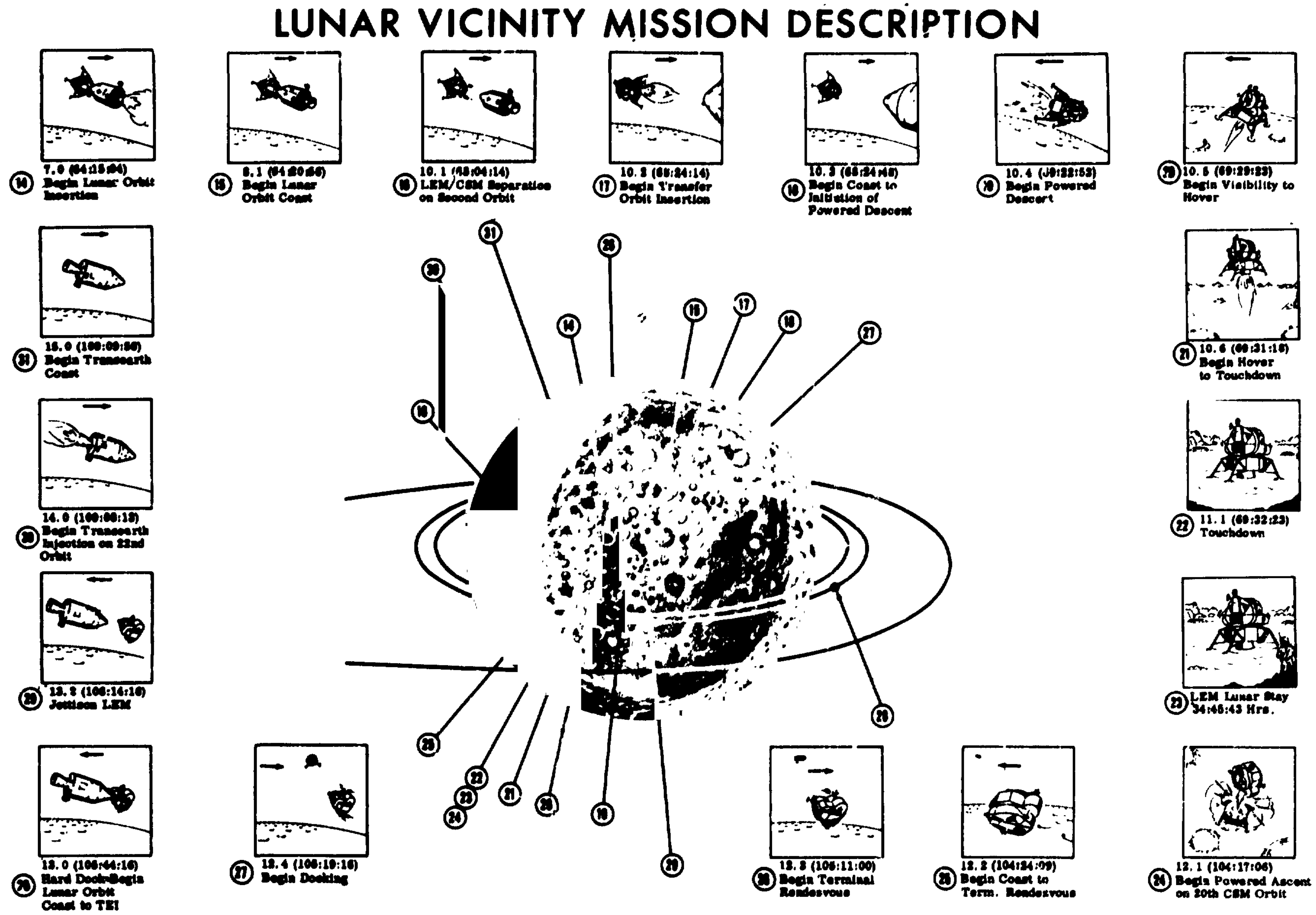


Figure 2. - Lunar vicinity mission

TRANSEARTH AND ENTRY MISSION DESCRIPTION

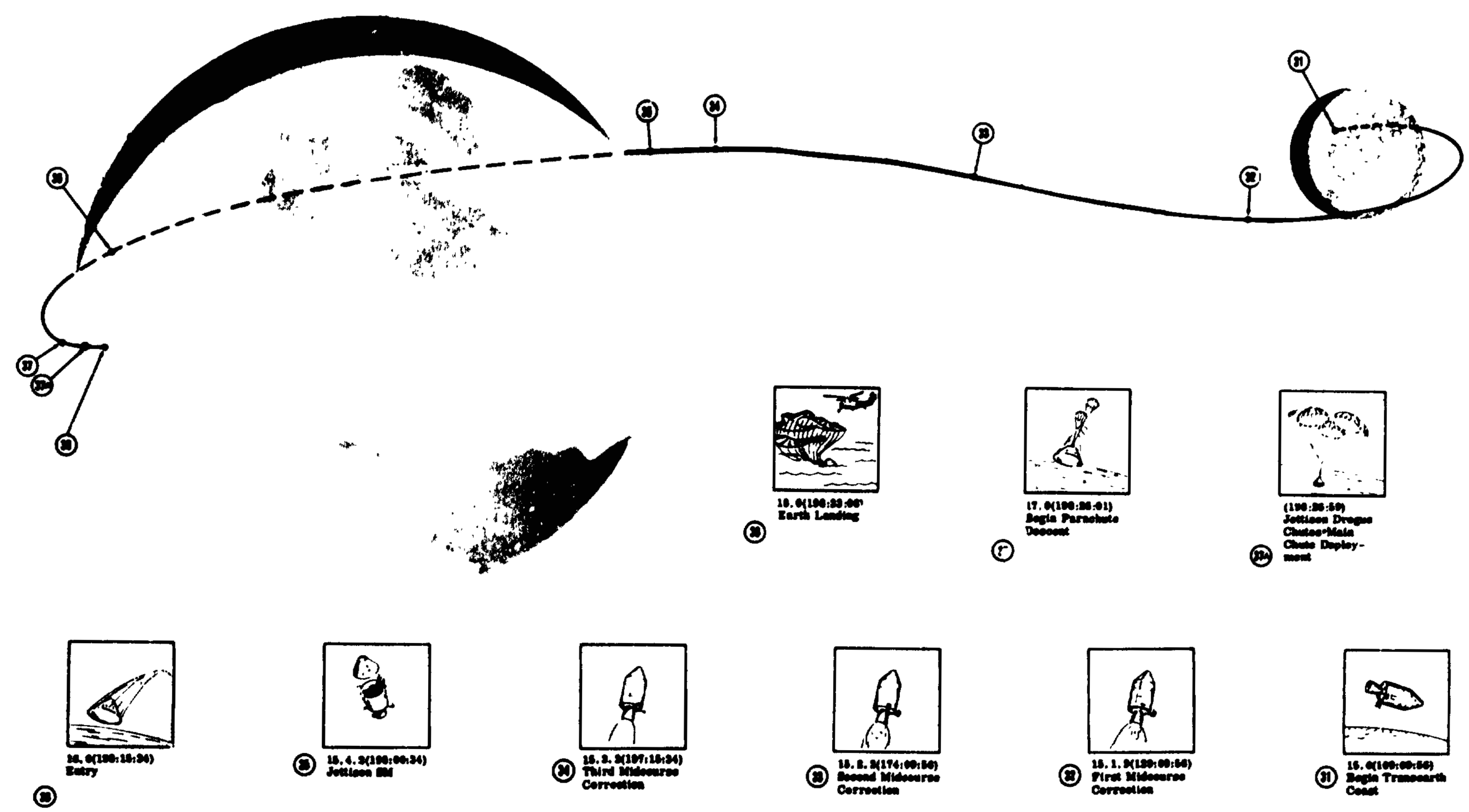


Figure 3.- Transearth and entry mission

NASA

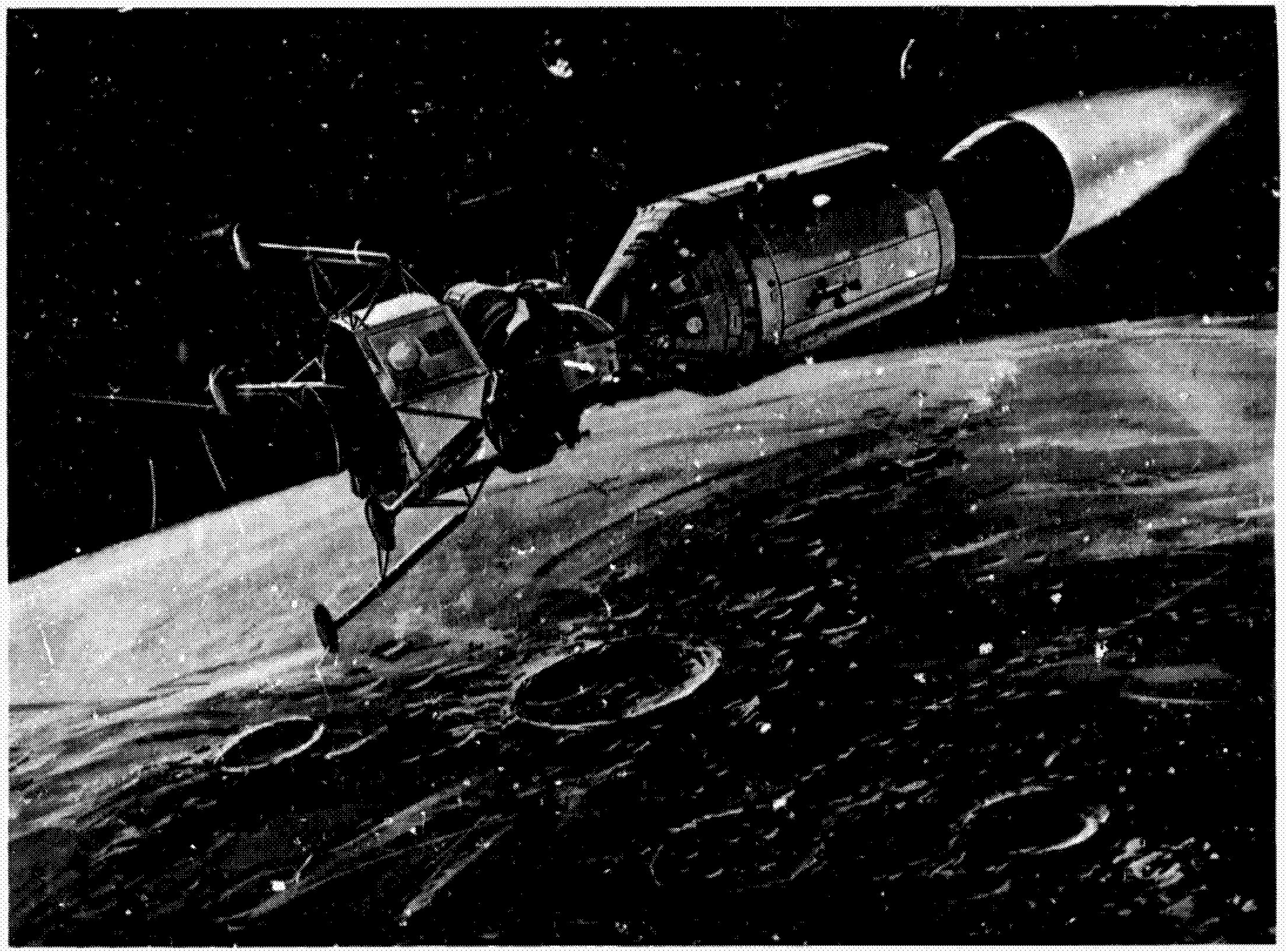


Figure 4. - The Apollo spacecraft

SERVICE PROPULSION SYSTEM

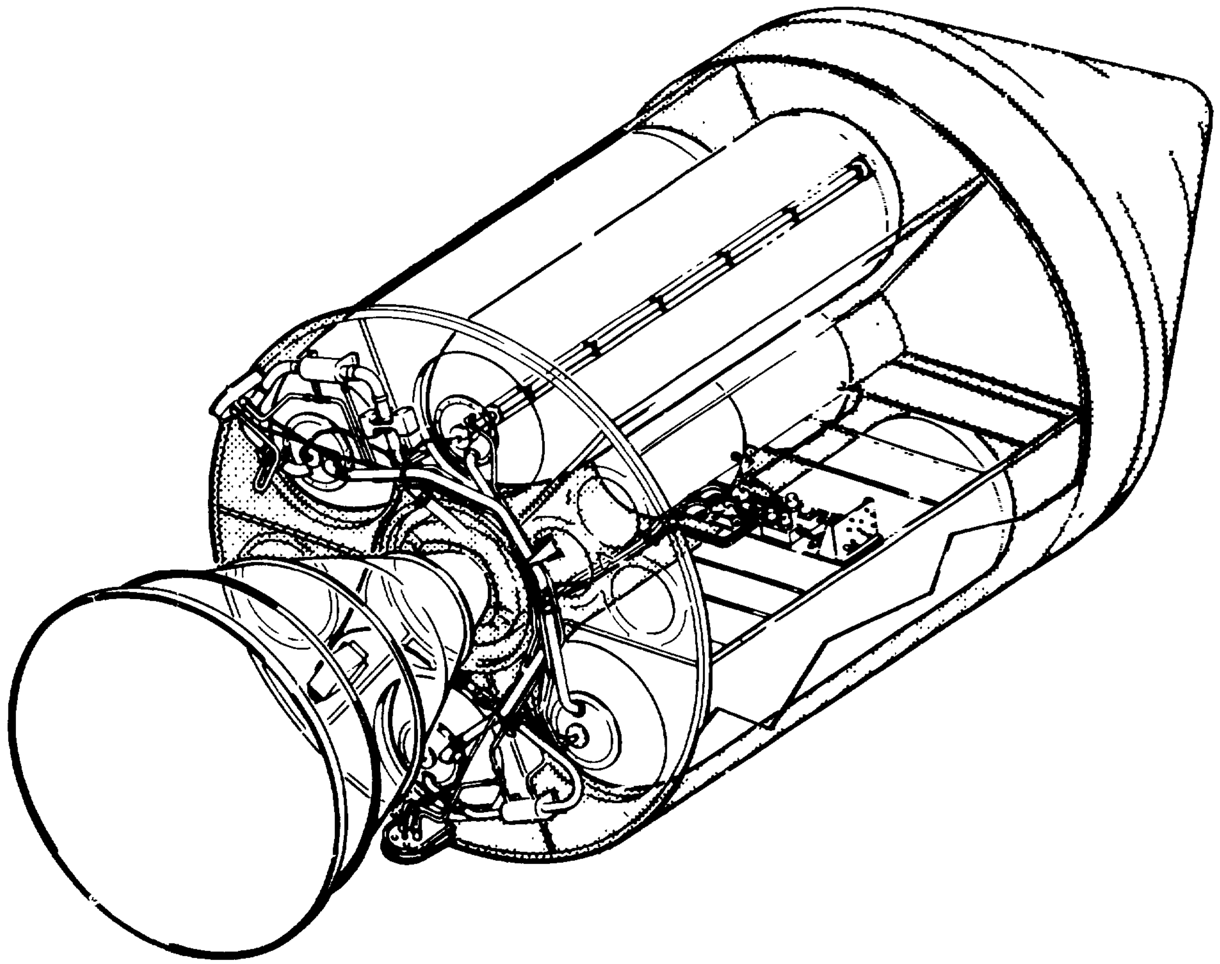


Figure 5. - Service propulsion system

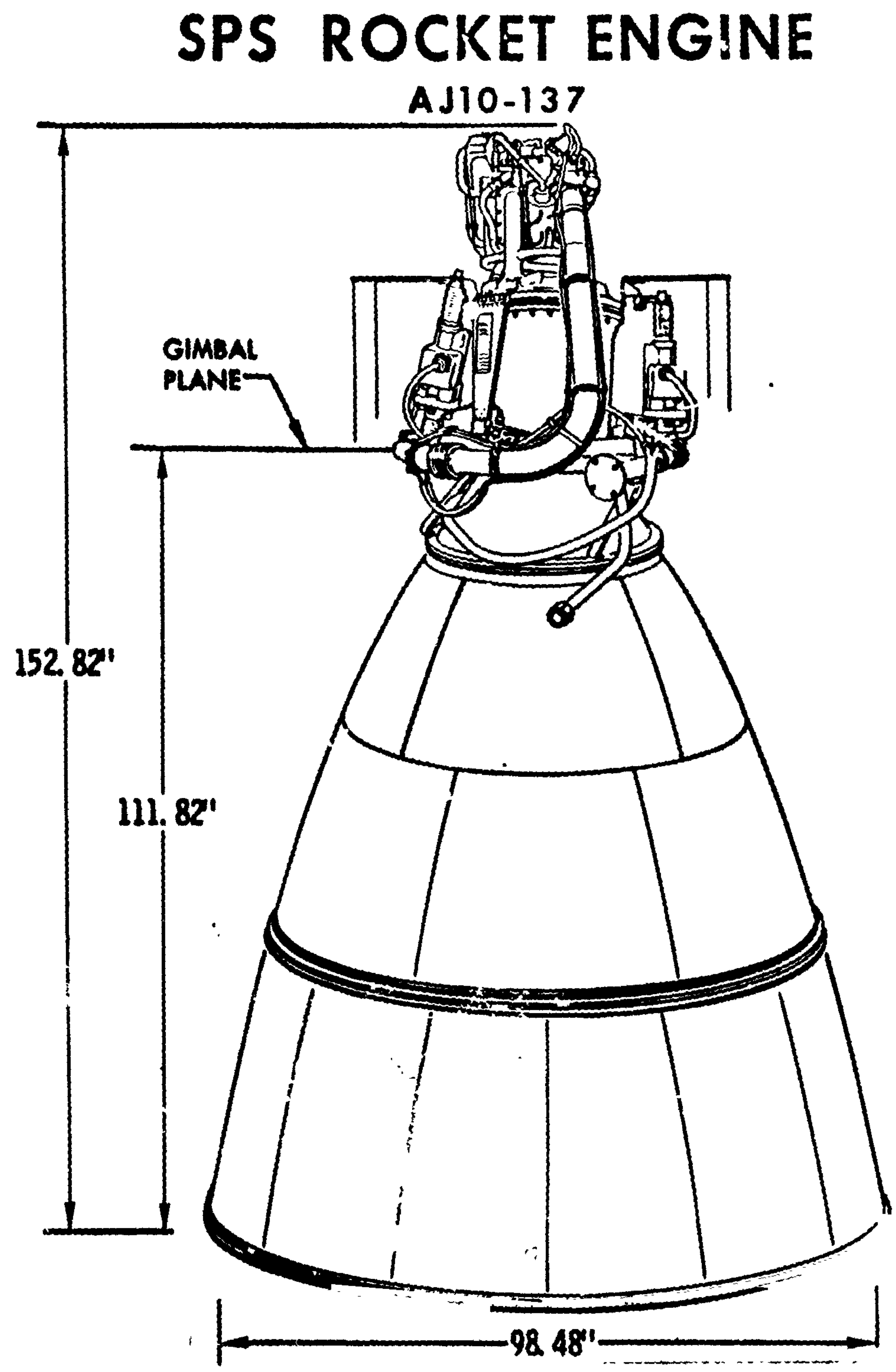


Figure 6. - SPS engine

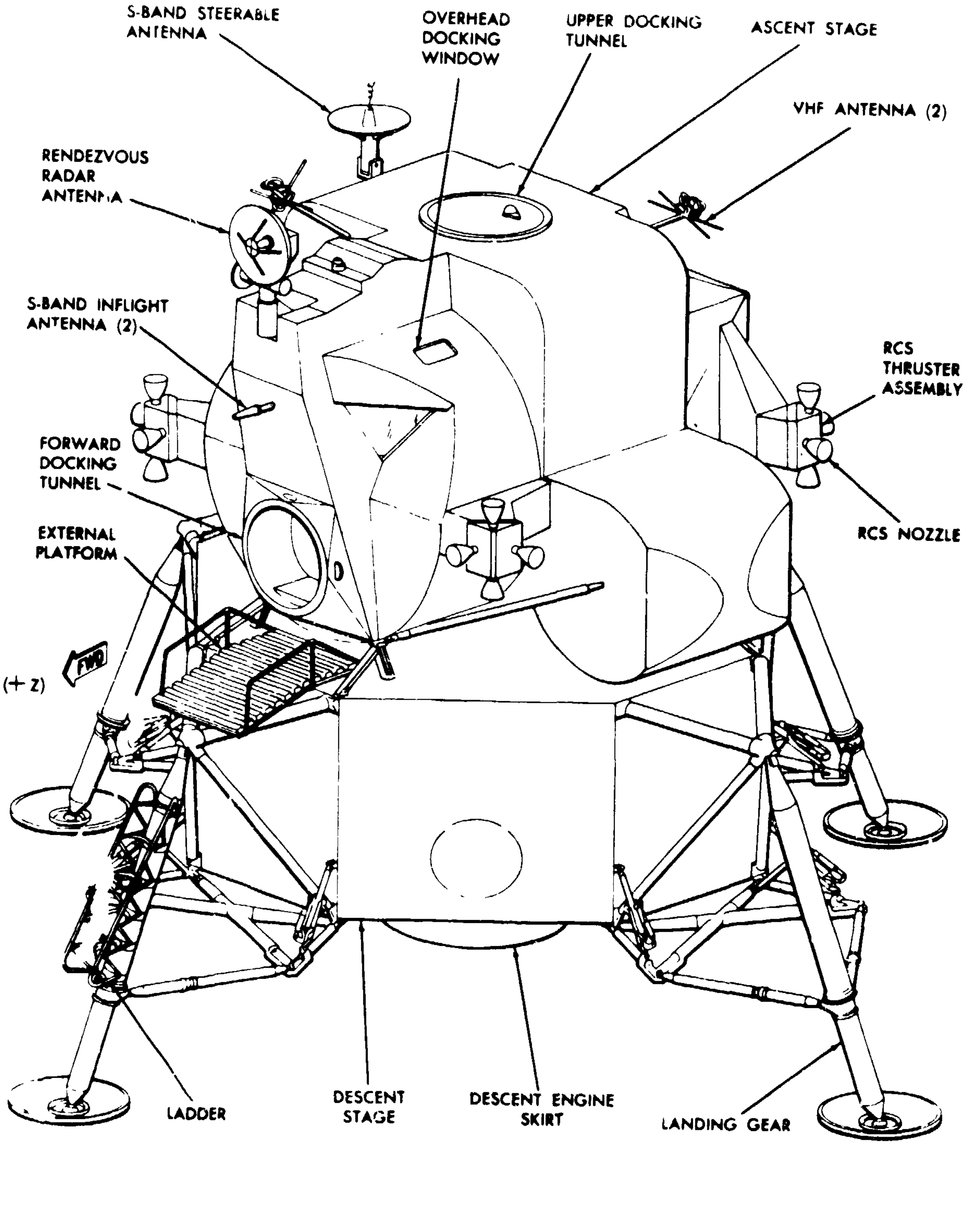


Figure 7. - Lunar excursion module

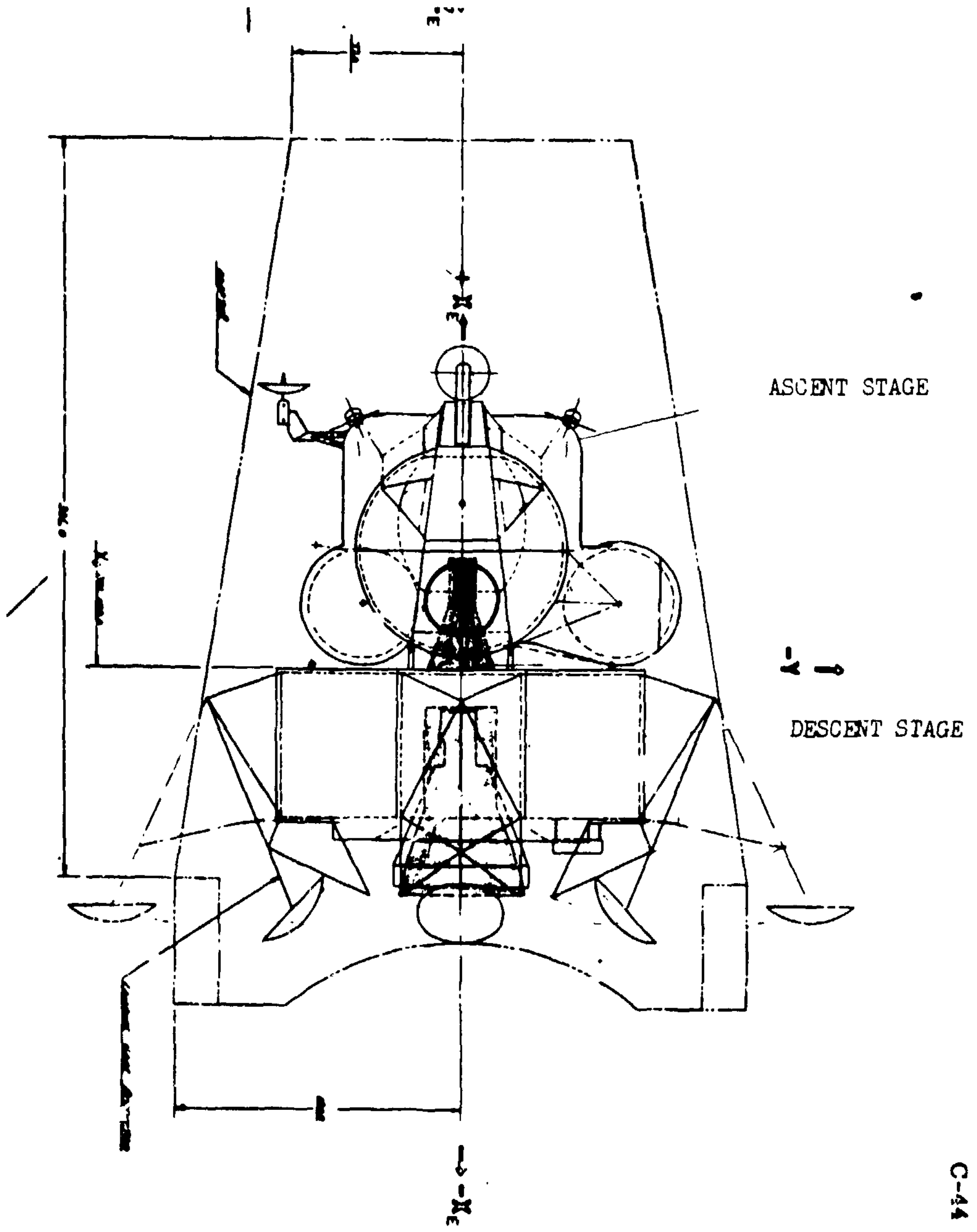
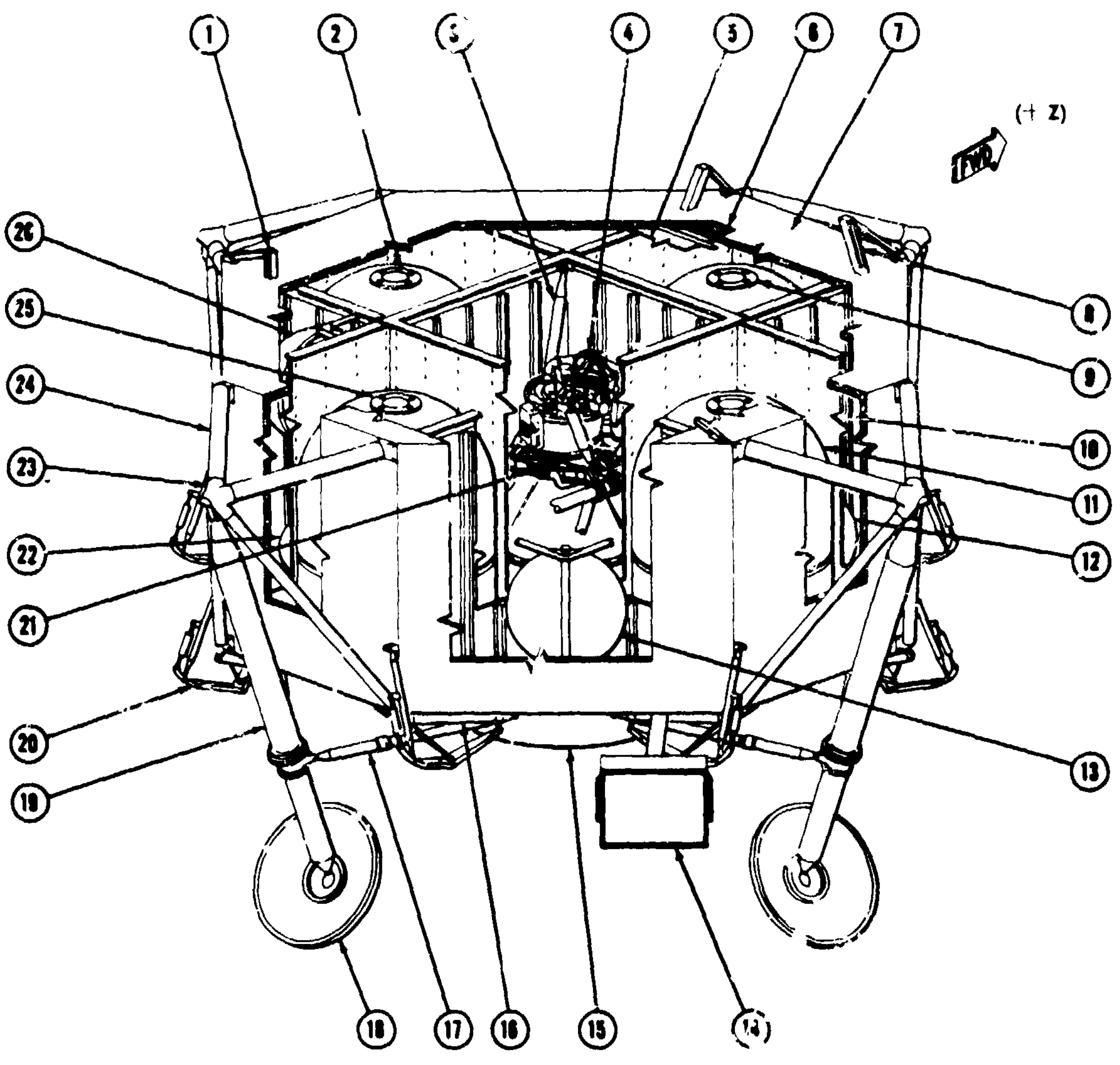


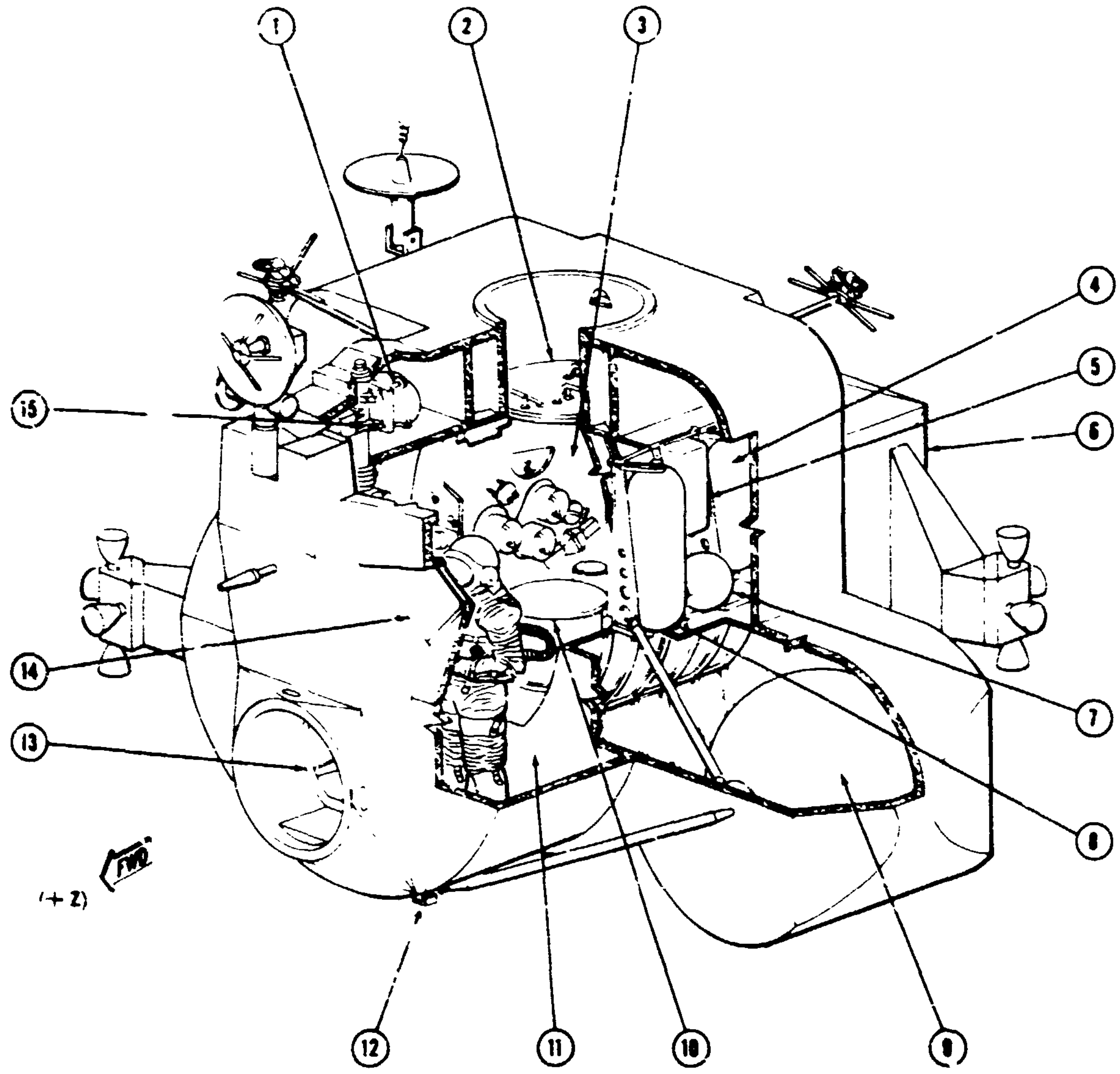
Figure 8. - Descent and ascent engines as installed in LEM



1 AFT INTERSTAGE FITTING
2 FUEL TANK
3 ENGINE MOUNT
4 DESCENT ENGINE
5. STRUCTURAL SKIN
6 INSULATION
7 THERMAL SHIELD
8 FORWARD INTERSTAGE FITTING
9 OXIDIZER TANK
10 SCIENTIFIC EQUIPMENT BAY
11 FUEL TANK
12 WATER TANK
13 HELIUM TANK
14 LANDING RADAR ANTENNA
15 DESCENT ENGINE SKIRT
16 TRUSS ASSEMBLY
17. SECONDARY STRUT
18 PAD
19. PRIMARY STRUT
20. LOCK ASSEMBLY
21. GIMBAL RING
22. OXYGEN TANK
23 ADAPTER ATTACHMENT POINT
24 OUTRIGGER
25. OXIDIZER TANK
26. HYDROGEN TANK

NOTE:
LANDING GEAR SHOWN IN
RETRACTED POSITION

Figure 9. - Descent stage



1 INERTIAL MEASURING UNIT
2 UPPER HATCH
3 MIDSECTION
4 FUEL TANK (RCS)
5 HELIUM PRESSURE REGULATING MODULE
6. AFT EQUIPMENT BAY
7 HELIUM TANK (RCS)
8 OXIDIZER TANK (RCS)
9. FUEL TANK
10 ASCENT ENGINE COVER
11. CREW COMPARTMENT
12. FORWARD INTERSTAGE FITTING
13. FORWARD HATCH
14. WINDOW
15. ALIGNMENT OPTICAL TELESCOPE

Figure 10. - Ascent stage

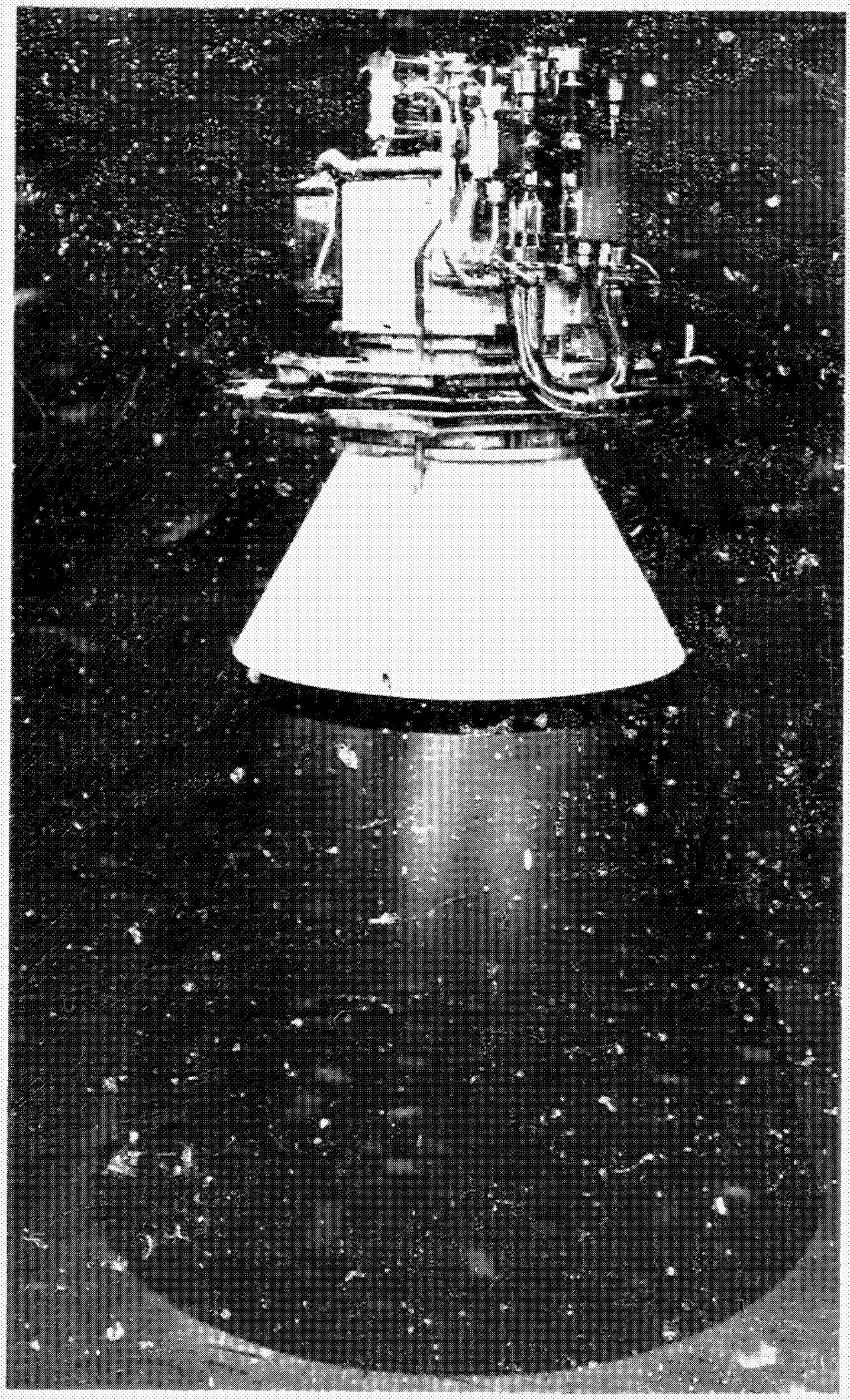


Figure 11. - LEM descent engine

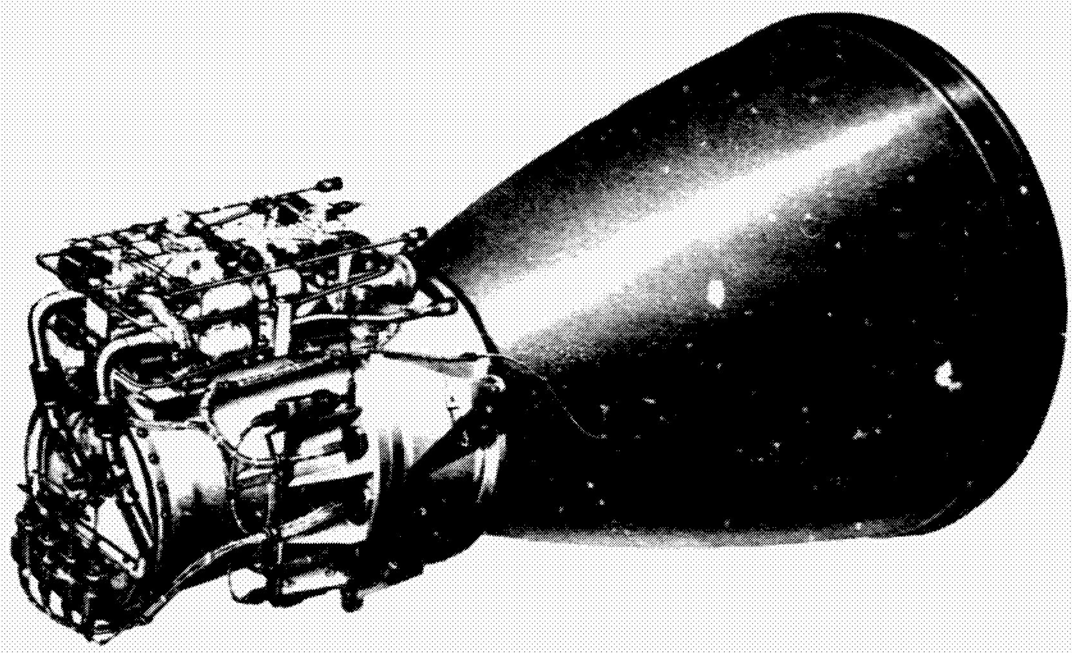


Figure 12. - LEM ascent engine

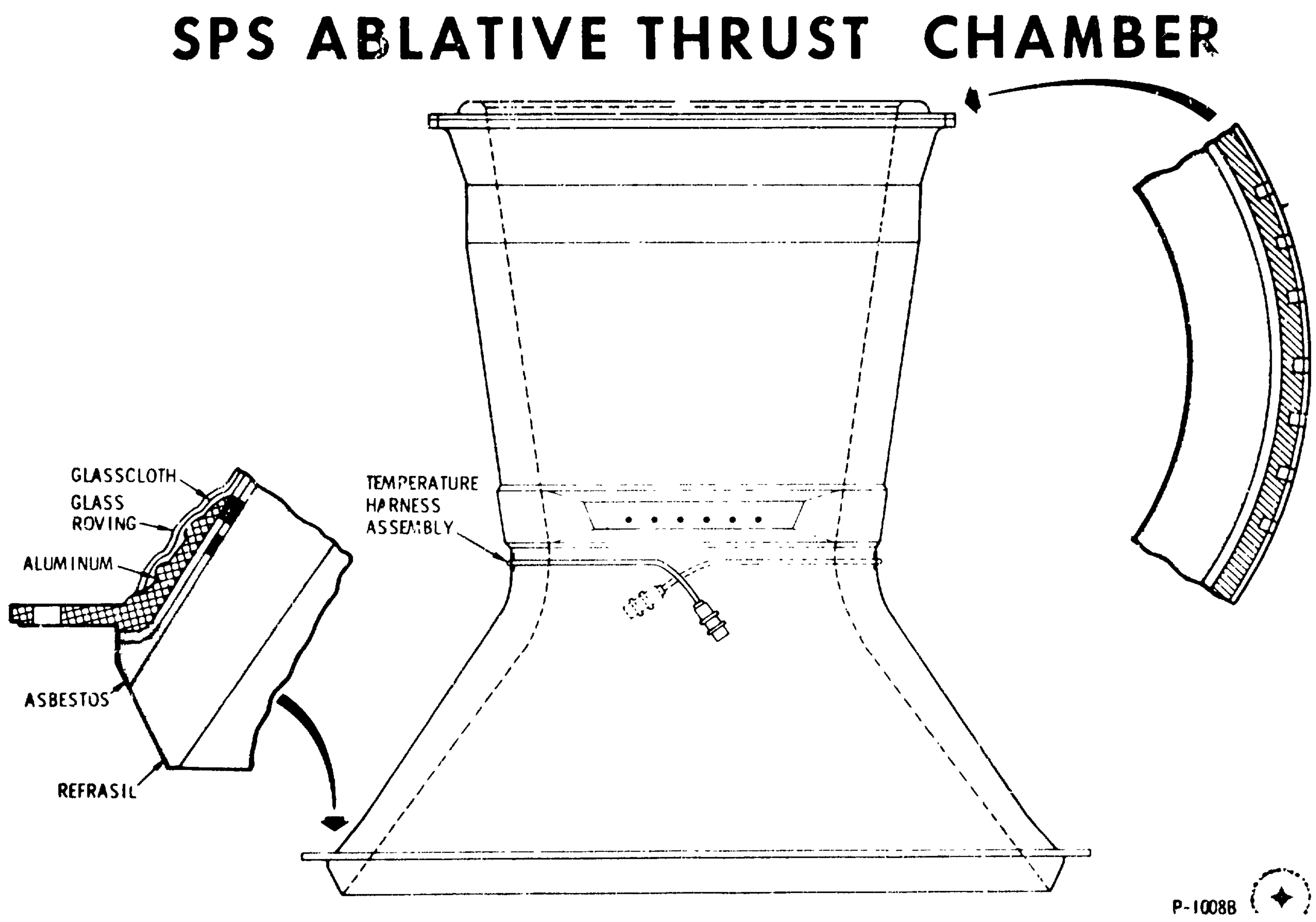


Figure 13. - SPS thrust chamber

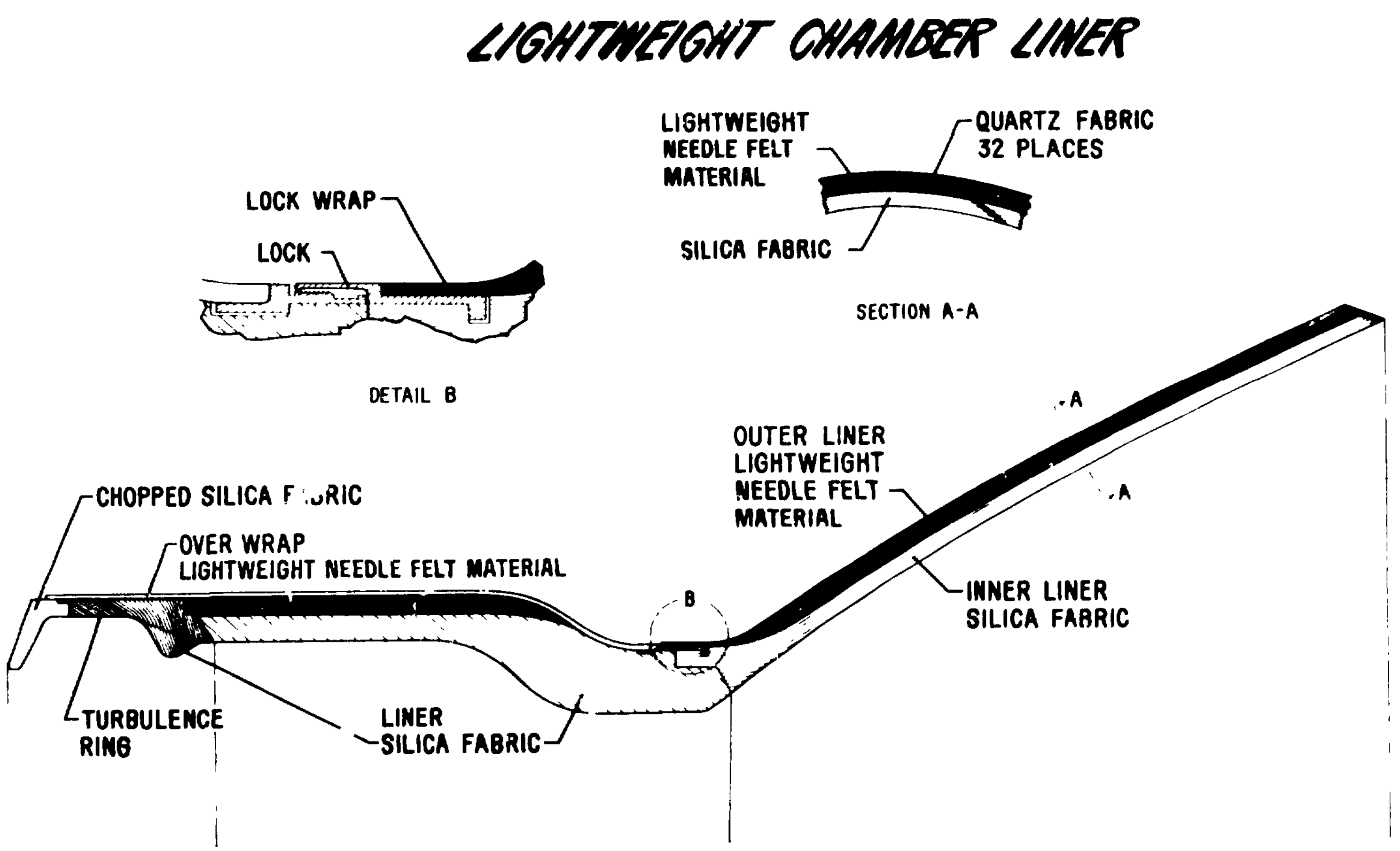


Figure 14 - DPS thrust chamber

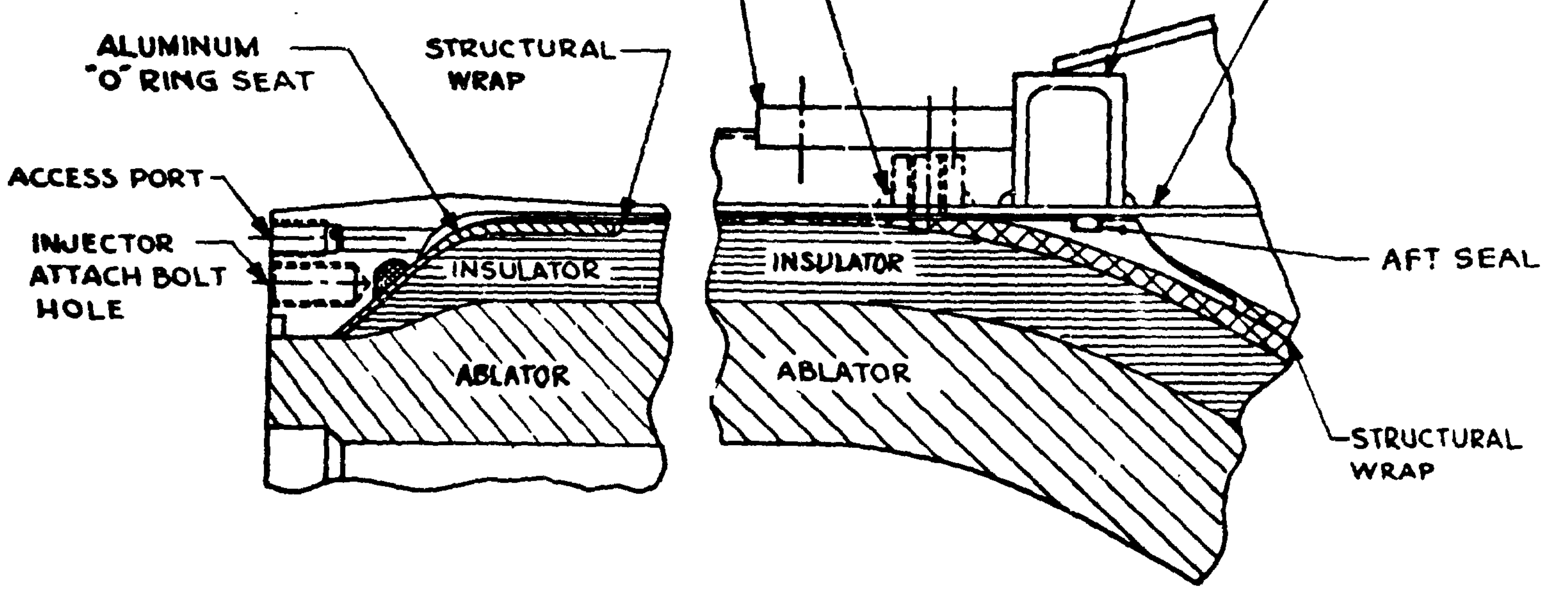


Figure 15 - Ascent engine chamber detail

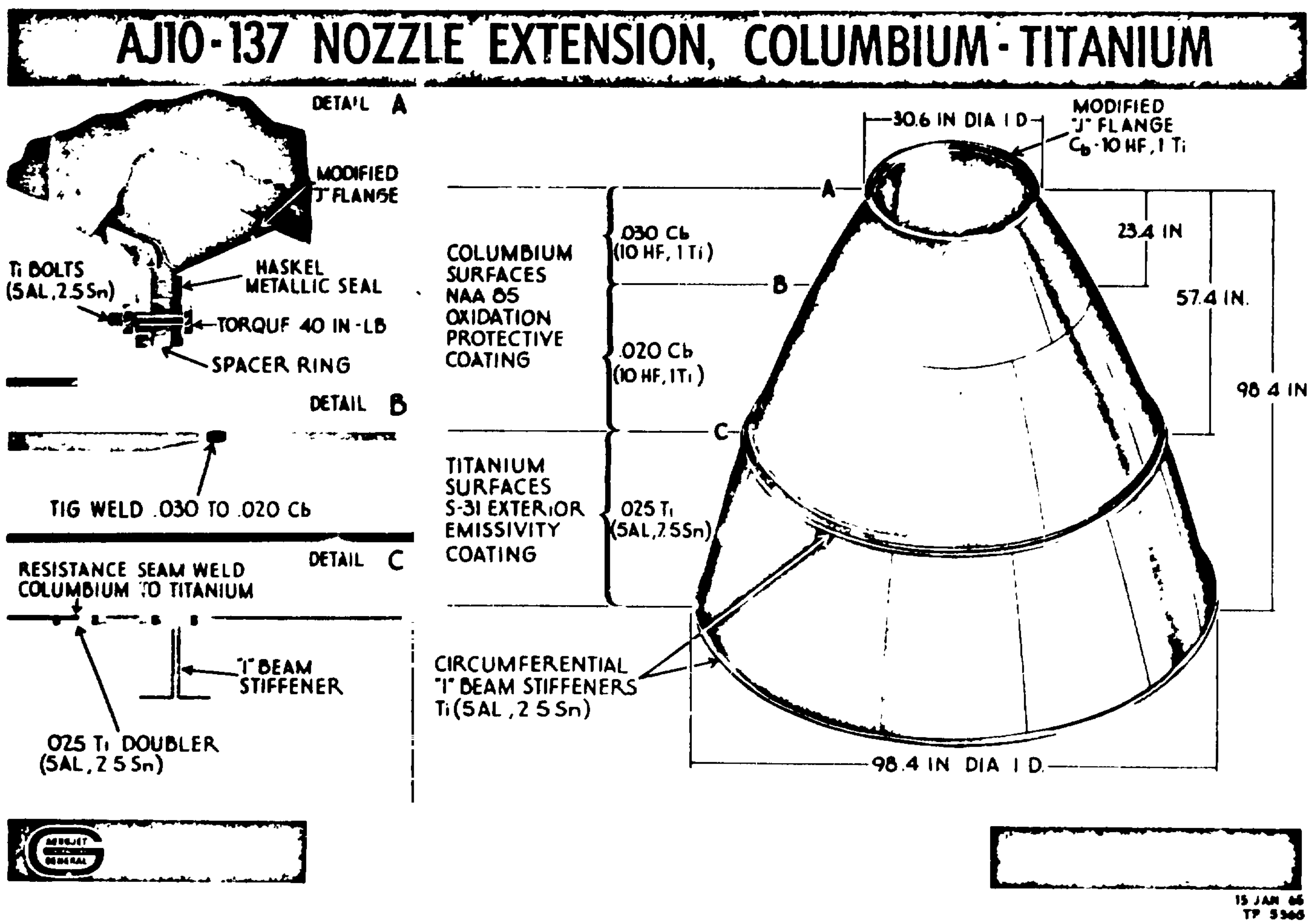


Figure 16 - SPS nozzle extension

DESCENT ENGINE CROSS SECTION

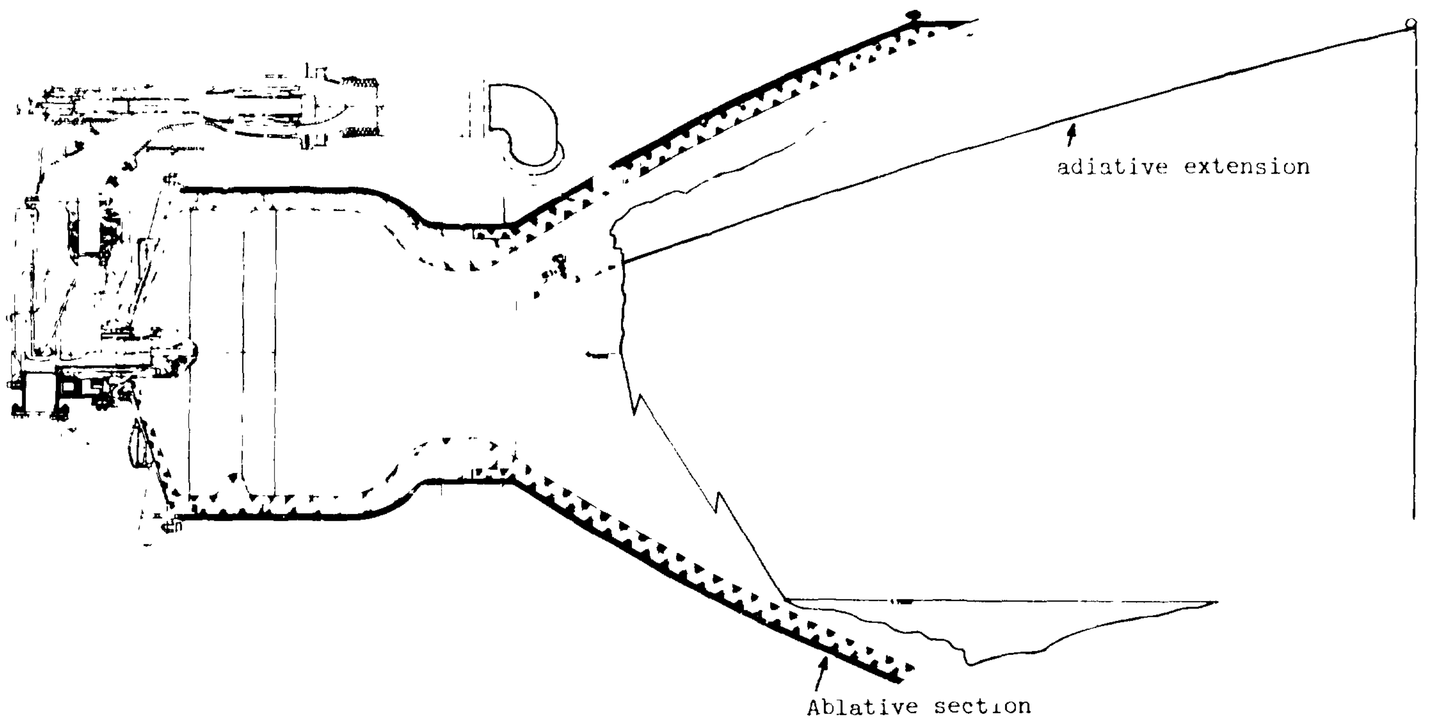


Figure 17. - Descent engine cross section

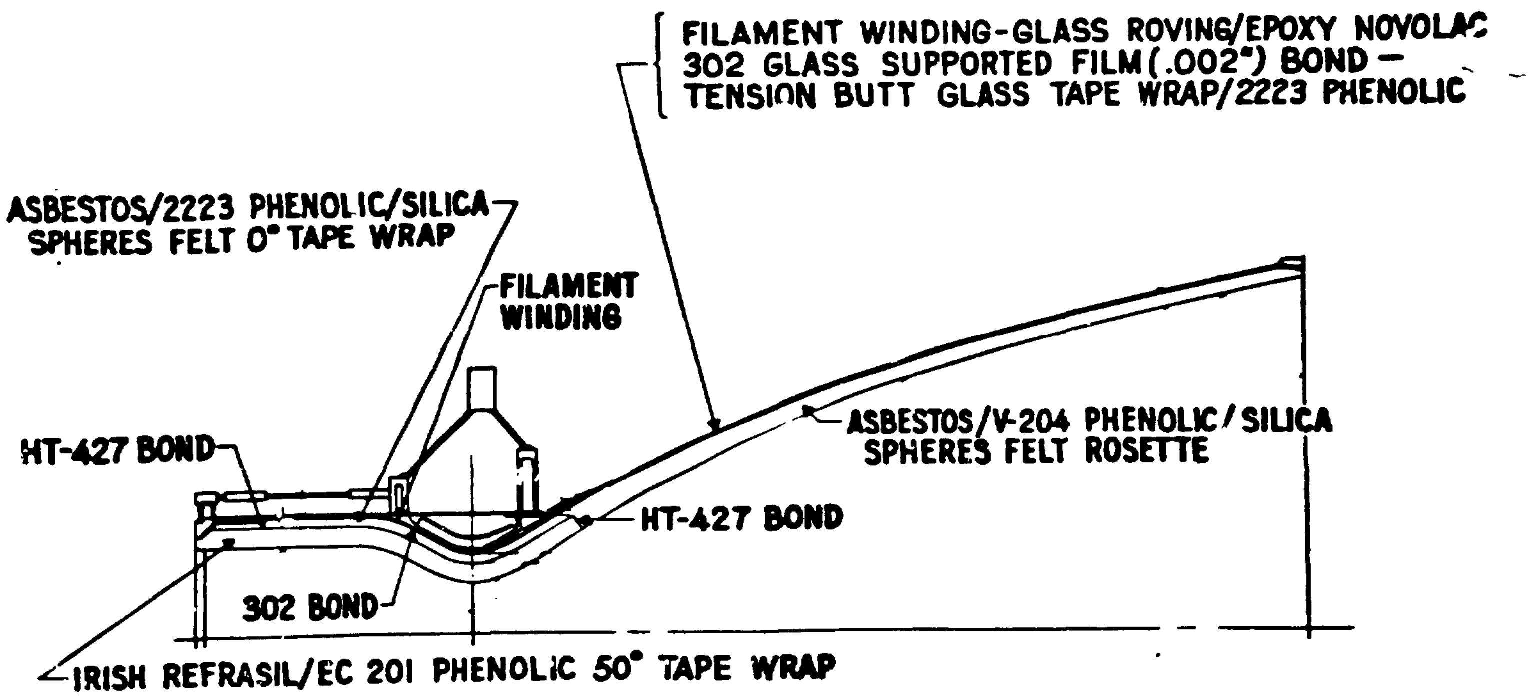


Figure 18 - Ascent engine cross section

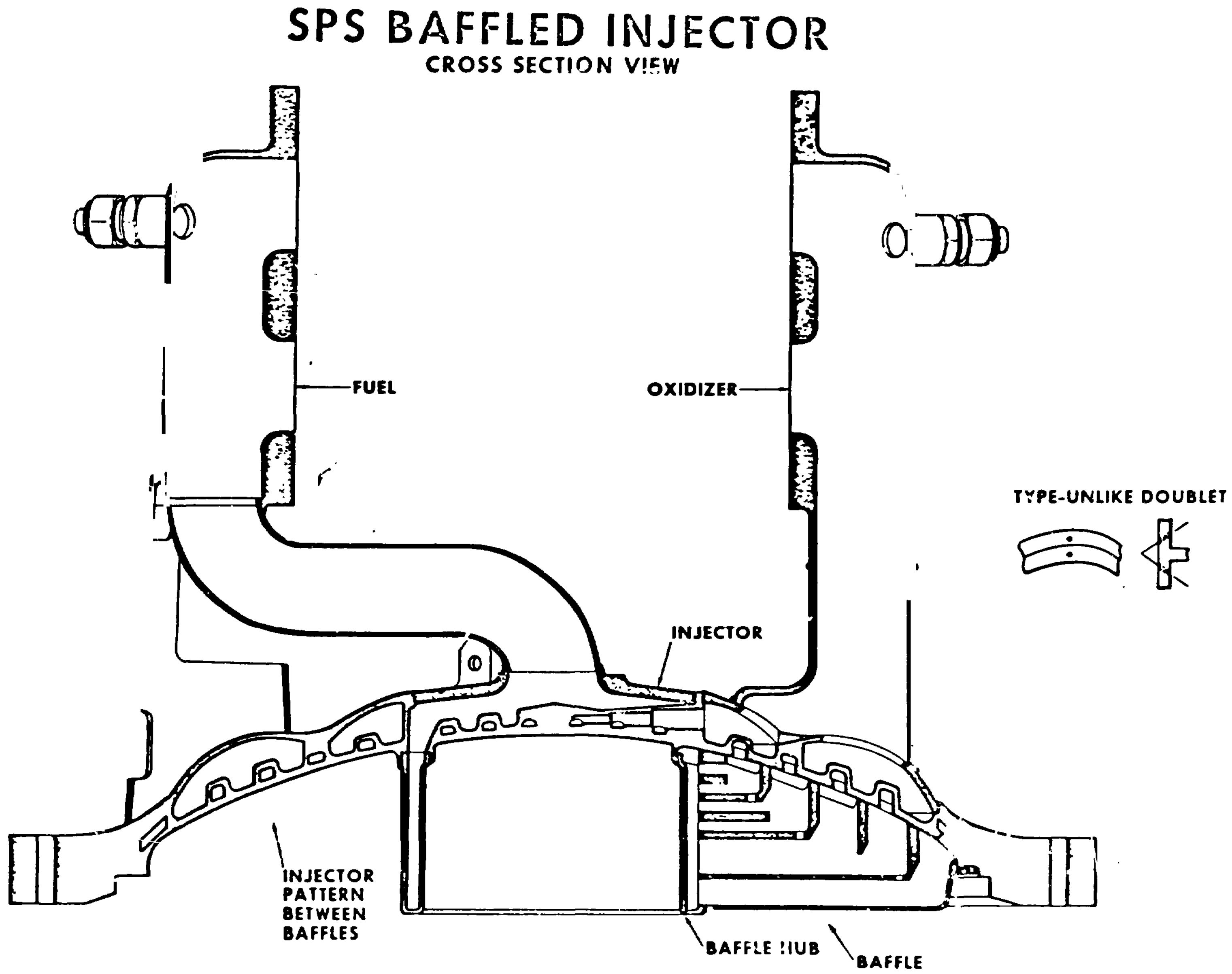


Figure 19. - SPS injector

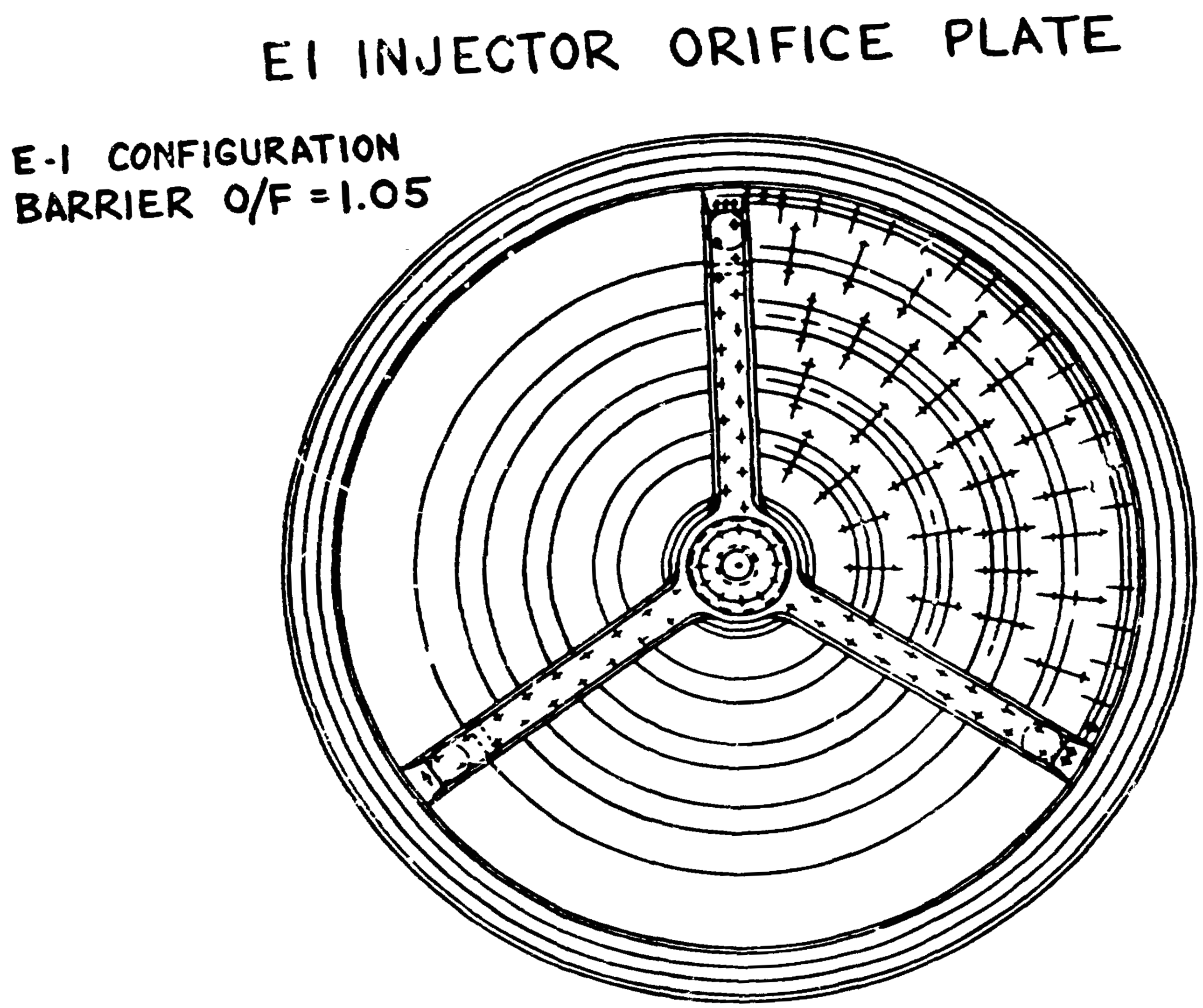


Figure 20. - Ascent engine injector

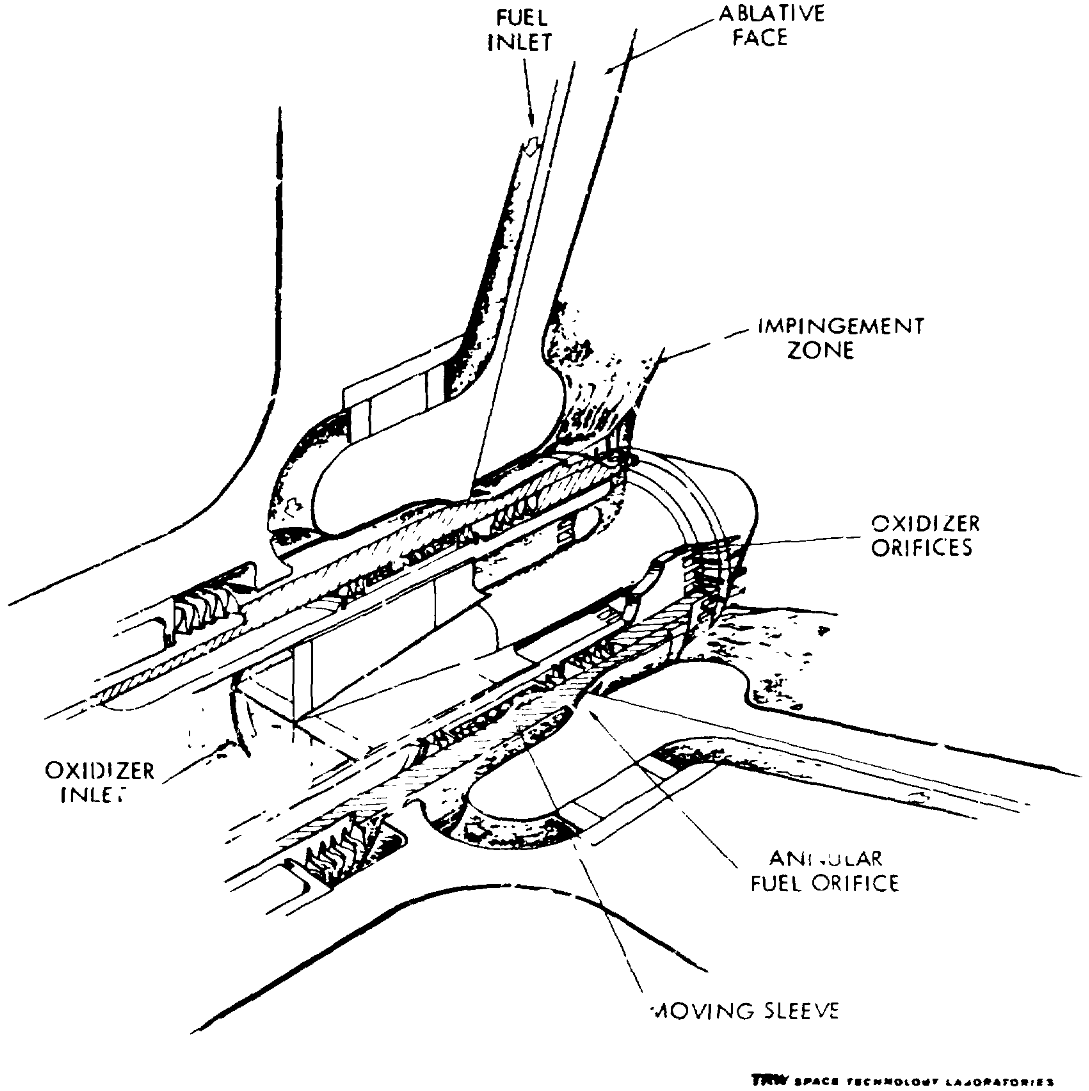


Figure 21. - Descent engine injector detail

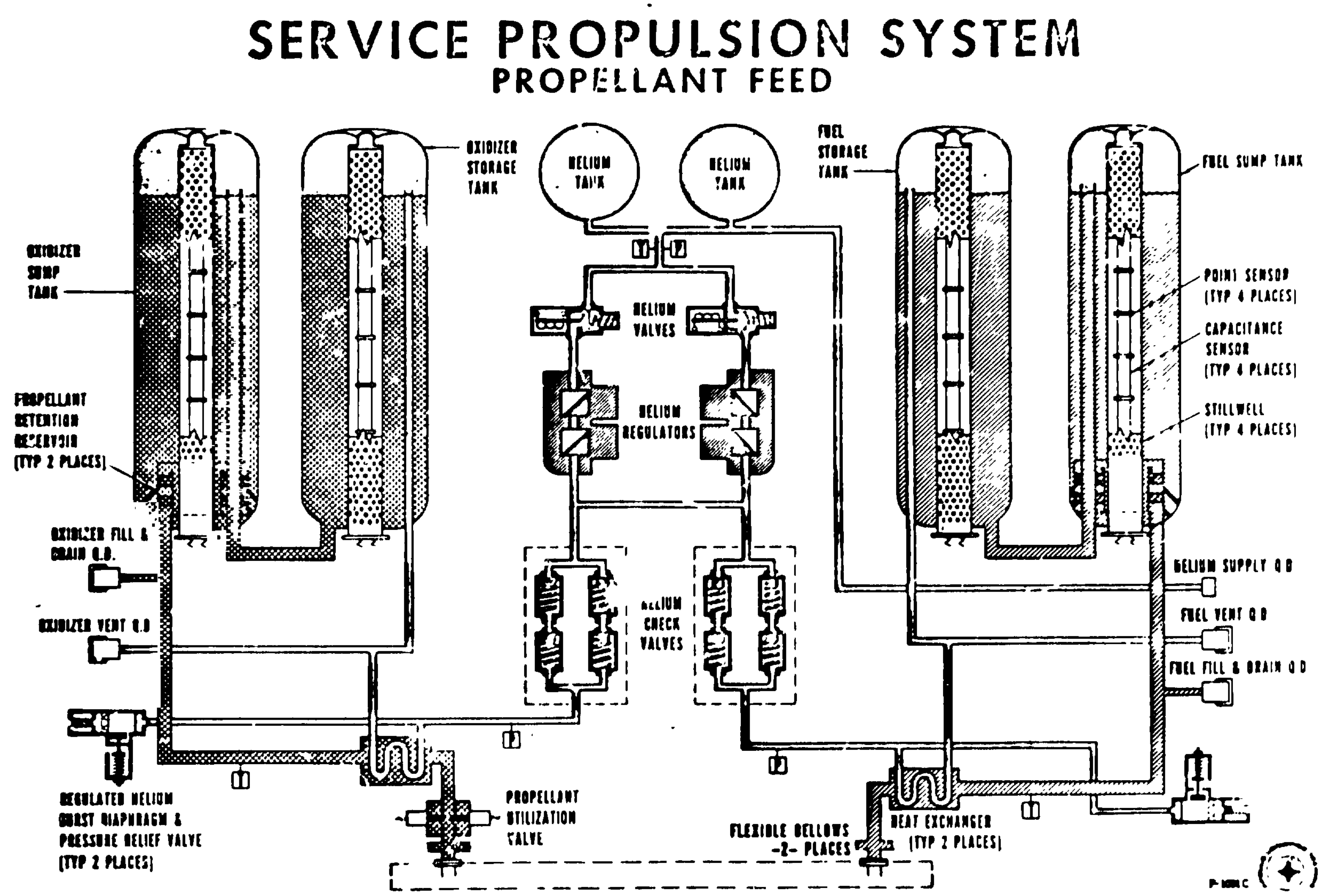


Figure 22. - SPS pressurization and propellant system

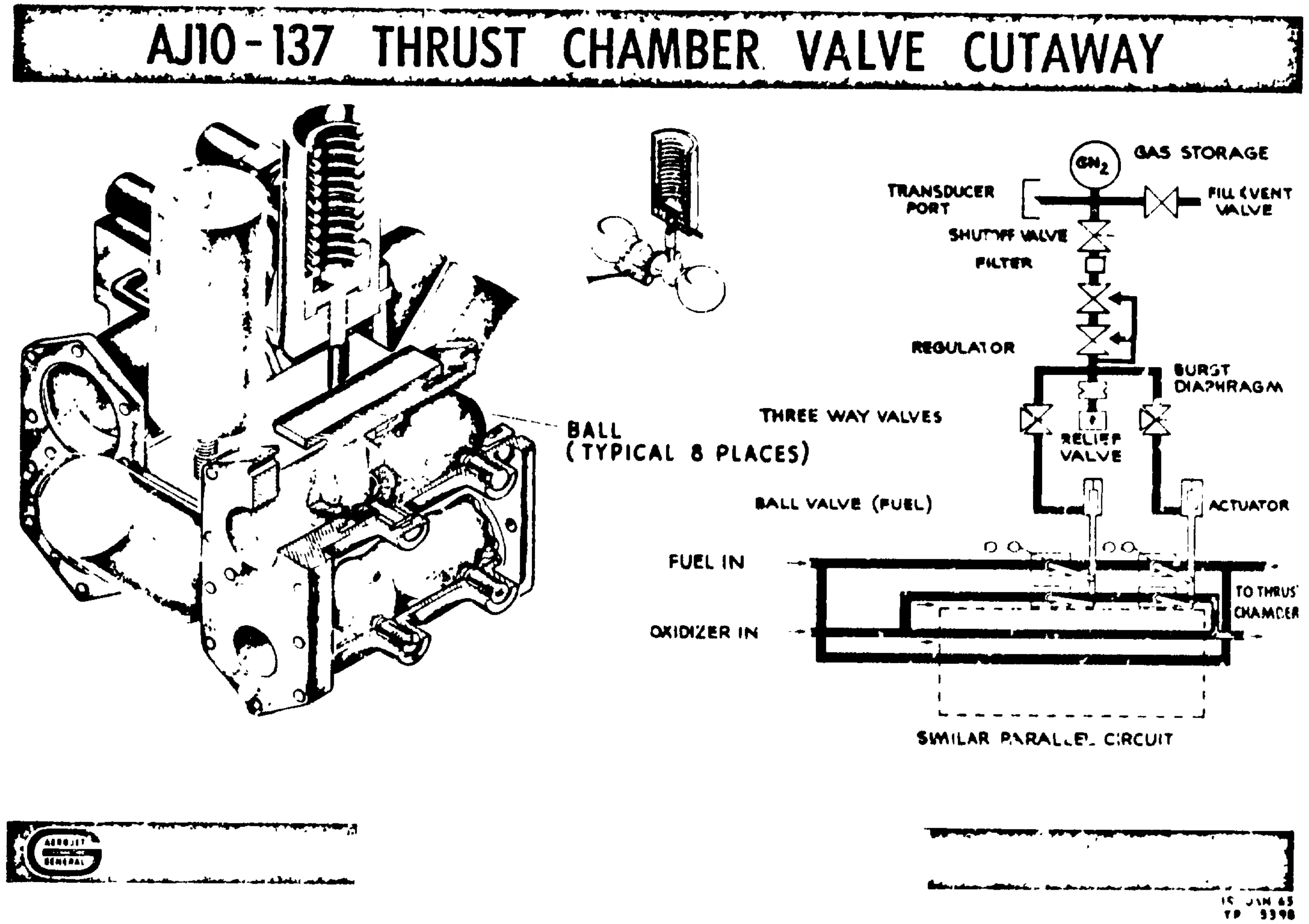


Figure 23. - SPS propellant valve assembly

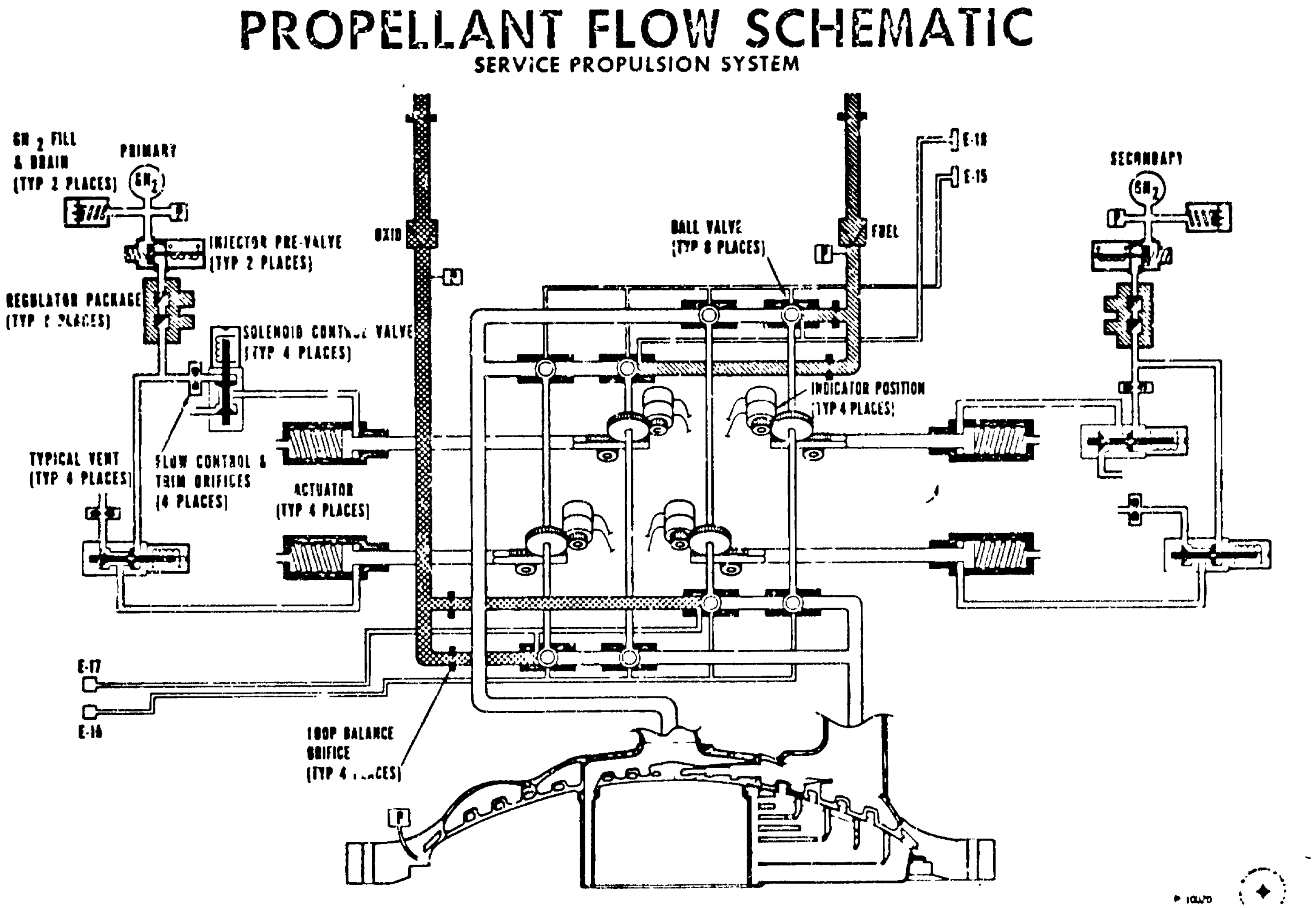


Figure 24. - SPS propellant flow

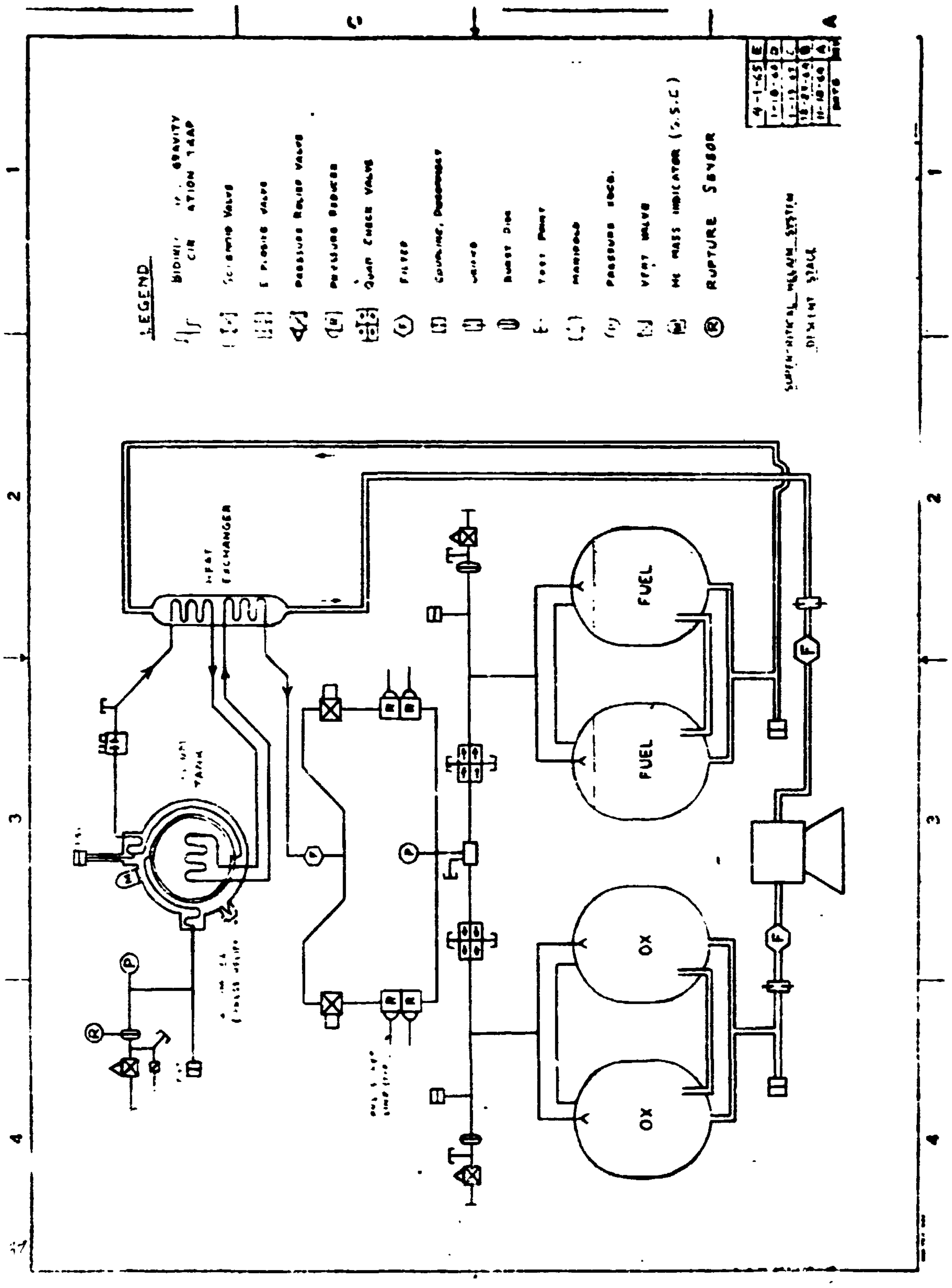


Figure 25. - Descent stage supercritical helium system

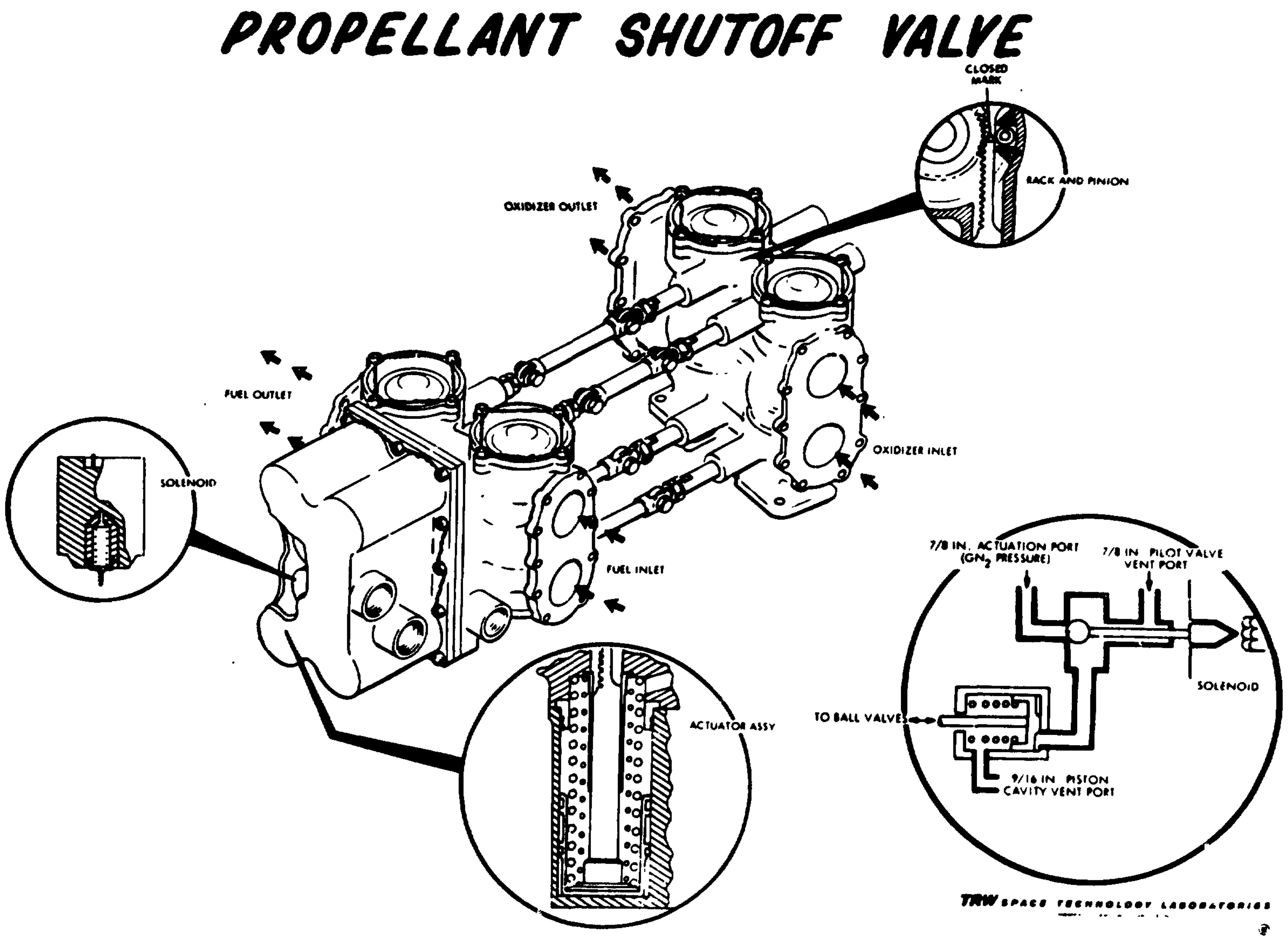


Figure 26. - Descent engine flow control

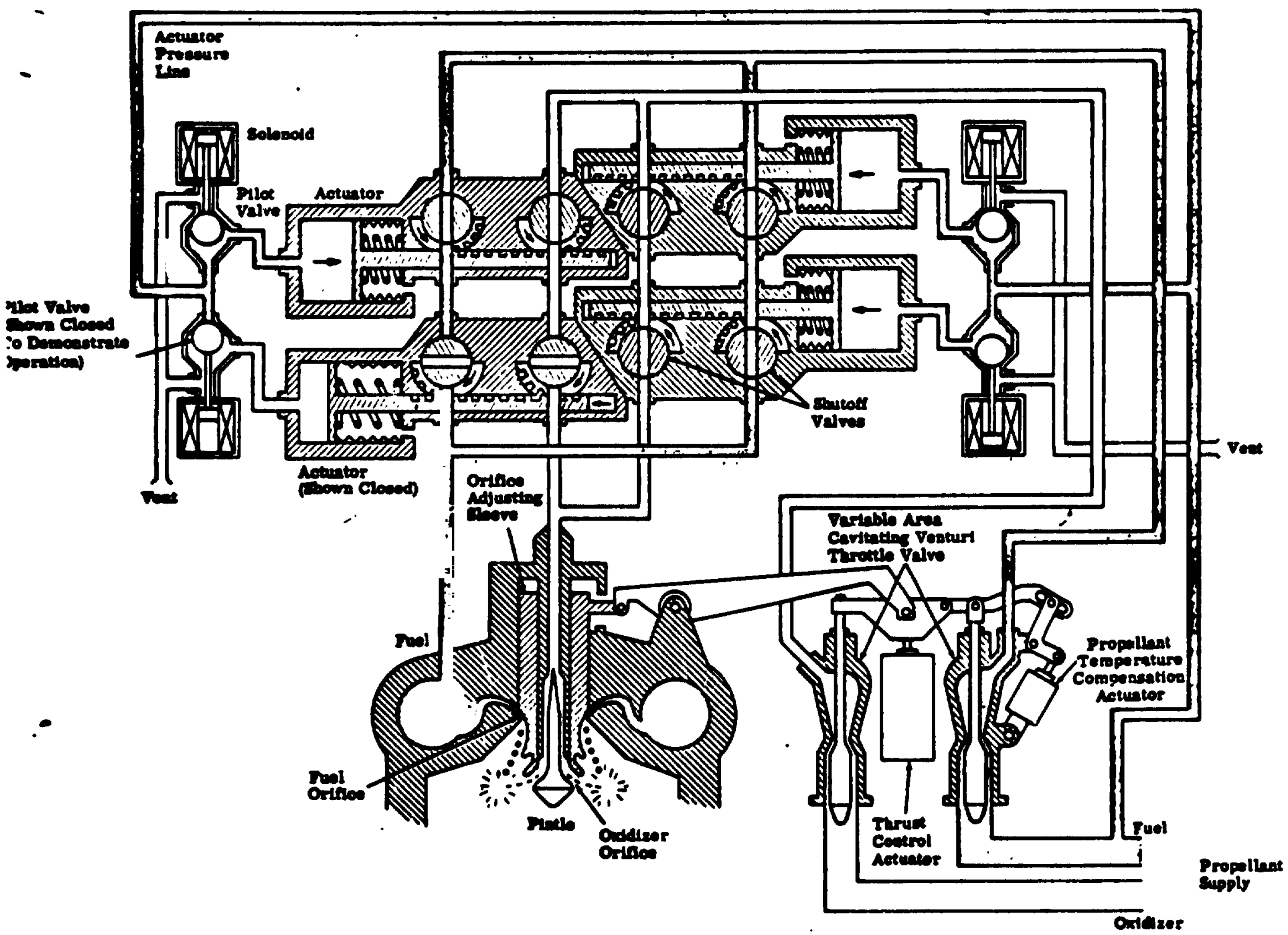


Figure 27. - Descent engine flow control system

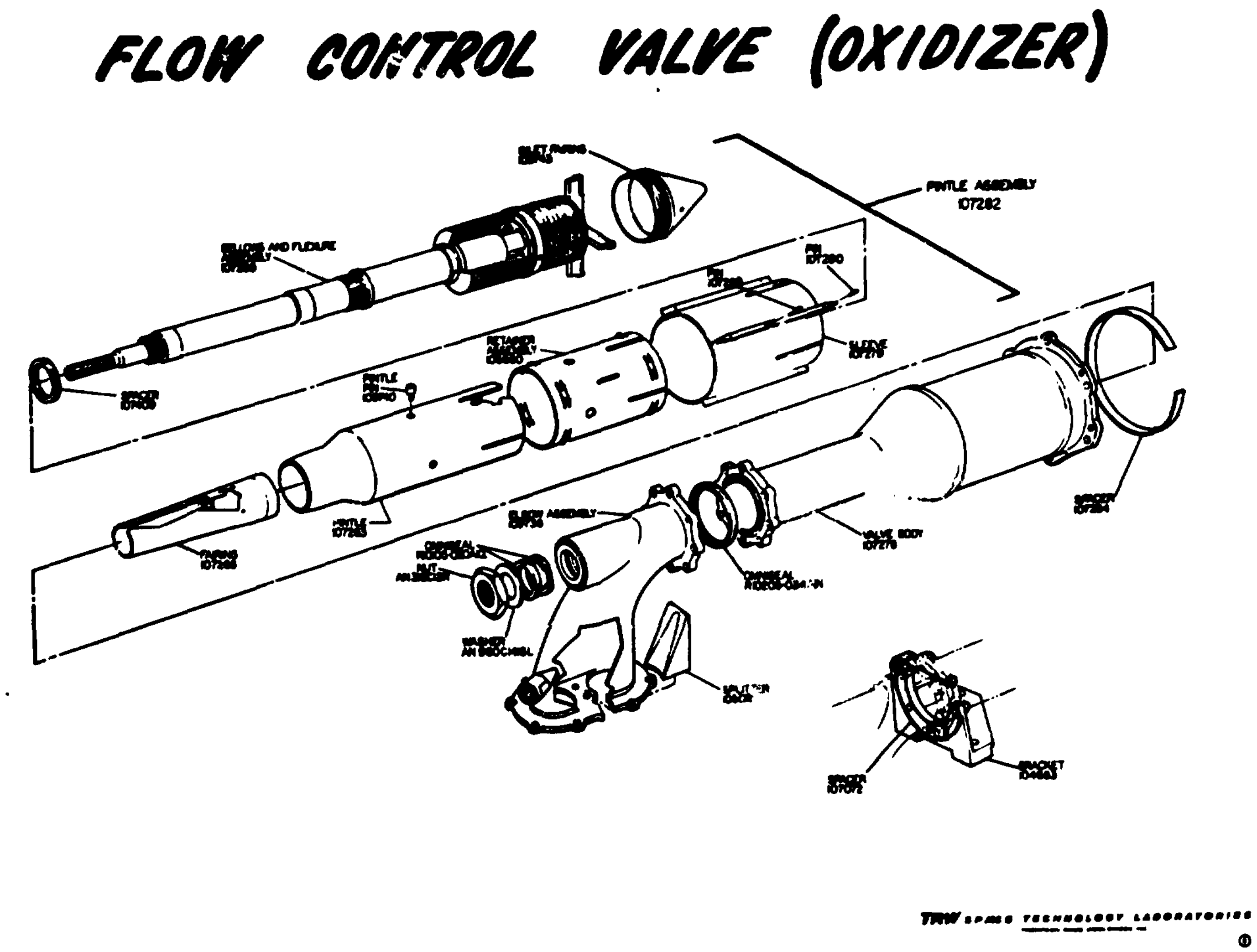


Figure 28. - Descent engine flow control valve

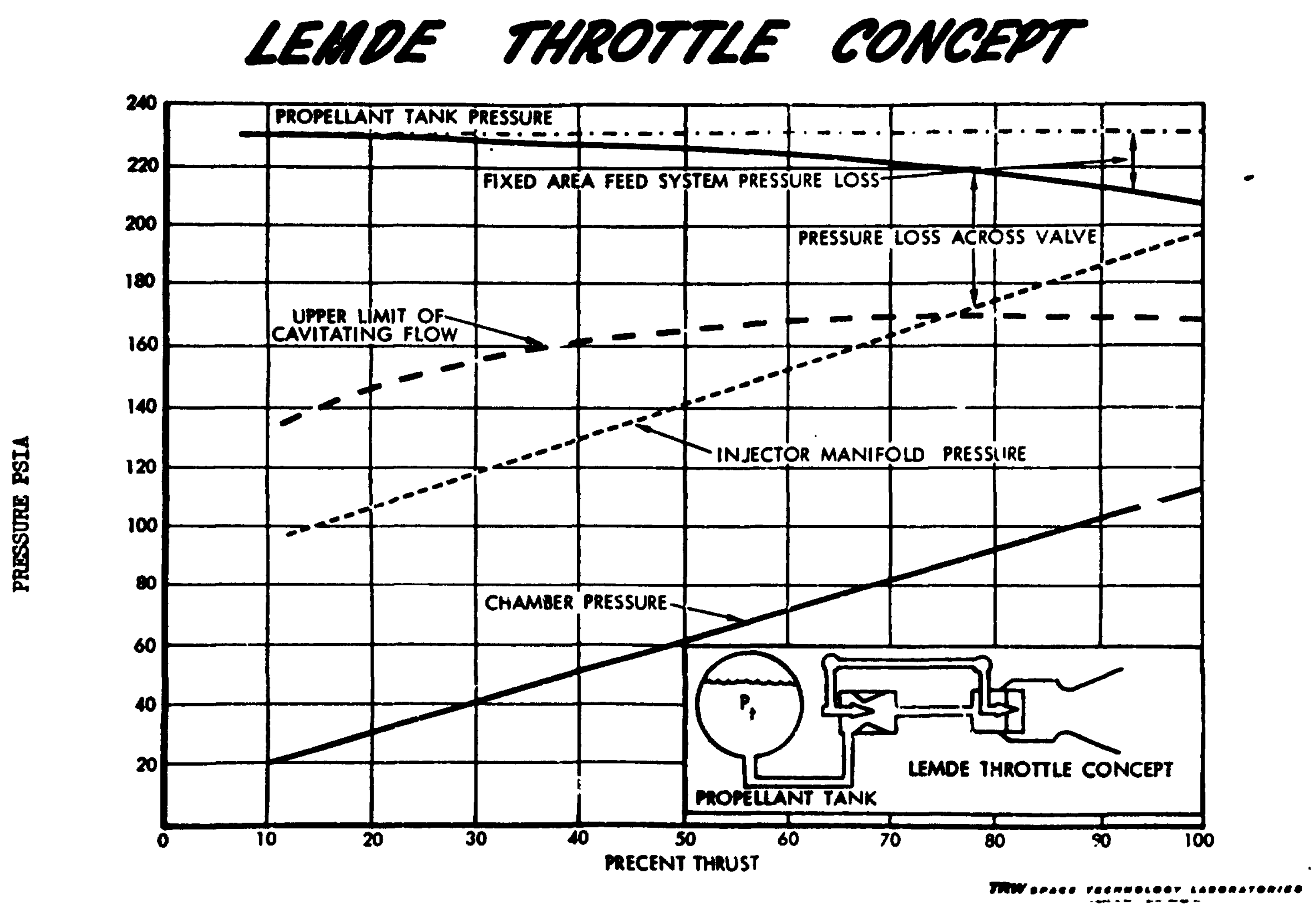


Figure 29. - Descent engine throttle concept

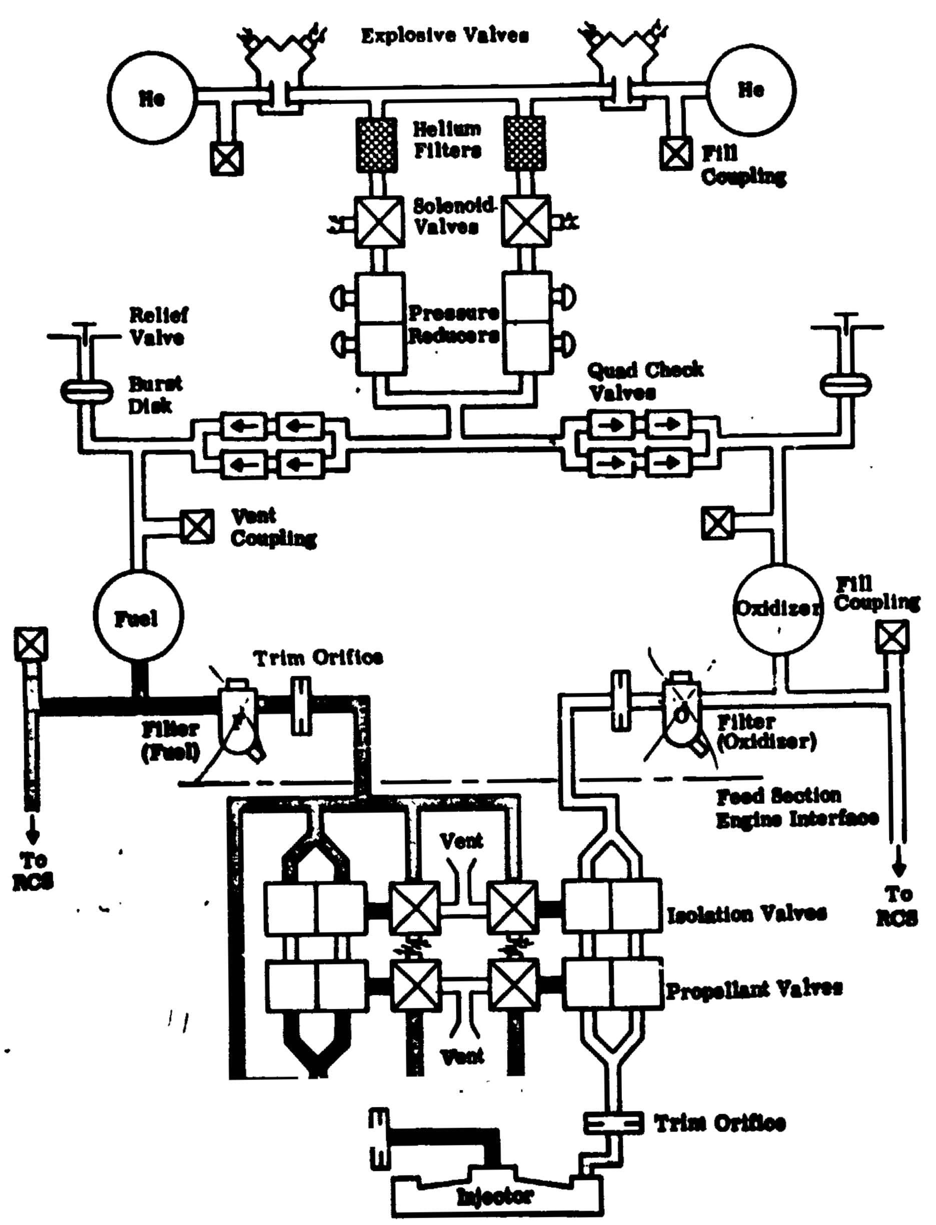


Figure 30. - Ascent engine pressurization and propellant system

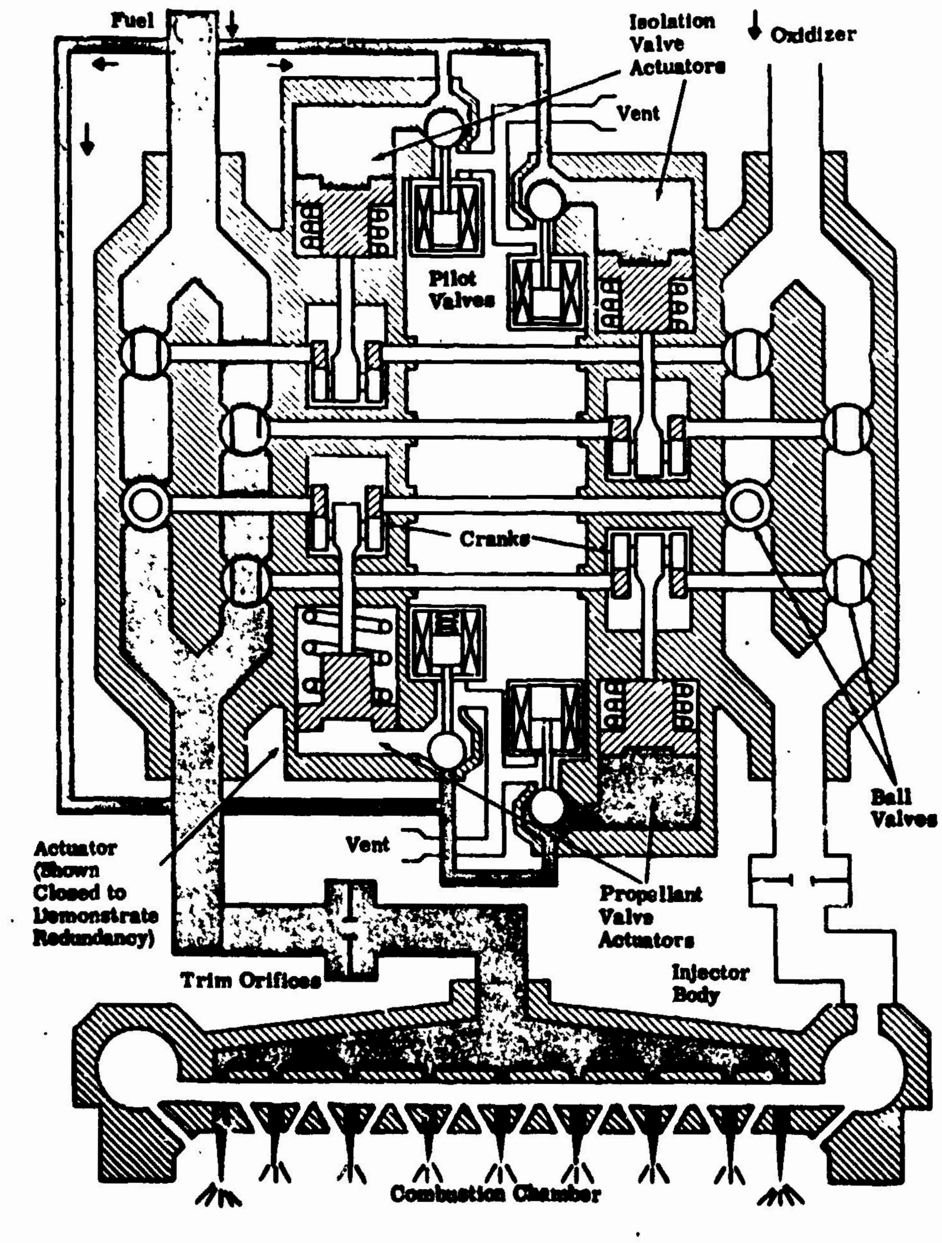


Figure 31. - Ascent engine flow control