

MAIN PROPULSION

QUICK REFERENCE DATA

DESCENT PROPULSION SECTION

Pressurization section

Ambient helium tank

Volume	1 cubic foot
Initial filling weight of helium	1.12 pounds
Initial helium pressure and temperature	1,635 psia at +70° F
Proof pressure	2,333 psi

Supercritical helium tank

Volume	5.9 cubic feet
Initial filling weight of helium	51.2 pounds
Initial helium filling pressure and temperature	178 psia at -450° F
Nominal helium storage pressure and temperature	1,555 psia at -400° F
Maximum helium storage pressure and temperature	1,780 psia at -312° F
Density	8.7 pounds per cubic foot
Proof pressure	2,274 psi
Burst-disk rupture pressure	1,881 to 1,967 psi

Helium filters absolute filtration

15 microns

Helium pressure regulators

Outlet pressure	245 ± 3 psia
Normal operation flow rate range	0.52 to 5.5 pounds per minute
Nominal flow rate at full throttle	5.2 pounds per minute
Inlet pressure range	320 to 1,750 psia
Maximum lockup pressure	253 psia at inlet pressure of 400 to 1,750 psia 255 psia at inlet pressure of 320 to 400 psia

Relief valve assembly

Burst-disk rupture pressure	260 to 275 psi
Relief valve cracking pressure	260 psi
Fully open flow rate	10 pounds per minute
Minimum reseal pressure	254 psi

Propellant feed section

Propellant tanks

Capacity (each tank)	67.3 cubic feet
Total fuel	7,513 pounds
Total oxidizer	11,993 pounds
Minimum ullage volume (each tank)	1,728 cubic inches
Usable fuel	7,492 pounds
Usable oxidizer	11,953 pounds
Nominal ullage pressure (at full throttle position)	235 psia
Nominal propellant temperature	+70° F
Propellant temperature range	+50° to +90° F
Proof pressure	360 psia
Propellant filters absolute filtration	60 microns

Engine assembly

Nominal engine thrust (full throttle)	9,900 pounds (FTP)
Minimum engine thrust (low stop)	1,280 pounds (12.2%)
Nominal combustion chamber pressure (FTP)	103.4 psia
Engine-gimbaling capability	+6 ^o to -6 ^o from center, along Y-axis and Z-axis
Propellant injection ratio (oxidizer to fuel)	1.6 to 1 (approximate)
Engine restart capability	20 times
Engine life	910 seconds or 17,510 pounds of propellant consumption
Approximate weight	348 pounds
Overall length	95 inches
Nozzle expansion area ratio	47.4 to 1
Nozzle exit diameter	63 inches

ASCENT PROPULSION SECTION

Pressurization section

Helium tanks

Volume (each tank)	3.35 cubic feet
Initial filling weight of helium (each tank)	6.5 pounds
Initial helium pressure and temperature	3,050 psia at +70 ^o F
Maximum operating pressure of helium	3,500 psia at +160 ^o F
Proof pressure	4,650 psia at +160 ^o F

Helium filters absolute filtration

15 microns

Helium pressure regulator assemblies

Primary path outlet pressure	
Upstream regulator	184 ± 4 psia
Downstream regulator	190 ± 4 psia
Secondary path outlet pressure	
Upstream regulator	176 ± 4 psia
Downstream regulator	182 ± 4 psia
Maximum lockup pressure	203 psia
Maximum outlet flow rate (each regulator path)	5.5 pounds per minute
Inlet pressure range	400 to 3,500 psia
Nominal helium flow rate	1.45 pounds per minute

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Relief valve assembly

Burst-disk rupture pressure	226 to 250 psia
Relief valve cracking pressure	245 psia
Fully open flow rate	4 pounds per minute
Reseat pressure	225 psia

Propellant feed section

Propellant tanks

Capacity (each tank)	36 cubic feet
Total fuel	2,011 pounds
Total oxidizer	3,217 pounds
Minimum ullage volume (each tank)	0.5 cubic foot per tank at +90° F
Usable fuel	2,001 pounds
Usable oxidizer	3,190 pounds
Propellant temperature range	+50° to +90° F
Nominal propellant temperature	+70° F
Nominal ullage pressure	184 psia
Proof pressure	333 psia

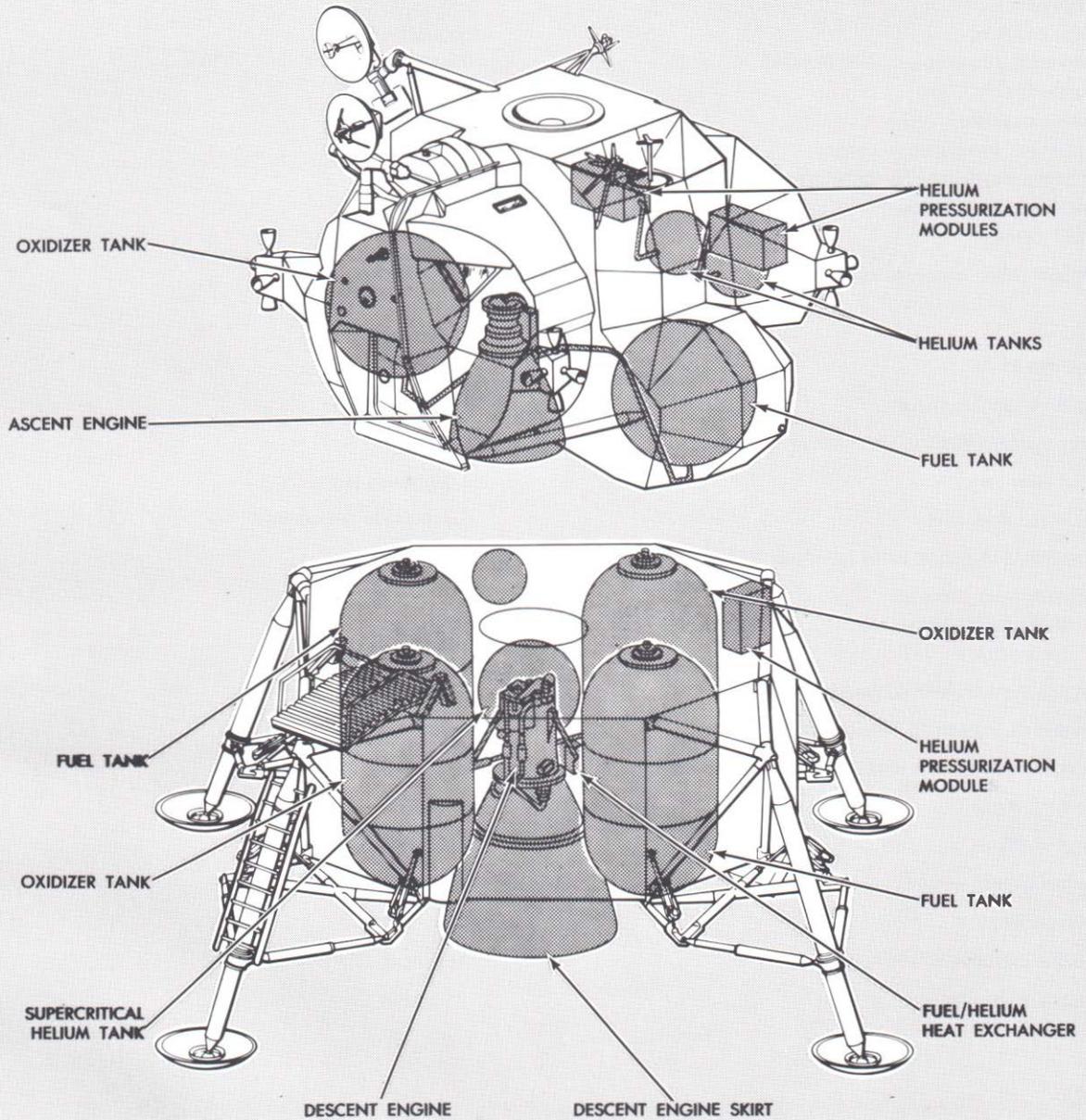
Propellant filters absolute filtration 200 microns

Engine assembly

Nominal engine thrust	3,500 pounds
Nominal combustion chamber pressure	120 psia
Fuel flow rate	4.3 pounds per second
Oxidizer flow rate	6.9 pounds per second
Propellant injection ratio (oxidizer to fuel)	1.6 to 1
Injector inlet pressure	
Steady-state operation	145 psia
Engine start	185 to 203 psia
Engine start to 90% of rated thrust	0.310 second
Engine shutdown to 10% of rated thrust	0.200 second
Nominal propellant temperature at injector inlet	+70° F
Restart capability	35 times
Engine life	460 seconds
Approximate weight	200 pounds
Overall length	47 inches
Nozzle expansion area ratio	45.6 to 1
Nozzle exit diameter	31 inches

The Main Propulsion Subsystem (MPS) consists of two separate, complete, and independent propulsion sections: the descent propulsion section and the ascent propulsion section. Each propulsion section performs a series of specific tasks during the lunar-landing mission. The descent propulsion section provides propulsion for the LM from the time it separates from the CSM until it lands on the lunar surface, the ascent propulsion section lifts the ascent stage off the lunar surface and boosts it

into orbit. Both propulsion sections operate in conjunction with the Reaction Control Subsystem (RCS), which provides propulsion used mainly for precise attitude and translation maneuvers. The ascent propellant tanks are connected to the RCS to supplement its propellant supply during certain mission phases. If a mission abort becomes necessary during the descent trajectory, the ascent or descent engine can be used to return to a rendezvous orbit with the CSM. The choice of engines



R-75

Major Main Propulsion Equipment Location

depends on the cause for abort, the amount of propellant remaining in the descent stage, and the length of time that the descent engine had been firing.

Each propulsion section consists of a liquid-propellant, pressure-fed rocket engine and propellant storage, pressurization, and feed components. For reliability, many vital components in each section are redundant. In both propulsion sections, pressurized helium forces the hypergolic propellants from the tanks to the engine injector. Both engine assemblies have control valves that start and stop a metered propellant flow to the combustion chamber upon command, trim orifices, an injector that determines the spray pattern of the propellants as they enter the combustion chamber, and a combustion chamber, where the propellants meet and ignite. The gases produced by combustion pass through a throat area into the engine nozzle, where they expand at an extremely high velocity before being ejected. The momentum of the exhaust gases produces the reactive force that propels the vehicle.

The more complicated tasks required of the descent propulsion section — such as propelling the entire LM and hovering over the lunar surface while the astronauts select a landing site — dictate that the descent propulsion section be the larger and more sophisticated of the two propulsion sections. It has a propellant supply that is more than three times that of the ascent propulsion section. The descent engine is almost twice as large as the ascent engine, produces more thrust (almost 10,000 pounds at full throttle), is throttleable for thrust control, and is gimbled (can be tilted) for thrust vector control. The ascent engine, which cannot be tilted, delivers a fixed thrust of 3,500 pounds, sufficient to launch the ascent stage from the lunar surface and place it into a predetermined orbit.

The primary characteristics demanded of the LM propellants are high performance per weight; storability over long periods without undue vaporization or pressure buildup; hypergolicity for easy, closely spaced engine starts; no shock sensitivity; freezing and boiling points within controllable extremes; and chemical stability. The ascent and

descent propulsion sections, as well as the RCS, use identical fuel/oxidizer combinations. In the ascent and descent propulsion sections, the injection ratio of oxidizer to fuel is approximately 1.6 to 1, by weight.

The fuel is a blend of hydrazine (N_2H_4) and unsymmetrical dimethylhydrazine (UDMH), commercially known as Aerozine 50. The proportions, by weight, are approximately 50% hydrazine, and 50% dimethylhydrazine.

The oxidizer is nitrogen tetroxide (N_2O_4). It has a minimum purity of 99.5% and a maximum water content of 0.1%.

The astronauts monitor the performance and status of the MPS with their panel-mounted pressure, temperature, and quantity indicators; talkbacks (flags indicating open or closed position of vital valves); and caution and warning annunciators (placarded lights that go on when specific out-of-tolerance conditions occur). These data, originating at sensors and position switches in the MPS, are processed in the Instrumentation Subsystem, and are simultaneously displayed to the astronauts in the LM cabin and transmitted to mission controllers through MSFN via the Communications Subsystem. The MPS obtains 28-volt d-c and 115-volt a-c primary power from the Electrical Power Subsystem.

Before starting either engine, the propellants must be settled to the bottom of the tanks. Under weightless conditions, this requires an ullage maneuver; that is, the LM must be moved in the +X, or upward, direction. To perform this maneuver, an astronaut or the automatic guidance equipment operates the downward-firing thrusters of the RCS.

The MPS is operated by the Guidance, Navigation, and Control Subsystem (GN&CS), which issues automatic (and processes manually initiated) on and off commands to the descent or ascent engine. The GN&CS also furnishes gimbal-drive and thrust-level commands to the descent propulsion section.

DESCENT ENGINE OPERATION AND CONTROL

After initial pressurization of the descent propulsion section, the descent engine start requires two separate and distinct operations: arming and firing. Engine arming is performed by the astronauts; engine firing can be performed by the astronauts, or it can be automatically initiated by the LM guidance computer. When the astronauts set a switch to arm the descent engine, power is simultaneously routed to open the actuator isolation valves in the descent engine, enable the instrumentation circuits in the descent propulsion section, and issue a command to the throttling controls to start the descent engine at the required 10% thrust level. The LM guidance computer and the abort guidance section receive an engine-armed status signal. This signal enables an automatic engine-on program in the GN&CS, resulting in a descent engine start. A manual start is accomplished when the Commander pushes his engine-start pushbutton. (Either astronaut can stop the engine because separate engine-stop pushbuttons are provided at both flight stations.)

The normal start profile for all descent engine starts must be at 10% throttle setting. Because the thrust vector at engine start may not be directed through the LM center of gravity, a low-thrust start (10%) will permit corrective gimbaling. If the engine is started at high thrust, RCS propellants must be used to stabilize the LM.

The astronauts can, with panel controls, select automatic or manual throttle control modes and Commander or LM Pilot thrust/translation controller authority, and can override automatic engine operation. Redundant circuits, under astronaut control, ensure descent engine operation if prime control circuits fail.

Signals from the GN&CS automatically control descent engine gimbal trim a maximum of 6° from the center position in the Y- and Z-axes to compensate for center-of-gravity offsets during descent engine firing. This ensures that the thrust vector passes through the LM center of gravity. The astronauts can control the gimbaling only to the extent

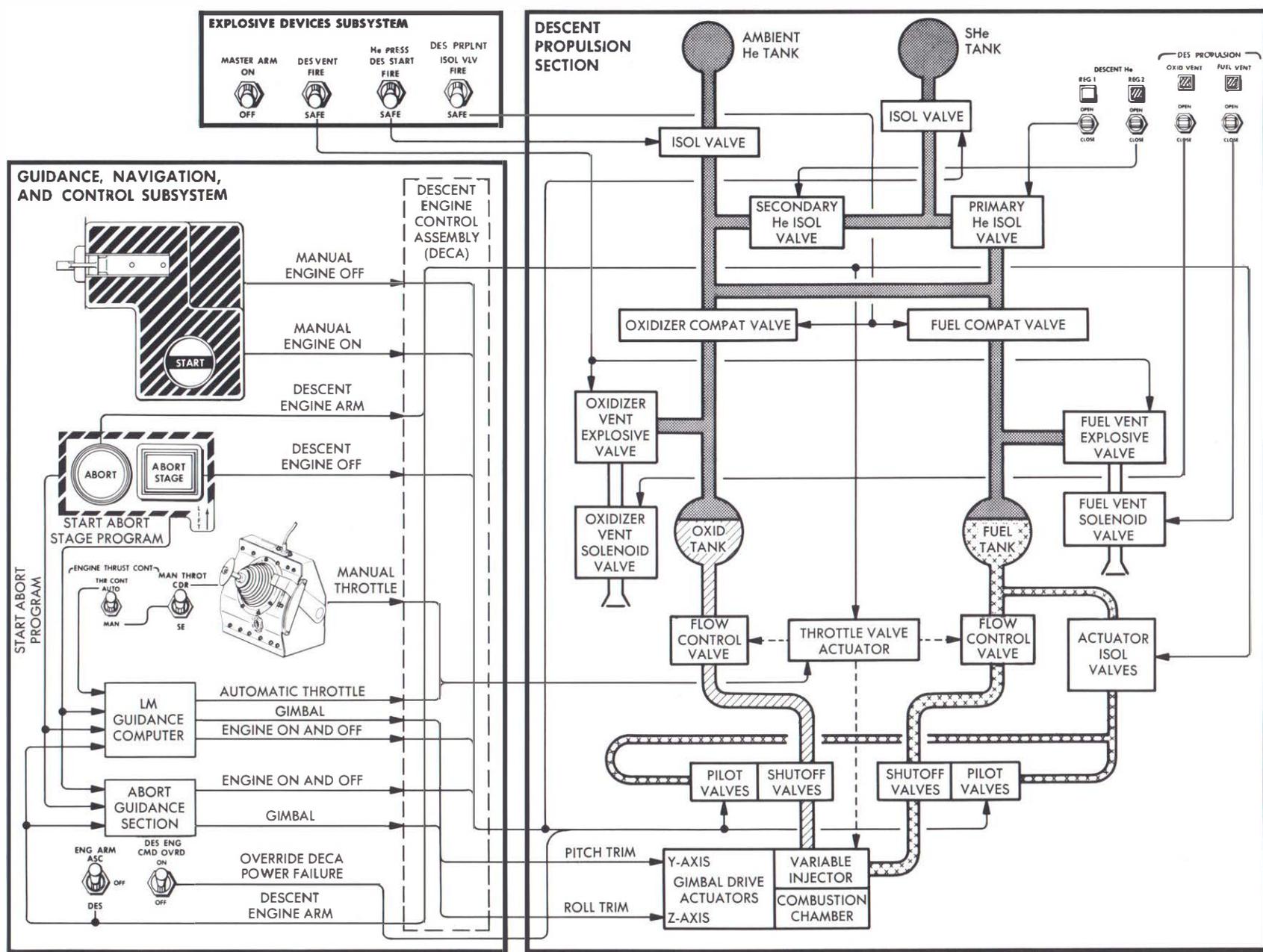
that they can interrupt the tilt capability of the descent engine which they would do if a caution light indicates that the gimbal drive actuators are not following the gimbal commands.

DESCENT PROPULSION SECTION FUNCTIONAL DESCRIPTION

The descent propulsion section consists of an ambient and supercritical helium tank with associated helium pressurization components; two fuel and two oxidizer tanks with associated feed components; and a pressure-fed, ablative, throttleable rocket engine. The engine can be shut down and restarted as required by the mission. At the full-throttle position, the engine develops a nominal thrust of 9,900 pounds; it can also be operated within a range of 1,280 to 6,400 pounds of thrust. Functionally, the descent propulsion section can be subdivided into a pressurization section, a propellant feed section, and an engine assembly.

PRESSURIZATION SECTION

Before earth launch, all the LM propellant tanks are only partly pressurized (less than 230 psia), so that the tanks will be maintained within a safe pressure level under the temperature changes experienced during launch and earth orbit. Before initial engine start, the ullage space in each propellant tank requires additional pressurization. This initial pressurization is accomplished with a relatively small amount of helium stored at ambient temperature and at an intermediate pressure. To open the path from the ambient helium tank to the propellant tanks, the astronauts fire three explosive valves: an ambient helium isolation valve and the two propellant compatibility valves that prevent backflow of propellant vapors from degrading upstream components. After flowing through a filter, the ambient helium enters a pressure regulator which reduces the helium pressure to approximately 245 psi. The regulated helium then enters parallel paths which lead through quadruple check valves into the propellant tanks. The quadruple check valves, consisting of four valves in a series-parallel arrangement, permit flow in one direction only. This protects upstream components against corrosive propellant vapors and prevents hypergolic action due to backflow from the propellant tanks.



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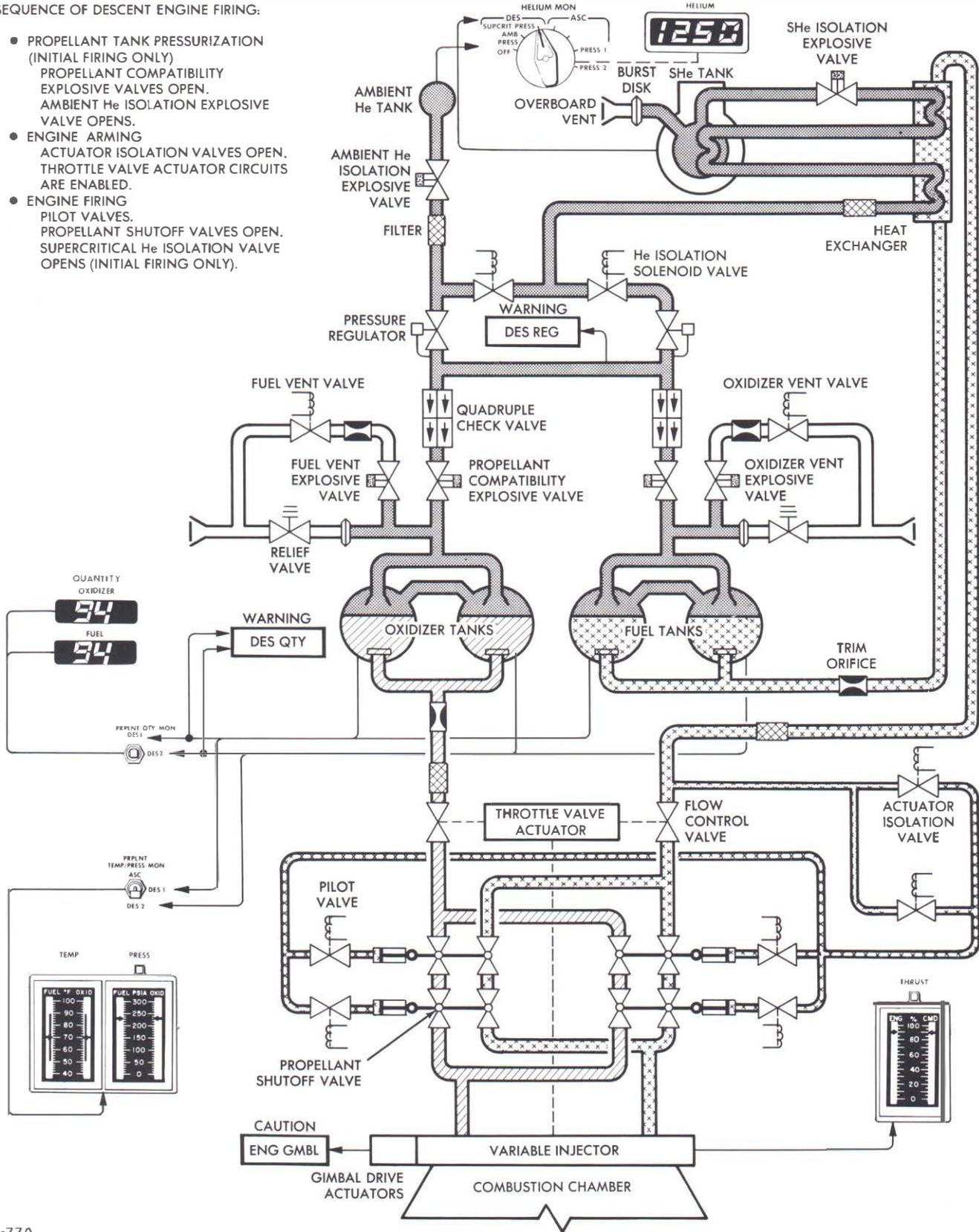
R-76

Descent Propulsion Control Diagram

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SEQUENCE OF DESCENT ENGINE FIRING:

- PROPELLANT TANK PRESSURIZATION (INITIAL FIRING ONLY)
 PROPELLANT COMPATIBILITY EXPLOSIVE VALVES OPEN.
 AMBIENT He ISOLATION EXPLOSIVE VALVE OPENS.
- ENGINE ARMING
 ACTUATOR ISOLATION VALVES OPEN.
 THROTTLE VALVE ACTUATOR CIRCUITS ARE ENABLED.
- ENGINE FIRING
 PILOT VALVES.
 PROPELLANT SHUTOFF VALVES OPEN.
 SUPERCritical He ISOLATION VALVE OPENS (INITIAL FIRING ONLY).



R-77A

Descent Propulsion Flow Diagram



After initial pressurization, supercritical helium is used to pressurize the propellants. The supercritical helium tank is isolated by an explosive valve, which is automatically fired 1.3 seconds after the descent engine is started. The time delay prevents the supercritical helium from entering the fuel/helium heat exchanger until propellant flow is established so that the fuel cannot freeze in the heat exchanger. After the explosive valve opens, the supercritical helium enters the two-pass fuel/helium heat exchanger where it is slightly warmed by the fuel. The helium then flows back into a heat exchanger in the supercritical helium tank where it increases the temperature of the supercritical helium in the tank, causing a pressure rise and ensuring continuous expulsion of helium throughout the entire period of operation. Finally, the helium flows through the second loop of the fuel/helium heat exchanger where it is heated to operational temperature before it is regulated and routed to the propellant tanks.

The system that reduces the helium pressure consists of two parallel, redundant regulators. If one pressure regulator fails, the astronauts close the malfunctioning line and open the redundant line, to restore normal propellant tank pressurization.

Each propellant tank is protected against overpressurization by a relief valve, which opens at approximately 260 psia and reseats after overpressurization is relieved. A thrust neutralizer prevents the gas from generating unidirectional thrust. Each relief valve is paralleled by two series-connected vent valves, which are operated by panel switches. After landing, the astronauts relieve pressure buildup in the tanks, caused by rising temperatures, to prevent uncontrolled venting through the relief valves. The fuel and oxidizer fumes are vented separately; supercritical helium is vented at the same time.

PROPELLANT FEED SECTION

The descent section propellant supply is contained in two fuel tanks and two oxidizer tanks. Each pair of like propellant tanks is manifolded into a common delivery line.

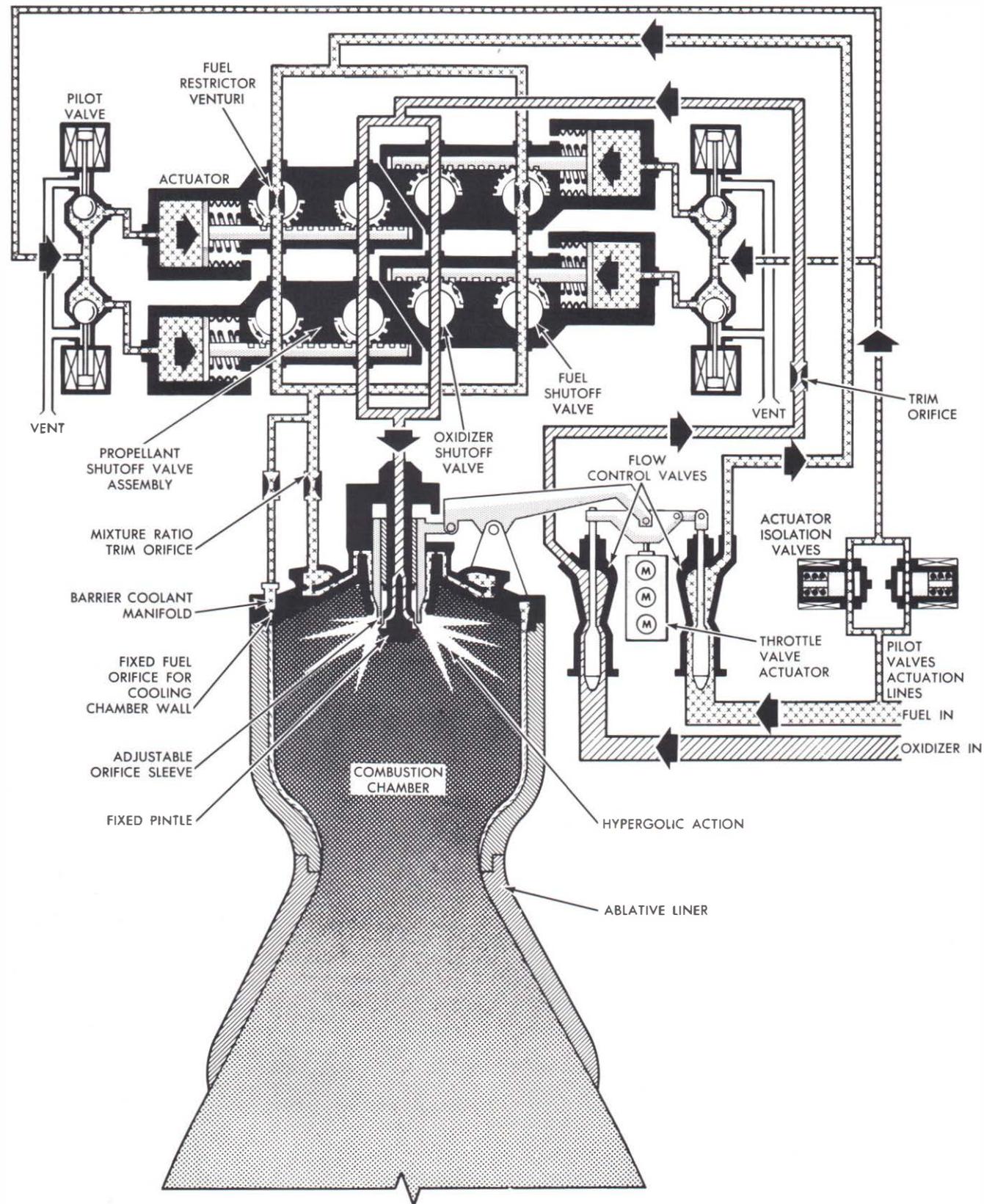
Pressurized helium, acting on the surface of the propellant, forces the fuel and oxidizer into the delivery lines through a propellant retention device that maintains the propellant in the lines during negative-g acceleration. The oxidizer is piped directly to the engine assembly; the fuel circulates through the fuel/helium heat exchanger before it is routed to the engine assembly. Each delivery line contains a trim orifice and a woven, stainless-steel-wire-mesh filter. The trim orifices provide engine inlet pressure of approximately 222 psia at full throttle position. The filters prevent debris, originating at the explosive valves or in the propellant tanks, from contaminating downstream components.

ENGINE ASSEMBLY

The descent engine is mounted in the center compartment of the descent stage cruciform. Fuel and oxidizer entering the engine assembly are routed through flow control valves to the propellant shutoff valves. A total of eight propellant shutoff valves are used; they are arranged in series-parallel redundancy, four in the fuel line and four in the oxidizer line. The series redundancy ensures engine shutoff, should one valve fail to close. The parallel redundancy ensures engine start, should one valve fail to open.

To prevent rough engine starts, the engine is designed to allow the oxidizer to reach the injector first. The propellants are then injected into the combustion chamber, where hypergolic action occurs.

The propellant shutoff valves are actuator operated. The actuation line branches off the main fuel line at the engine inlet and passes through the parallel-redundant actuator isolation valves to four solenoid-operated pilot valves. From the pilot valves, the fuel enters the hydraulically operated actuators, which open the propellant shutoff valves. The actuator pistons are connected to rack-and-pinion linkages that rotate the balls of the shutoff valves 90° to the open position. The



R-78

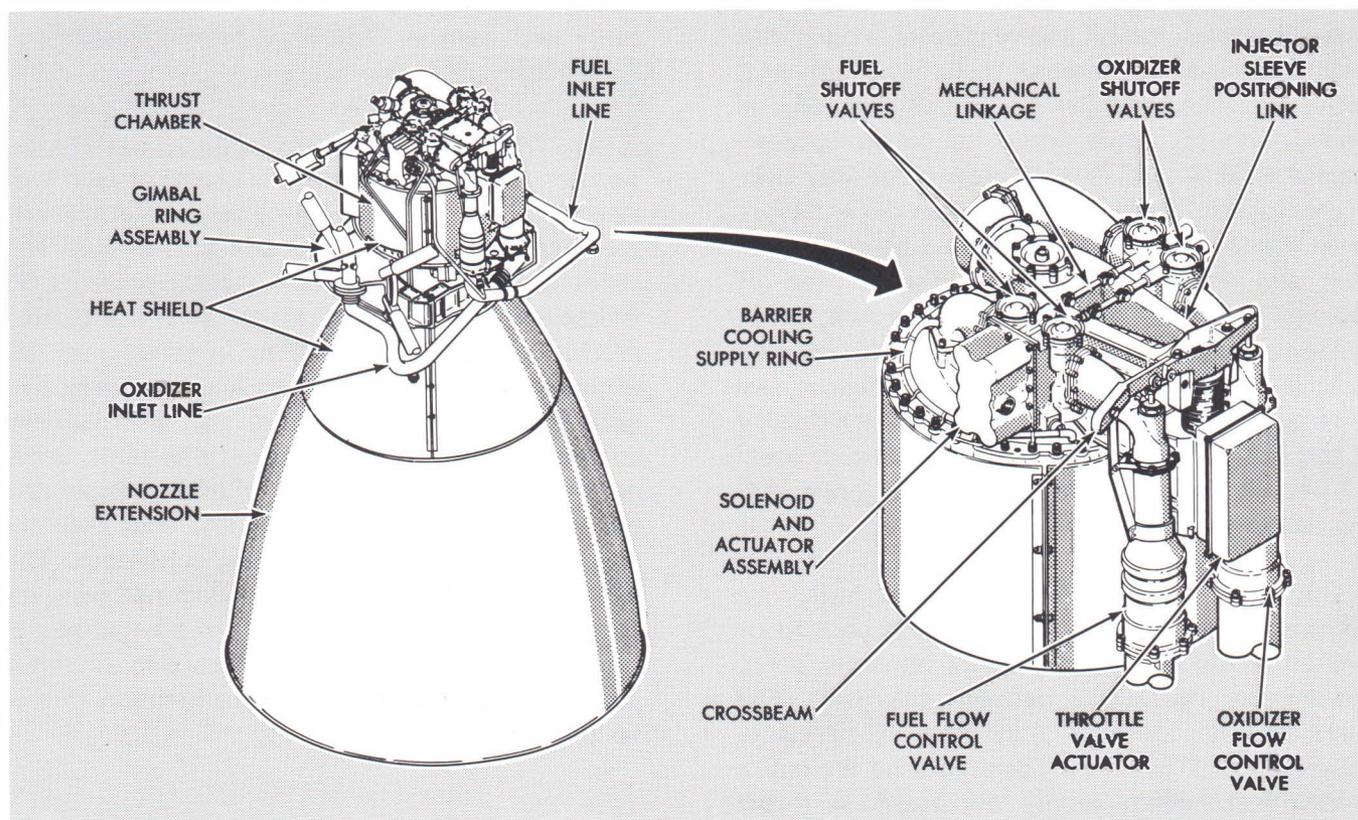
Descent Engine Flow Diagram

actuator isolation valves open when the astronauts arm the descent engine. When an engine-on command is initiated, the four pilot valves open simultaneously, permitting the actuation fuel to open the propellant shutoff ball valves, thus routing fuel and oxidizer to the combustion chamber.

The flow control valves, in conjunction with the adjustable orifice sleeve in the injector, control the descent engine thrust. At full throttle, and during the momentary transition from full throttle to the 65% range, throttling takes place primarily in the injector and, to a lesser degree, in the flow control valves. Below the 65% thrust level, the propellant-metering function is entirely controlled by the flow control valves. The flow control valves and

the injector sleeve are adjusted simultaneously by a mechanical linkage. Throttling is controlled by the throttle valve actuator, which positions the linkage in response to electrical input signals.

The fuel and oxidizer are injected into the combustion chamber at velocities and angles compatible with variations in weight flow. The fuel is emitted in the form of a thin cylindrical sheet; the oxidizer sprays break up the fuel stream and establish the injection pattern at all thrust settings. Some fuel is tapped off upstream of the injector and is routed through a trim orifice into the barrier coolant manifold. From here, it is sprayed against the combustion chamber wall through fixed orifices, maintaining the chamber wall at an acceptable temperature.



R-79

Descent Engine and Head End Assembly

DESCENT PROPULSION SECTION EQUIPMENT

SUPERCRITICAL HELIUM TANK

Supercritical helium is stored at a density approximately eight times that of ambient helium. Because heat transfer from the outside to the inside of the cryogenic storage vessel causes a gradual increase in pressure (approximately 10 psi per hour maximum), the initial loading pressure is planned so that the supercritical helium will be maintained within a safe pressure/time envelope throughout the mission.

The supercritical helium tank is double walled; it consists of an inner spherical tank and an outer jacket. The void between the tank and the jacket is filled with aluminized mylar insulation and evacuated to minimize ambient heat transfer into the tank. The vessel has fill and vent ports, a burst disk assembly, and an internal helium/helium heat exchanger. The inner tank is initially vented and loaded with cryogenic liquid helium at approximately 8° R (-452° F) at a pressure of 14.7 psia. The cryogenic liquid becomes supercritical helium when the fill sequence is completed by closing the vent and introducing a high-pressure head of gaseous helium. As the high-pressure, low-temperature gas is introduced, the density and pressure of the cryogenic liquid helium are increased. At the end of pressurization, the density of the stored supercritical helium is approximately 8.7 pounds per cubic foot and the final pressure is approximately 178 psi.

The burst disk assembly prevents hazardous overpressurization within the vessel. It consists of two burst disks in series, with a normally open, low-pressure vent valve between the disks. The burst disks are identical; they burst at a pressure between 1,881 and 1,967 psid to vent the entire supercritical helium supply overboard. A thrust neutralizer at the outlet of the downstream burst disk diverts the escaping gas into opposite directions to prevent unidirectional thrust generation. The vent valve prevents low-pressure buildup between the burst disks if the upstream burst disk leaks slightly. The valve is open at pressures below 150 psia; it closes when the pressure exceeds 150 psia.

FUEL/HELIUM HEAT EXCHANGER

Fuel is routed directly from the fuel tanks to the two-pass fuel/helium heat exchanger, where heat from the fuel is transferred to the supercritical helium. The helium reaches operating temperature after flowing through the second heat exchanger passage. The fuel/helium heat exchanger is of finned tube construction; the first and second helium passages are in parallel crossflow with respect to the fuel. Helium flows in the tubes and fuel flows in the outer shell across the bundle of staggered, straight tubes.

PROPELLANT STORAGE TANKS

The propellant supply is contained in four cylindrical, spherical-ended titanium tanks of identical size and construction. Two tanks contain fuel; the other two, oxidizer. Each pair of tanks containing like propellants is interconnected at the top and all propellant lines downstream of the tanks contain trim orifices, to ensure balanced propellant flow. A diffuser at the helium inlet port (top) of each tank distributes the pressurizing helium uniformly into the tank. An antivortex device in the form of a series of vanes, at each tank outlet, prevents the propellant from swirling into the outlet port, thus precluding inadvertent helium ingestion into the engine. Each tank outlet also has a propellant retention device (negative-g can) that permits unrestricted propellant flow from the tank under normal pressurization, but blocks reverse propellant flow (from the outlet line back into the tank) under zero-g or negative-g conditions. This arrangement ensures that helium does not enter the propellant outlet line as a result of a negative-g or zero-g condition or propellant vortexing; it eliminates the possibility of engine malfunction due to helium ingestion.

PROPELLANT QUANTITY GAGING SYSTEM

The propellant quantity gaging system enables the astronauts to monitor the quantity of propellants remaining in the four descent tanks. The propellant quantity gaging system consists of four quantity-sensing probes with low-level sensors (one for each tank), a control unit, two quantity indica-

tors that display remaining fuel and oxidizer quantities, a switch that permits the astronauts to select a set of tanks (one fuel and one oxidizer) to be monitored, and a descent propellant quantity low-level warning light. The low-level sensors provide a discrete signal to cause the warning light to go on when the propellant level in any tank is down to 9.4 inches (equivalent to 5.6% propellant remaining). When this warning light goes on, the quantity of propellant remaining is sufficient for only 2 minutes of engine burn at hover thrust (approximately 25%).

PROPELLANT SHUTOFF VALVE ASSEMBLIES

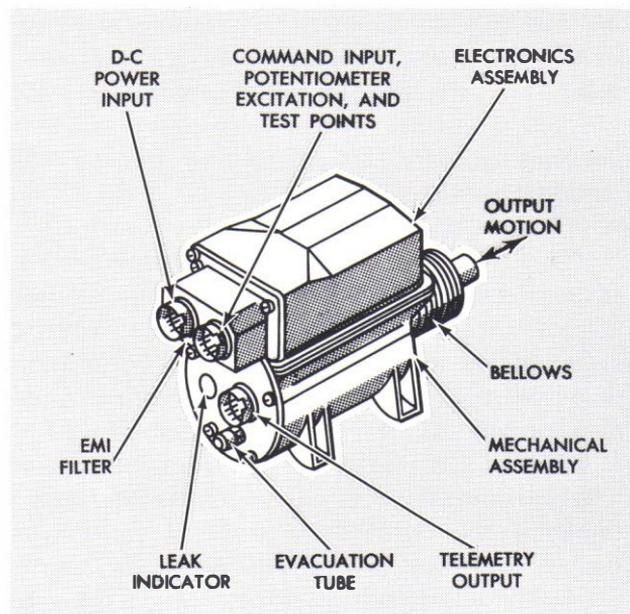
Each of the four propellant shutoff valve assemblies consists of a fuel shutoff valve, an oxidizer shutoff valve, a pilot valve, and a shutoff valve actuator. The shutoff valve actuator and the fuel shutoff valve are in a common housing. The four solenoid-operated pilot valves control the fuel that is used as actuation fluid to open the fuel shutoff valves. The oxidizer shutoff valve is actuated by a mechanical linkage driven from the fuel shutoff valve. When the pilot valves are opened, the actuation fluid flow (at approximately 110 psia) acts against the spring-loaded actuator plunger, opening the shutoff valves. When the engine-firing signal is removed, the pilot valves close and seal off the actuation fluid. The propellant shutoff valves are closed by the return action of the actuator piston springs, which expels the fuel entrapped in the cylinders and valve passages through the pilot valve vent port.

The propellant shutoff valves are ball valves. The ball element operates against a spring-loaded soft seat to ensure positive sealing when the valve is closed. The individual valves are rotated by a rack-and-pinion-gear arrangement, which translates the linear displacement of the pistons in the shutoff valve actuators.

THROTTLE VALVE ACTUATOR

The throttle valve actuator is a linear-motion electromechanical servoactuator which moves the throttle linkage in response to an electrical input

command. Moving the throttle linkage simultaneously changes the position of the flow control valve pintles and the injector sleeve, thereby varying the amount of fuel and oxidizer metered into the engine and changing the magnitude of engine thrust. The throttle valve actuator is located between the fuel and oxidizer flow control valves; its housing is rigidly attached to the engine head end and its output shaft is attached to the throttle linkage.



R-80

Throttle Valve Actuator

The actuator is controlled by three redundant electronic channels, which power three d-c torque motors. The motor shafts supply the input to a ball screw, which converts rotary motion to the linear motion of the throttle valve actuator output shaft. All mechanical moving parts of the actuator are within a hermetically sealed portion of the unit, pressurized to 0.25 psia with a 9 to 1 mixture of nitrogen and helium. A leak indicator in the cover provides visual evidence of loss of vacuum within the unit. Five potentiometers are ganged to the torque motor shaft through a single-stage planetary reduction gear. Three of these potentiometers supply position feedback information to the three motor amplifier channels, one to each channel. The other two potentiometers provide throttle actuator shaft position data for telemetry to MSFN. The redundancy within the throttle valve actuator

ensures that failure of any electrical component will not cause the actuator to fail. The throttle valve actuator also provides a fail-safe system in the event selective malfunctions external to the throttle valve actuator occur. If either the primary 28-volt d-c power or the command voltage is lost, the throttle valve actuator causes the descent engine to thrust automatically at full throttle.

FLOW CONTROL VALVES

The oxidizer and fuel flow control valves are on the side of the engine, immediately downstream of the propellant inlet lines. They are secured to the throttle valve actuator mounting bracket. The flow control valve pintle assemblies are mechanically linked to the throttle valve actuator by a crossbeam.

The flow control valves are nonredundant cavitating venturis with movable pintle sleeves. Engine throttling is initiated by an electrical signal to the throttle valve actuator, commanding an increase or decrease in engine thrust. Operation of the throttle valve actuator changes the position of the pintles in the flow control valves. This axial movement of the pintles decreases or increases the pintle flow areas to control propellant flow rate and thrust. Below an approximate 70% thrust setting, flow through the valves cavitates, and hydraulically uncouples the propellant transfer system (and thereby, the flow rate) from variations in combustion chamber pressure. In the throttling range between 65% and 92.5% thrust, operation of the cavitating venturis of the flow control valves becomes unpredictable and may cause an improper fuel-oxidizer mixture ratio, which will result in excessive engine erosion and early combustion chamber burn-through.

VARIABLE-AREA INJECTOR

The variable-area injector consists of a pintle assembly, drive assembly, and manifold assembly. The pintle assembly introduces the propellant uniformly into the combustion chamber. The drive assembly has a twofold function: first, it serves as a passage for conducting the oxidizer into the pintle assembly; second, it contains the

bearing and sealing components that permit accurate positioning of the injector sleeve. The injector sleeve varies the injection area so that near-optimum injector pressure drops and propellant velocities are maintained at each thrust level. The primary function of the manifold assembly is to distribute the fuel uniformly around the outer surface of the sleeve. Fuel enters the manifold assembly at two locations and is passed through a series of distribution plates near the outer diameter of the assembly.

At the center of the manifold, the fuel passes through a series of holes before it is admitted into a narrow passage formed by the manifold body and a faceplate. The passage smooths out gross fuel discontinuities and assists in cooling the injector face. The fuel then passes onto the outer surface of the sleeve, past a fuel-metering lip. The fuel is injected in the form of a hollow cylinder so that it reaches the impingement zone with a uniform circumferential velocity profile and without atomizing, at all flow rates. The oxidizer is injected through a double-slotted sleeve so that it forms a large number of radial filaments. Each filament partially penetrates the fuel cylinder and is enfolded by fuel in such a way that little separation of oxidizer and fuel can occur. For given propellant densities, overall mixture ratio, and injector geometry, there is a range of propellant injection velocity ratios that result in maximum mixture ratio uniformity throughout the resultant expanding propellant spray. When they occur, the liquid-phase reactions generate gas and vapor that atomize and distribute the remaining liquid oxidizer and fuel uniformly in all directions, resulting in high combustion efficiency.

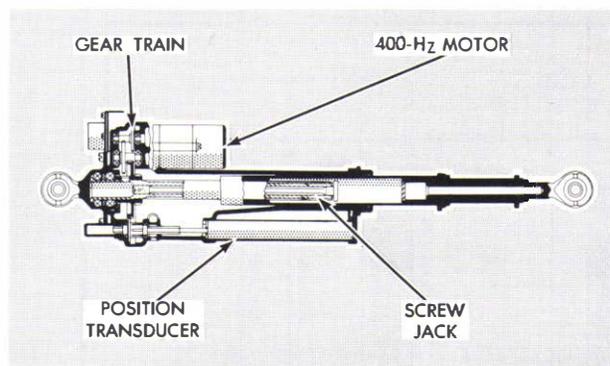
COMBUSTION CHAMBER AND NOZZLE EXTENSION

The combustion chamber consists of an ablative-cooled chamber section, nozzle throat, and nozzle divergent section. The ablative sections are enclosed in a continuous titanium shell and jacketed in a thermal blanket composed of aluminized nickel foil and glass wool. A seal prevents leakage between the combustion chamber and nozzle extension.

The nozzle extension is a radiation-cooled, crushable skirt; it can collapse a distance of 28 inches on lunar impact so as not to affect the stability of the LM. The nozzle extension is made of columbium coated with aluminide. It is attached to the combustion chamber case at a nozzle area ratio of 16 to 1 and extends to an exit area ratio of 54.0 to 1.

GIMBAL RING AND GIMBAL DRIVE ACTUATORS

The gimbal ring is located at the plane of the combustion chamber throat. It consists of a rectangular beam frame and four trunnion sub-assemblies. The gimbal drive actuators under control of the descent engine control assembly, tilt the descent engine in the gimbal ring along the pitch and roll axes so that the engine thrust vector goes through the LM center of gravity. One actuator controls the pitch gimbal; the other, the roll gimbal. The gimbal drive actuators consist of a single-phase motor, a feedback potentiometer, and associated mechanical devices. They can extend or retract 2 inches from the mid-position to tilt the descent engine a maximum of 6° along the Y-axis and Z-axis.



R-81

Gimbal Drive Actuator

ASCENT ENGINE OPERATION AND CONTROL

Shortly before initial ascent engine use, the astronauts fire explosive valves to pressurize the ascent propulsion section. The ascent engine, like the descent engine, requires manual arming before

it can be fired. When the astronauts arm the ascent engine, a shutoff command is sent to the descent engine. Then, enabling signals are sent to the ascent engine control circuitry to permit a manual or computer-initiated ascent engine start. For manual engine on and off commands, the astronauts push the same start and stop push-buttons used for the descent engine. For automatic commands, the stabilization and control assemblies in the GN&CS provide sequential control of LM staging and ascent engine on and off commands. The initial ascent engine firing — whether for normal lift-off from the lunar surface or in-flight abort — is a fire-in-the-hole (FITH) operation; that is, the engine fires while the ascent and descent stages are still mated although no longer mechanically secured to each other. If, during the descent trajectory, an abort situation necessitates using the ascent engine to return to the CSM, the astronauts abort stage sequence. This results in an immediate descent engine shutdown followed by a time delay to ensure that the engine has stopped thrusting before staging occurs. The next command automatically pressurizes the ascent propellant tanks, after which the staging command is issued. This results in severing of hardware that secures the ascent stage to the descent stage and the interconnecting cables. The ascent engine fire command completes the abort stage sequence.

ASCENT PROPULSION SECTION FUNCTIONAL DESCRIPTION

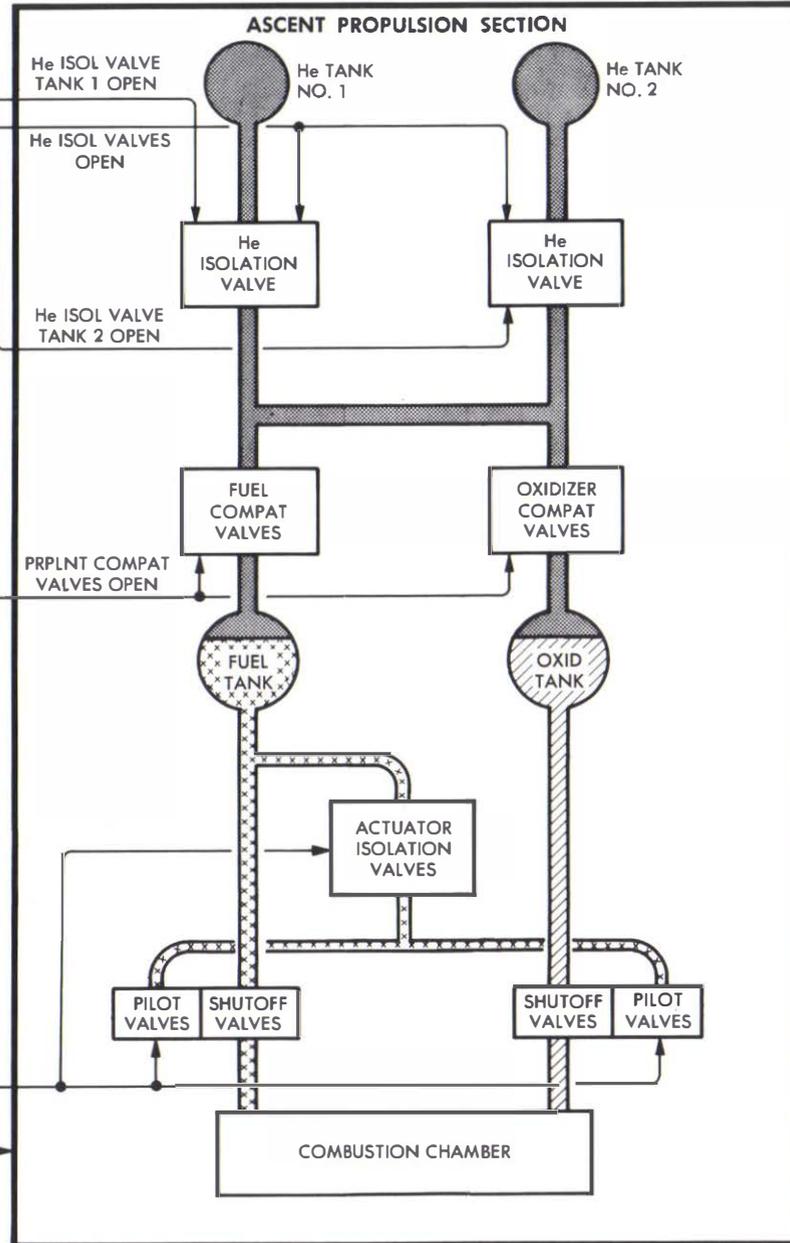
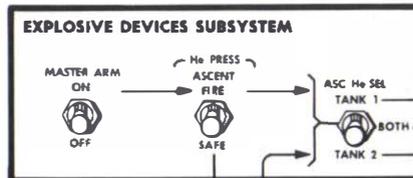
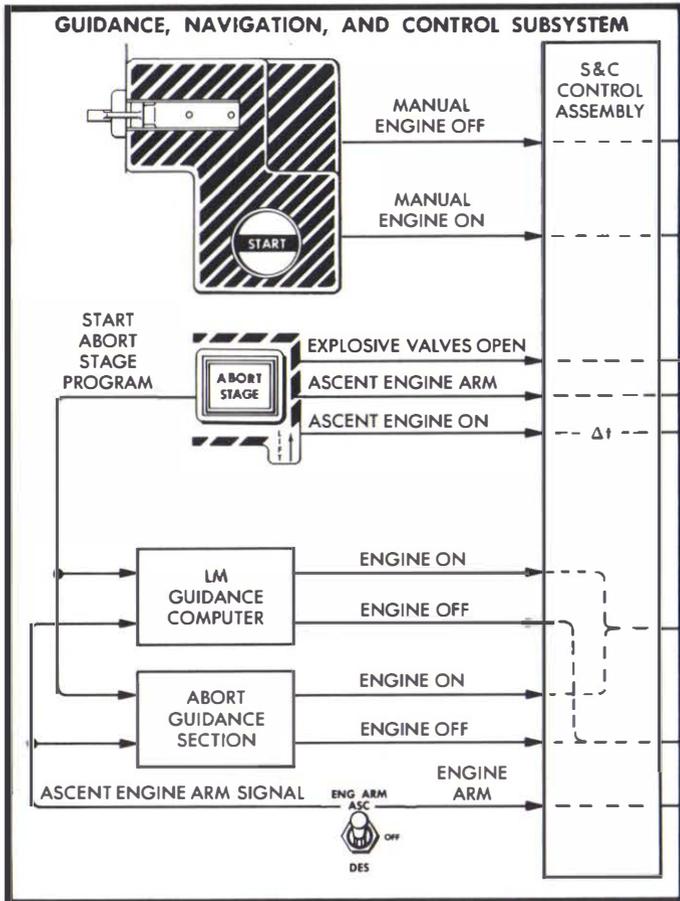
The ascent propulsion section consists of a constant-thrust, pressure-fed rocket engine, one fuel and one oxidizer tank, two helium tanks, and associated propellant feed and helium pressurization components. The engine develops 3,500 pounds of thrust in a vacuum, it can be shut down and restarted, as required by the mission. Like the descent propulsion section, the ascent propulsion section can functionally be subdivided into a pressurization section, a propellant feed section, and an engine assembly.

PRESSURIZATION SECTION

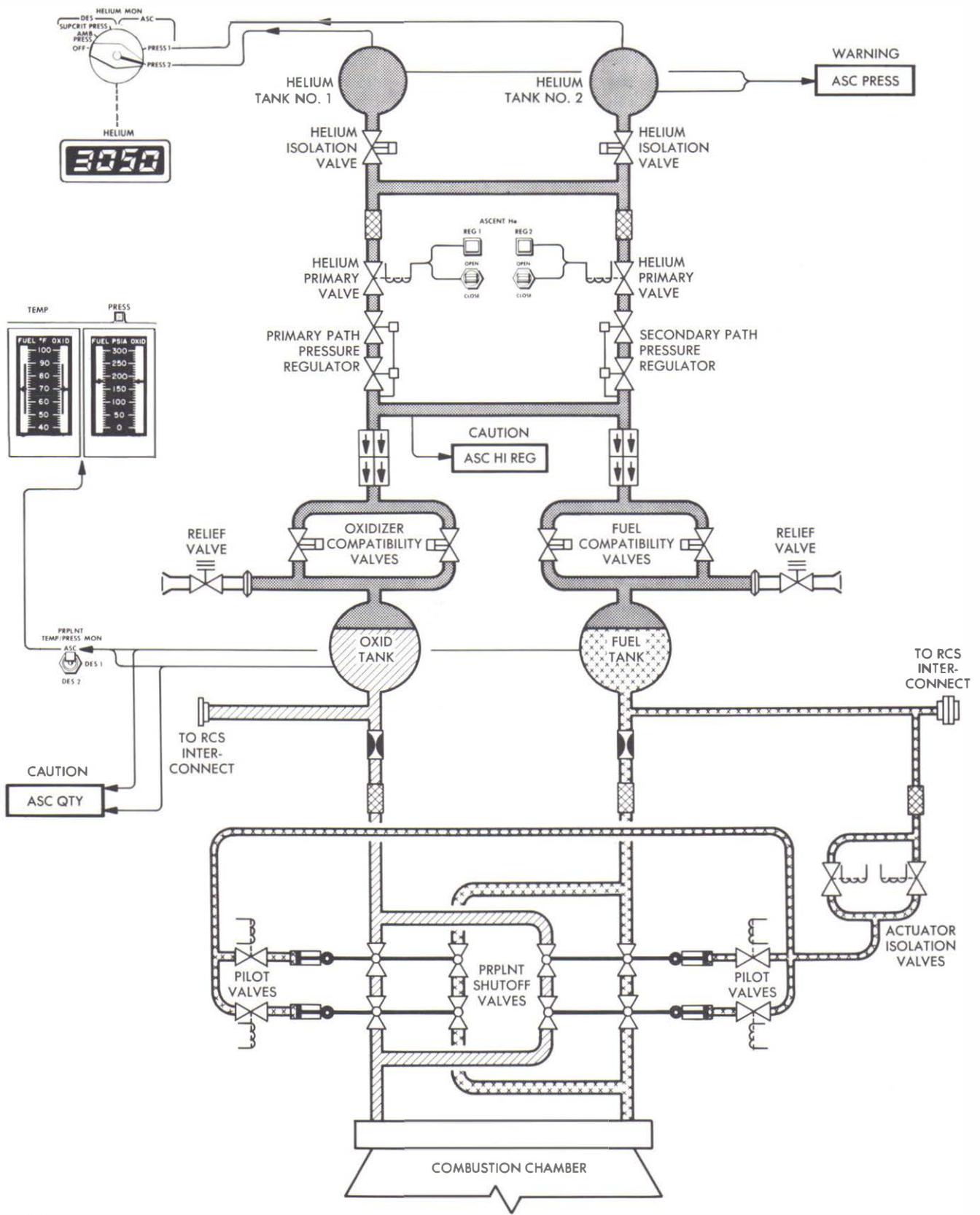
Before initial ascent engine start, the propellant tanks must be fully pressurized with gaseous helium. This helium is stored in two identical

SEQUENCE OF ASCENT ENGINE FIRING:

- PROPELLANT TANK PRESSURIZATION (INITIAL FIRING ONLY)
ALL EXPLOSIVE VALVES OPEN
- ENGINE ARMING
ACTUATOR ISOLATION VALVES ARE ENABLED
- ENGINE FIRING
ACTUATOR ISOLATION VALVES OPEN.
PILOT VALVES OPEN.
PROPELLANT SHUTOFF VALVES OPEN.



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R-83A

Ascent Propulsion Flow Diagram



tanks at a nominal pressure of 3,050 psia at a temperature of +70° F. An explosive valve at the outlet of each helium tank prevents the helium from leaving the tanks until shortly before initial ascent engine use. To open the helium paths to the propellant tanks, the astronauts normally fire six explosive valves simultaneously: two helium isolation valves and four propellant compatibility valves (two connected in parallel for redundancy in each pressurization path). Before firing the explosive valves, the astronauts check the pressure in each helium tank. If one tank provides an unusually low reading (indicating leakage), they can exclude the appropriate helium isolation explosive valve from the fire command. This will isolate the faulty tank from the pressurization system and will prevent helium loss through the leaking tank via the helium interconnect line.

Downstream of the interconnect line, the helium flows into the primary and secondary regulating paths, each containing a filter, a normally open solenoid valve and two series-connected pressure regulators. Two downstream regulators are set to a slightly higher output pressure than the upstream regulators; the regulator pair in the primary flow path produces a slightly higher output than the pair in the secondary (redundant) flow path. This arrangement causes lockup of the regulators in the redundant flow path after the propellant tanks are pressurized, while the upstream regulator in the primary flow path maintains the propellant tanks at their normal pressure of 184 psia. If either regulator in the primary flow path fails closed, the regulators in the redundant flow path pressurize the propellant tanks. If an upstream regulator fails open, control is obtained through the downstream regulator in the same flow path. If both regulators in the same flow path fail open, pressure in the helium manifold increases above the acceptable limit of 220 psia, causing a caution light to go on. This advises the astronauts that they must identify the failed-open regulators and close the helium isolation solenoid valve in the malfunctioning flow path so that normal pressure can be restored.

Downstream of the regulators, a manifold routes the helium into two flow paths: one path leads to the oxidizer tank; the other, to the fuel tank. A quadruple check valve assembly, a series-

parallel arrangement in each path, isolates the upstream components from corrosive propellant vapors. The check valves also safeguard against possible hypergolic action in the common manifold, resulting from mixing of propellants or fumes flowing back from the propellant tanks. Immediately upstream of the fuel and oxidizer tanks, each helium path contains a burst disk and relief valve assembly to protect the propellant tanks against overpressurization. This assembly vents pressure in excess of approximately 245 psia and reseals the flow path after overpressurization is relieved. A thrust neutralizer eliminates unidirectional thrust generated by the escaping gas.

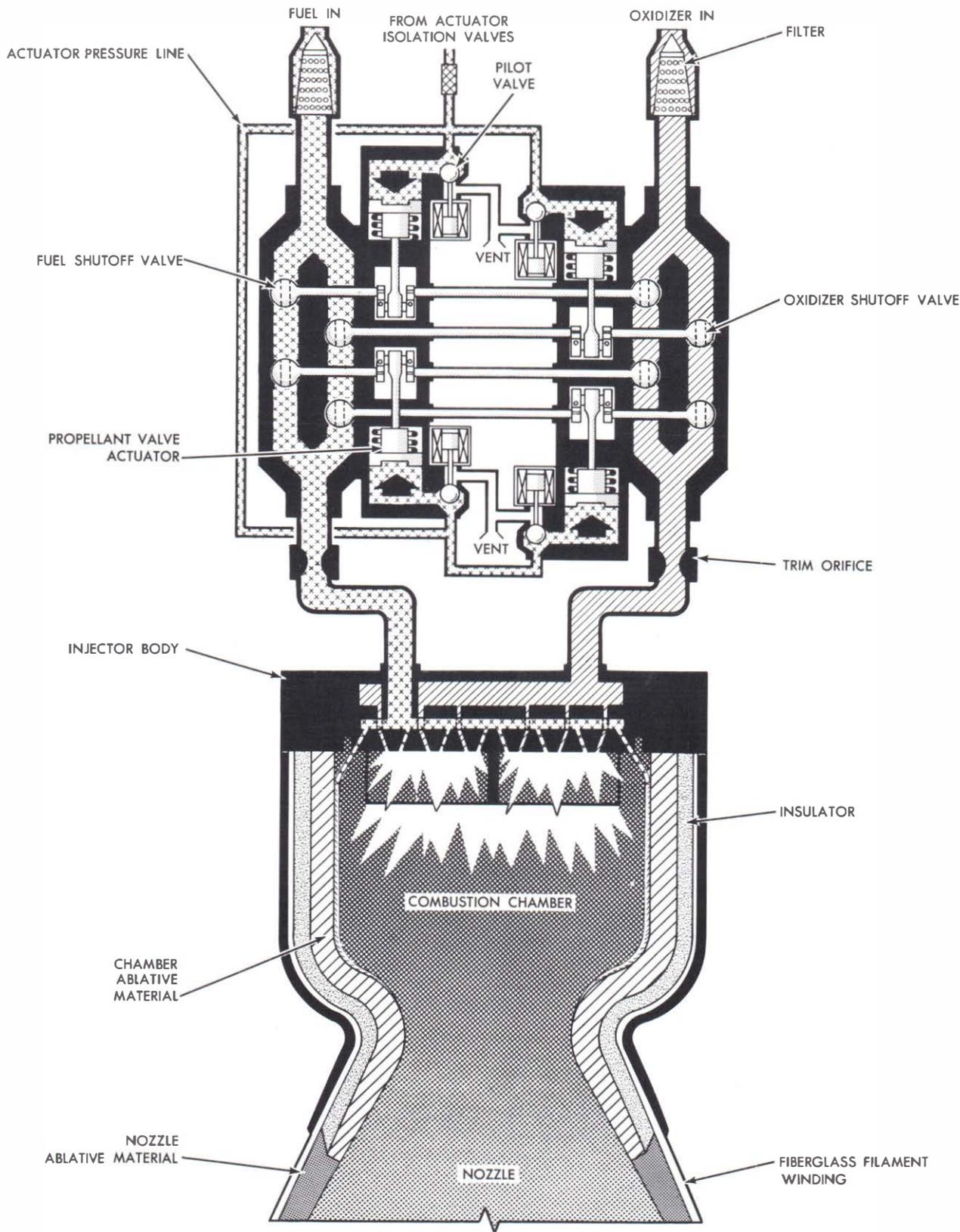
PROPELLANT FEED SECTION

The ascent propulsion section has one oxidizer tank and one fuel tank. Transducers in each tank enable the astronauts to monitor propellant temperature and ullage pressure. A caution light, activated by a low-level sensor in each tank warn the astronauts when the propellant supply has diminished to an amount sufficient for only 10 seconds of engine operation.

Helium flows into the top of the propellant tanks, where diffusers uniformly distribute it throughout the ullage space. The outflow from each propellant tank divides into two paths. The primary path routes each propellant through a trim orifice and a filter to the propellant shutoff valves in the engine assembly. The trim orifice provides an engine inlet pressure of 170 psia for proper propellant use. The secondary path connects the ascent propellant supply to the RCS. This interconnection permits the RCS to burn ascent propellants, providing the ascent tanks are pressurized and the ascent or descent engine is operating when the RCS thrusters are fired. A line branches off the RCS interconnect fuel path and leads to two parallel actuator isolation solenoid valves. This line routes fuel to the engine pilot valves that actuate the propellant shutoff valves.

ENGINE ASSEMBLY

The ascent engine is installed in the midsection of the ascent stage; it is tilted so that its centerline is 1.5° from the X-axis, in the +Z-direction.



R-84

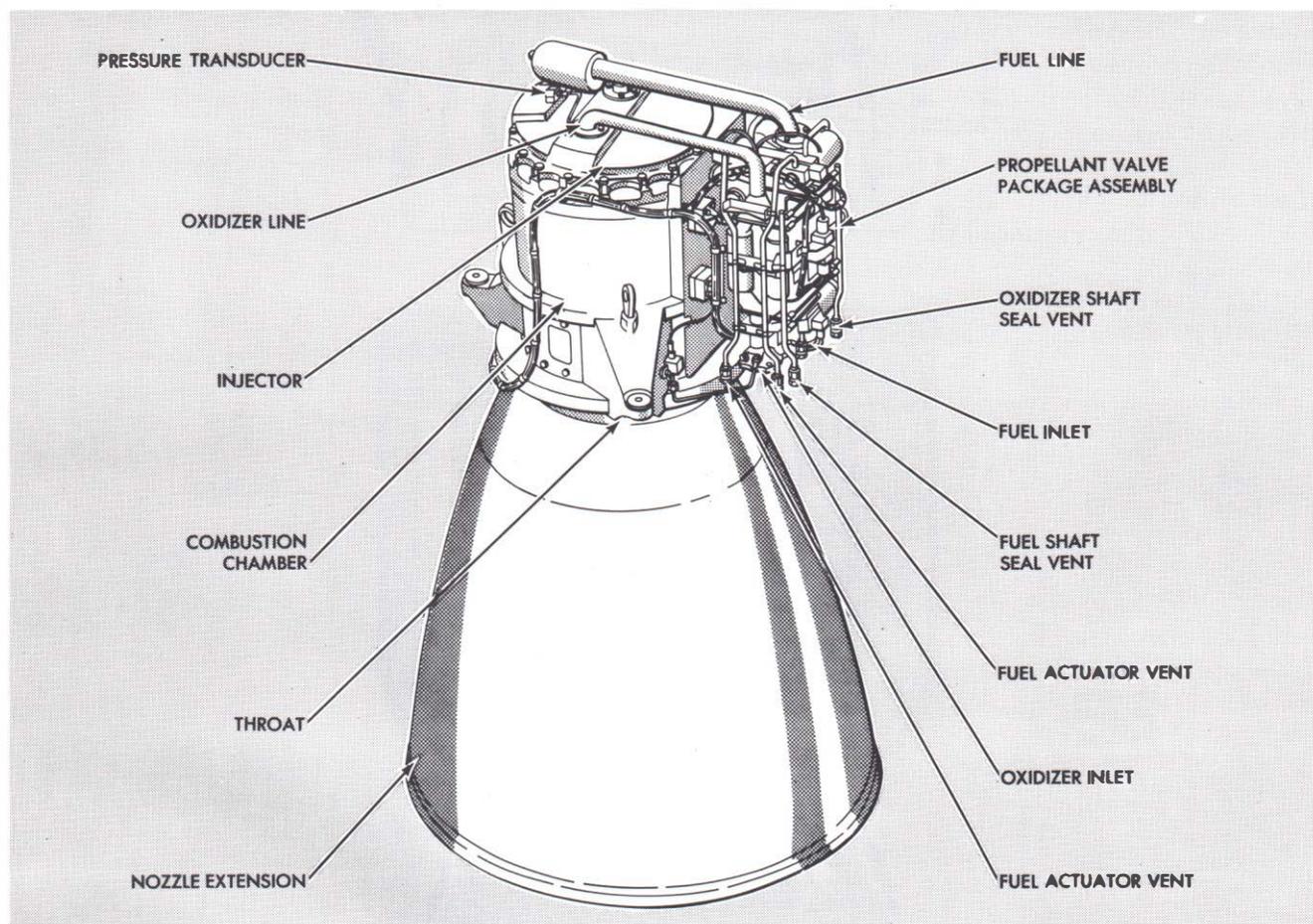
Ascent Engine Flow Diagram

Fuel and oxidizer entering the engine assembly are routed, through the filters, propellant shutoff valves, and trim orifices, to the injector. The propellants are injected into the combustion chamber, where the hypergolic ignition occurs. A separate fuel path leads from the actuator isolation valves to the pilot valves. The fuel in this line enters the actuators, which open the propellant shutoff valves.

Propellant flow into the combustion chamber is controlled by a valve package assembly, trim orifices, and the injector. The valve package assembly is similar to the propellant shutoff valve assemblies in the descent engine. The eight pro-

pellant shutoff valves are arranged in series-parallel redundant fuel-oxidizer pairs. Each pair is operated from a single crankshaft by its actuator.

When an engine-start command is received, the two actuator isolation valves and the four pilot valves open simultaneously. Fuel then flows through the actuator pressure line and the four pilot valves into the actuator chambers. Hydraulic pressure extends the actuator pistons, cranking the propellant shutoff valves 90° to the fully open position. The propellants now flow through the shutoff valves and a final set of trim orifices to the injector. The orifices trim the pressure differentials of the fuel and oxidizer to determine the mixture



R-85

Ascent Engine Assembly

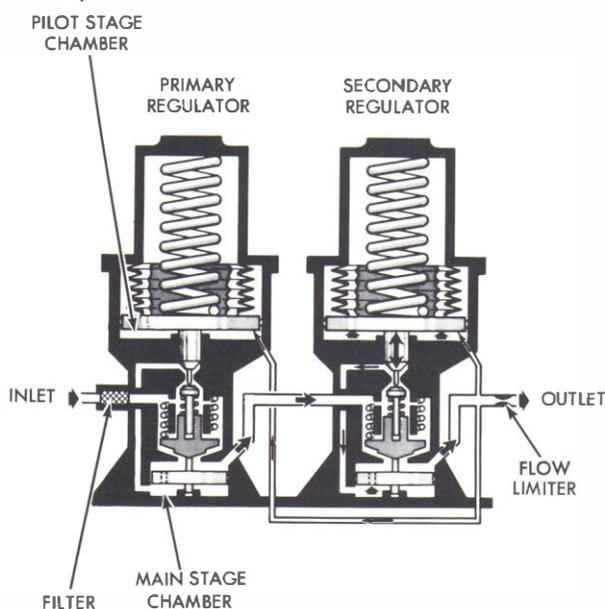
ratio of the propellants. The physical characteristics of the injector establish an oxidizer lead of approximately 50 milliseconds. This precludes the possibility of a fuel lead which could result in a rough engine start.

At engine shutdown, the actuator isolation valves are closed, preventing additional fuel from reaching the pilot valves. Simultaneously, the pilot valve solenoids are deenergized, opening the actuator ports to the overboard vents so that residual fuel in the actuators is vented into space. With the actuation fuel pressure removed, the actuator pistons are forced back by spring pressure, cranking the propellant shutoff valves to the closed position.

ASCENT PROPULSION SECTION EQUIPMENT

HELIUM PRESSURE REGULATOR ASSEMBLIES

Each helium pressure regulator assembly consists of two individual pressure regulators connected in series. The downstream regulator functions in the same manner as the upstream regulator; however, it is set to produce a higher outlet pressure so that it becomes a secondary unit that will only be in control if the upstream regulator (primary unit) fails open.



R-86 *Helium Pressure Regulator Assembly*

Each pressure regulator unit consists of a direct-sensing main stage and a pilot stage. The valve in the main stage is controlled by the valve in the pilot stage which senses small changes in the regulator outlet pressure and converts these changes to proportionally large changes in control pressure. A rise in outlet pressure decreases the pilot valve output, thereby reducing flow into the main stage chamber. An increase in the downstream demand causes a reduction in outlet pressure; this tends to open the pilot valve. The resultant increase in control pressure causes the main stage valve poppet to open, thus meeting the increased downstream demand.

A flow limiter at the outlet of the main stage valve of the secondary unit restricts maximum flow through the regulator assembly to 5.5 pounds of helium per minute, so that the propellant tanks are protected if the regulator fails open. The filter at the inlet of the primary unit prevents particles, which could cause excessive leakage at lockup, from reaching the regulator assembly.

PROPELLANT STORAGE TANKS

The propellant supply is contained in two spherical titanium tanks. The tanks are of identical size and construction. One tank contains fuel; the other, oxidizer. A helium diffuser at the inlet port of each tank distributes the pressurizing helium uniformly into the tank. An antivortex device (a cruciform at each tank outlet) prevents the propellant from swirling into the outlet port, precluding helium ingestion into the engine. Each tank outlet also has a propellant-retention device that permits unrestricted propellant flow from the tank under normal pressurization, but blocks reverse propellant flow (from the outlet line back into the tank) under zero-g or negative-g conditions. This arrangement ensures that helium does not enter the propellant outlet line while the engine is not firing; it eliminates the possibility of engine malfunction due to helium ingestion. A low-level sensor in each tank (approximately 4.4 inches above the tank bottom) supplies a discrete signal that causes a caution light to go on when the propellant remaining in either tank is sufficient for approximately 10 seconds of burn time (48 pounds of fuel, 69 pounds of oxidizer).

VALVE PACKAGE ASSEMBLY

At the propellant feed section/engine assembly interface, the oxidizer and fuel lines lead into the valve package assembly. The individual valves that make up the valve package assembly are in a series-parallel arrangement to provide redundant propellant flow paths and shutoff capability. The valve package assembly consists of eight propellant shutoff valves and four solenoid-operated pilot valve and actuator assemblies. Each valve assembly consists of one fuel shutoff valve and one oxidizer shutoff valve. These are ball valves that are operated by a common shaft, which is connected to its respective pilot valve and actuator assembly. Shaft seals and vented cavities prevent the propellants from coming into contact with each other. Separate overboard vent manifold assemblies drain the fuel and oxidizer that leaks past the valve seals, and the actuation fluid (fuel in the actuators when the pilot valves close), overboard. The eight shutoff valves open simultaneously to permit propellant flow to the engine while it is operating; they close simultaneously to terminate propellant flow at engine shutdown. The four nonlatching, solenoid-operated pilot valves control the actuation fluid (fuel).

INJECTOR ASSEMBLY

The injector assembly consists of the propellant inlet lines, a fuel manifold, a fuel reservoir chamber, an oxidizer manifold, and an injector orifice plate assembly. Because it takes longer to fill the fuel manifold and reservoir chamber assembly, the oxidizer reaches the combustion chamber **approximately 50 milliseconds** before the fuel, resulting in smooth engine starts. The injector orifice plate assembly is of the fixed-orifice type, which uses a baffle and a series of perimeter slots (acoustic cavities) for damping induced combustion disturbances. The baffle is

Y-shaped, with a 120° angle between each blade. The baffle is cooled by the propellants, which subsequently enter the combustion chamber through orifices on the baffle blades. The injector face is divided into two combustion zones: primary and baffle. The primary zone uses impinging doublets (one fuel and one oxidizer), which are spaced in concentric radial rings on the injector face. The baffle zone (1.75 inches below the injector face) uses impinging doublets placed at an angle to the injector face radius. The combustion chamber wall is cooled by spraying fuel against it through canted orifices, spaced around the perimeter of the injector. The nominal temperature of the propellant is +70° F as it enters the injector; with the fuel temperature within 10° of the oxidizer temperature. The temperature range at engine start may be +40° to **+500° F.**

COMBUSTION CHAMBER ASSEMBLY AND NOZZLE EXTENSION

The combustion chamber assembly consists of the engine case and mount assembly and an ablative material (plastic) assembly, which includes the nozzle extension. The two assemblies are bonded and locked together to form an integral unit. The plastic assembly provides ablative cooling for the combustion chamber; it consists of the chamber ablative material, the chamber insulator, the nozzle extension ablative material, and a structural filament winding. The chamber ablative material extends from the injector to an expansion ratio of 4.6. The chamber insulator, between the ablative material and the case, maintains the chamber skin temperature within design requirements. The ablative material of the nozzle extension extends from the expansion ratio of 4.6 to 45.6 (exit plane) and provides ablative cooling in this region. The structural filament winding provides structural support for the plastic assembly and ties the chamber and nozzle extension sections together.