quantity-sensing probes with low-level sensors (one for each tank), a control unit, two quantity indicators 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%).

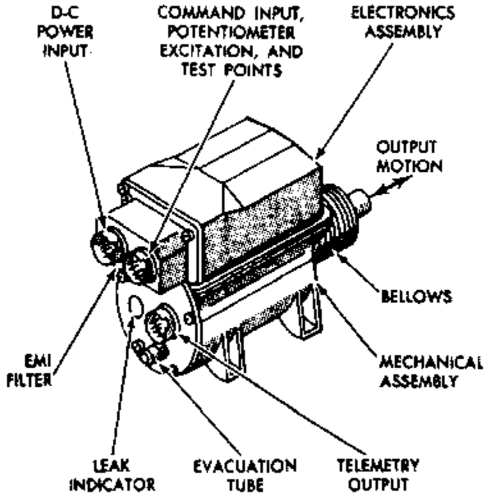
PROPELLANT SHUTOFF VALVE ASSEMBLIES

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 200 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 60% 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 smoothes 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 cumbustion efficiency.

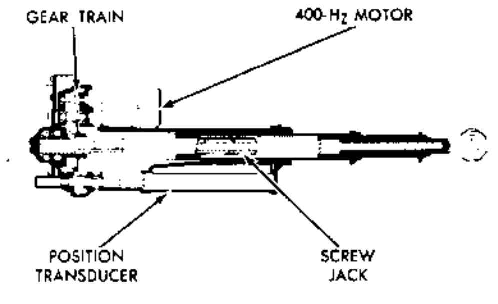
COMBUSTION CHAMBER AND NOZZLE EXTENSION

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 47.4 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 subassemblies. 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

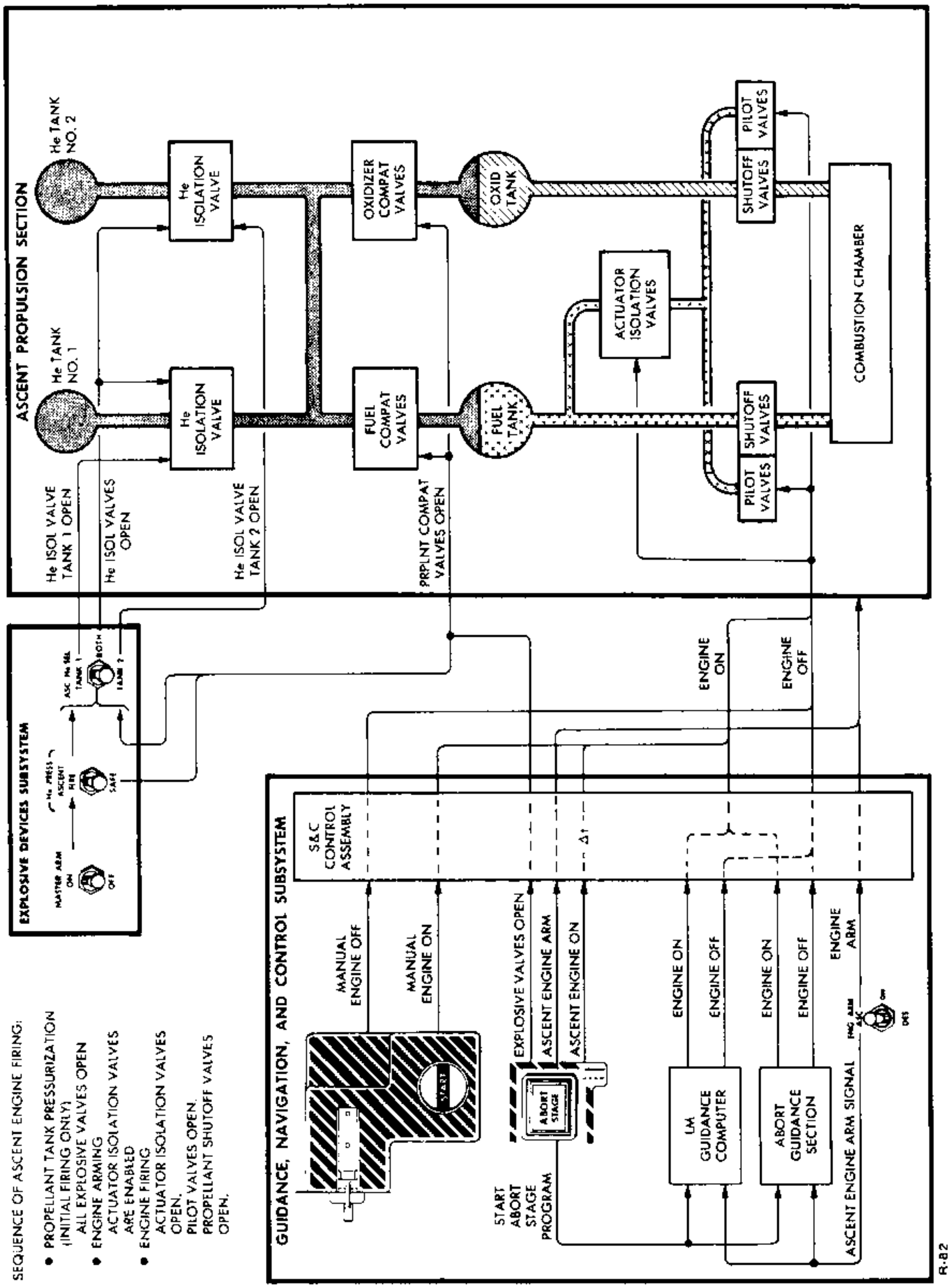
Shortly before initial ascent engine use, the astronauts fire explosive valves to pressurize the ascent propulsion section. The ascent engine, like the descent engine, requires manual arming before it can be fired. When the astronauts arm the ascent engine, a shutoff command is sent to the descent engine. 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

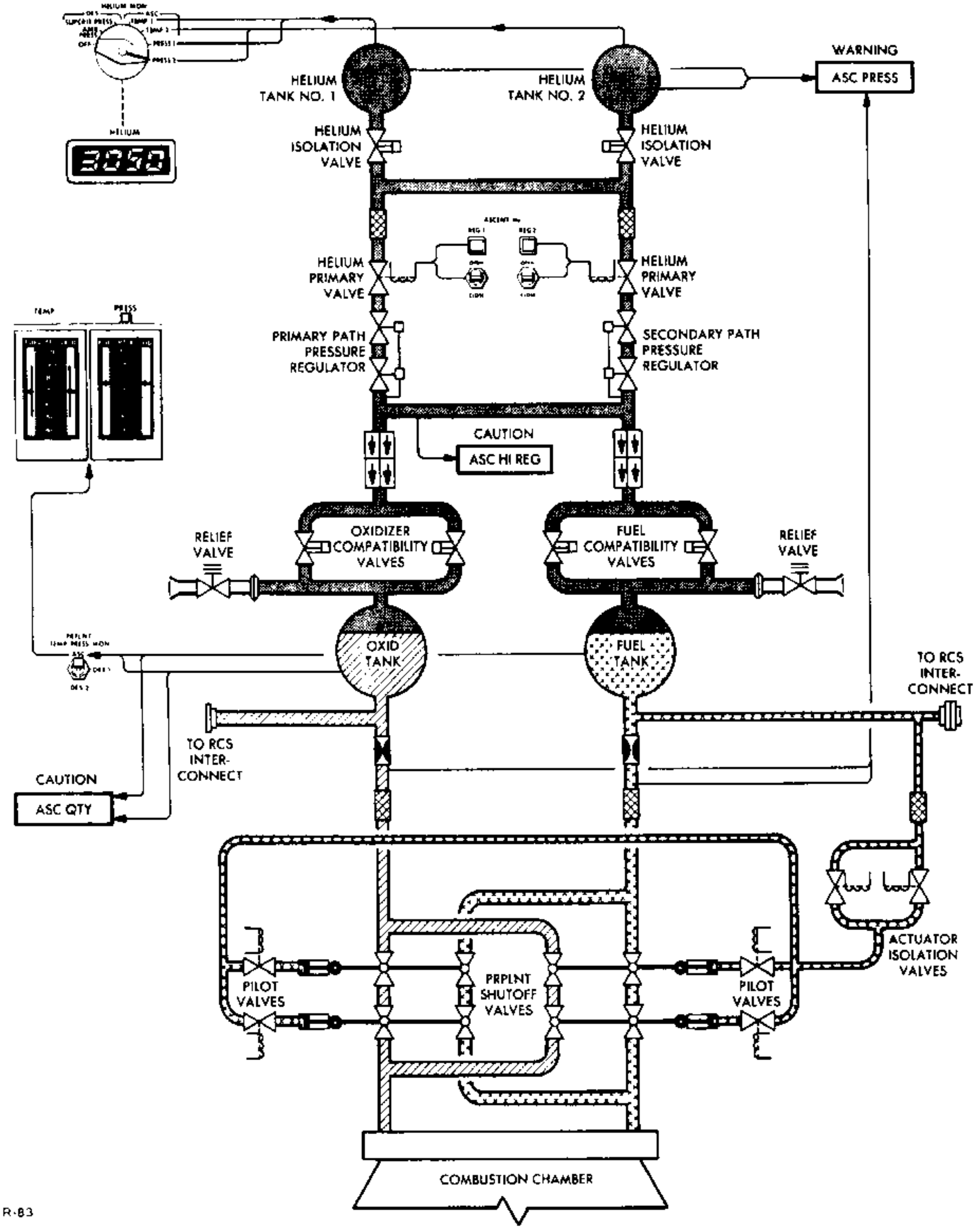
Before initial ascent engine start, the propellant tanks must be fully pressurized with gaseous helium. This helium is stored in two identical



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.

Ascent Propulsion Control Diagram



R-83

Ascent Propulsion Flow Diagram

Grumman

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 226 psia and reseals the flow path after overpressurization is relieved. A thrust neutralizer eliminates unidirectional thrust generated by the escaping gas.

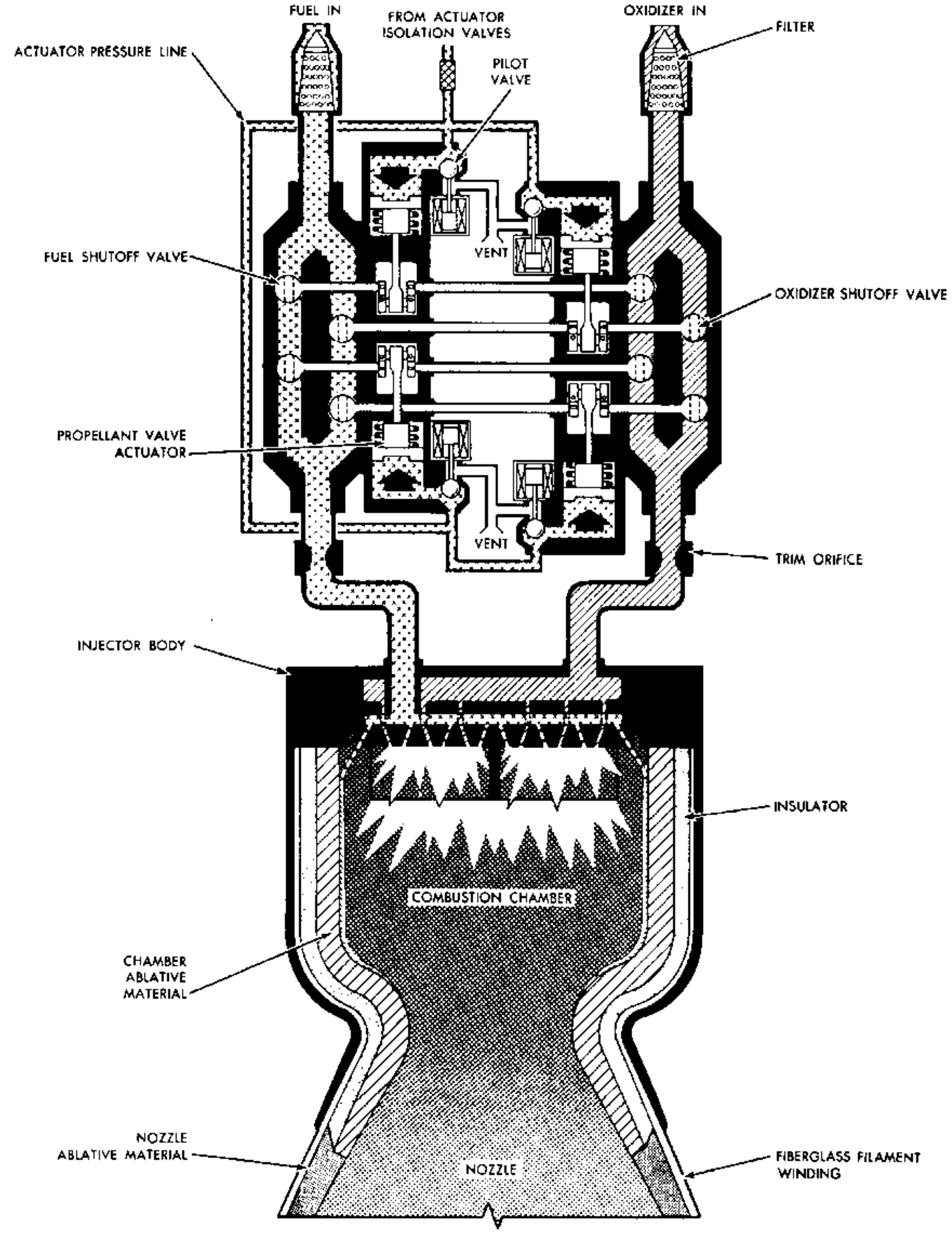
PROPELLANT FEED SECTION

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 165 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.

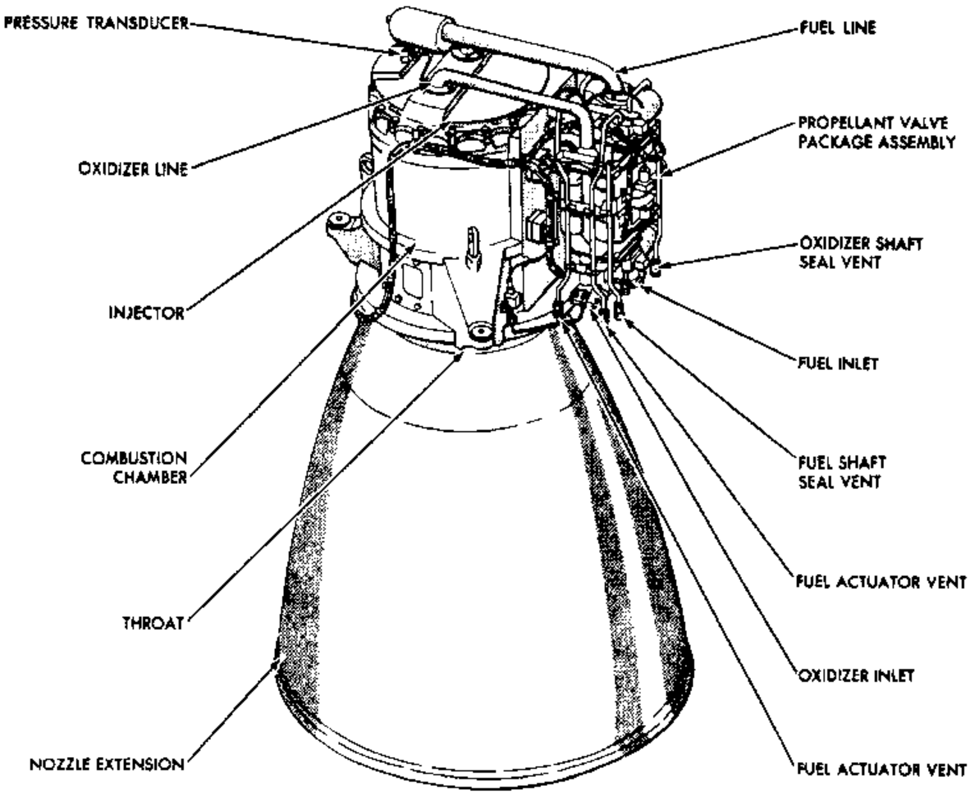


Ascent Engine Flow Diagram

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 propellant 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

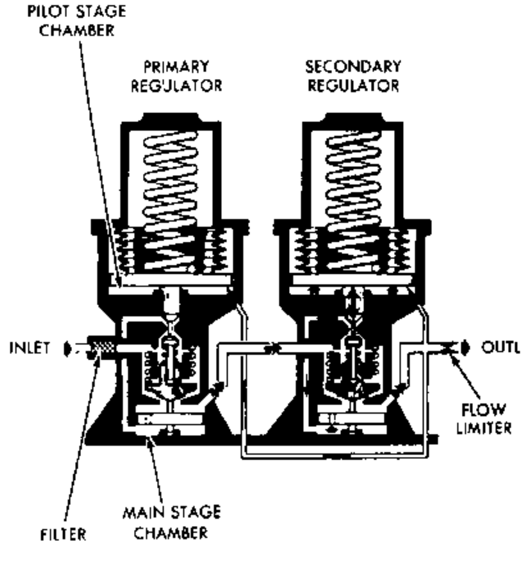
ratio of the propellants. The physical characteristics of the injector establish an oxidizer lead of approximately 70 milliseconds. This precludes the possibility of a fuel lead which could result in a rough engine start.

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 acutator 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 4.5 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 (43 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 70 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 +100° F.

COMBUSTION CHAMBER ASSEMBLY AND NOZZLE EXTENSION

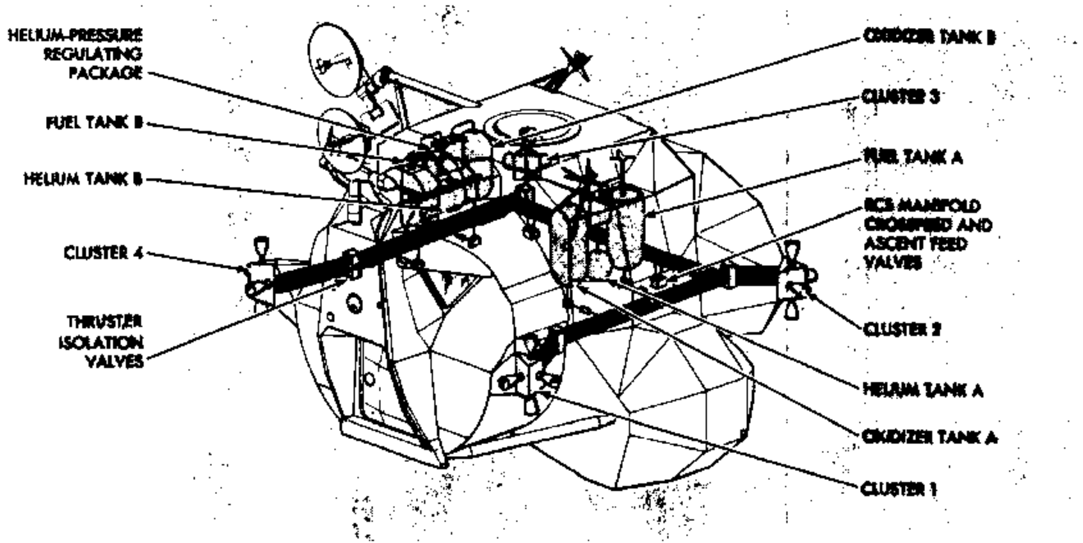
The combustion chamber assembly consists of the engine case and mount assembly and an ablative material (plastic) assembly, which includes the nozzle extension. The two assemblies are bonded and locked together to form an integral unit. The plastic assembly provides ablative cooling for the combustion 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.

REACTION CONTROL

QUICK REFERENCE DATA

Pressurization section	
Helium tanks	
Unpressurized volume (each tank)	910 cubic inches
Initial fill pressure and temperature	3,050±50 psia at +70° F
Initial filling weight of helium (each tank)	1.03 pounds
Helium temperature range	+40° to +100° F
Proof pressure	4,650 psia
Diameter	12.3 inches
Helium filter absolute filtration	12 microns
Primary pressure regulator	
Output	181±3 psia
Lockup pressure	188 psia (maximum)
Secondary pressure regulator	
Output	185±3 psia
Lockup pressure	192 psia (maximum)
Flow rate through pressure regulator assembly (single thruster operation)	0.036 pound per minute
Relief valve assembly	
Venting pressure	232 psia
Reseat pressure	212 psia (minimum)
Burst-disk rupture pressure	220 psia
Propellant feed section	
Propellant tanks	
Working pressure	176 psia
Proof pressure	333 psia
Propellant pad pressure	50 psia
Propellant storage temperature range	+40° to 100° F
Nominal temperature	+70° F
Diameter	12.5 inches
Oxidizer tanks	
Volume (each tank)	2.38 cubic feet
Ullage volume (each tank)	231.5 cubic inches
Oxidizer flow rate to each thruster	0.240 pound per second
Available oxidizer (each tank)	194.1 pounds
Oxidizer loaded in each system (tank and manifold)	208.8 pounds
Height	38 inches
Fuel tanks	
Volume (each tank)	1.91 cubic feet
Ullage volume (each tank)	117 cubic inches
Fuel flow rate to each thruster	0.117 pound per second
Available fuel (each tank)	99.3 pounds (minimum)
Fuel loaded in each system (tank and manifold)	107.7 pounds
Height	32 inches
Propellant filter absolute filtration	18 microns
Ascent feed filter absolute filtration	25 microns

Thrust chamber assembly	
Engine thrust	100 pounds
Engine life	
Total	1000 seconds
Steady-state mode	500 seconds
Pulse mode	500 seconds
Restart capability	10,000 times
Chamber-cooling method	Fuel-film cooling and radiation
Combustion chamber pressure	96 psia
Propellant injection ratio (oxidizer to fuel)	2.05 to 1
Heaters	
Type	Resistance-wire element
Operating power	28 volts dc
Power consumption (each heater)	17.5 watts at 24 volts
Oxidizer inlet pressure (steady state)	170±10 psia
Fuel inlet pressure (steady state)	170±10 psia
Approximate weight	5.25 pounds
Overall length	13.5 inches
Nozzle expansion area ratio	40 to 1
Nozzle exit diameter	5.75 inches



R-88

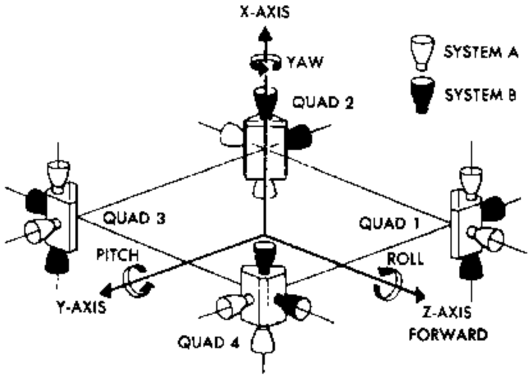
Major Reaction Control Equipment Location

The Reaction Control Subsystem (RCS) provides thrust impulses that stabilize the LM during the descent and ascent trajectory and controls attitude and translation – movement of the LM about and along its three axes – during hover, landing, rendezvous, and docking maneuvers. The RCS also provides the thrust required to separate the LM from the CSM and the +X-axis acceleration (ullage maneuver) required to settle Main Propulsion Subsystem (MPS) propellants before a descent or ascent engine start. The RCS accomplishes its task during coasting periods or while the descent or ascent engine is firing; it operates in response to automatic control commands from the Guidance, Navigation, and Control Subsystem (GN&CS) or manual commands from the astronauts.

The 16 thrust chamber assemblies (thrusters) and the propellant and helium sections that comprise the RCS are located in or on the ascent stage. The propellants used in the RCS are identical with those used in the MPS. The fuel – Aerozine 50 – is a mixture of approximately 50% each of hydrazine and unsymmetrical dimethylhydrazine. The oxidizer is nitrogen tetroxide. The injection ratio of oxidizer to fuel is approximately 2 to 1. The propellants are hypergolic; that is, they ignite spontaneously when they come in contact with each other.

The thrusters are small rocket engines, each capable of delivering 100 pounds of thrust. They are arranged in clusters of four, mounted on four outriggers equally spaced around the ascent stage. In each cluster, two thrusters are mounted parallel to the LM X-axis, facing in opposite directions; the other two are spaced 90° apart, in a plane normal to the X-axis and parallel to the Y-axis and Z-axis.

The RCS is made up of two parallel, independent systems (A and B), which, under normal conditions, function together to provide complete attitude and translation control. Each system consists of eight thrusters, a helium pressurization section, and a propellant feed section. The two systems are interconnected by a normally closed crossfeed arrangement that enables the astronauts to operate all 16 thrusters from a single propellant supply. Complete attitude and translation control is therefore available even if one system's propellant supply is depleted or fails. Functioning alone, either RCS system can control the LM, although with slightly reduced efficiency. This capability is due to the distribution of the thrusters, because each cluster has two thrusters of each system located in a relatively different position.

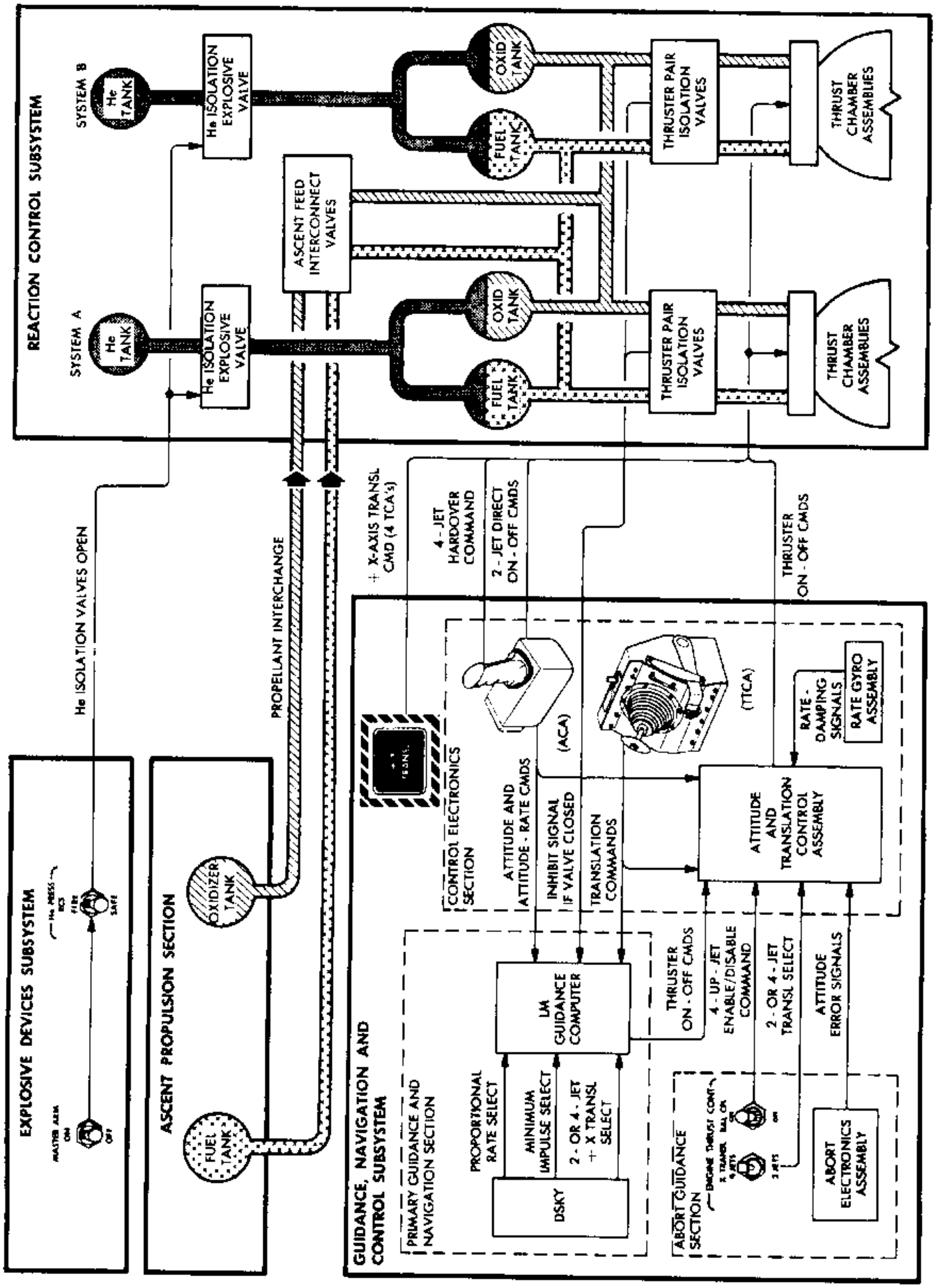


R-89

Thruster Arrangement

In addition to the RCS propellant supply, the thrusters can use propellants from the ascent propulsion section. This method of feeding the thrusters, which requires the astronauts to open interconnect lines between the ascent tanks and RCS manifolds, is normally used only during periods of ascent engine thrusting. Use of ascent propulsion section propellants is intended to conserve RCS propellants, which may be needed during docking maneuvers.

The astronauts monitor performance and status of the RCS with their panel-mounted pressure, temperature, and quantity indicators; talkbacks (flags, that indicate open or closed position of certain valves); and caution and warning annunciators (placarded lights that go on when specific out-of-tolerance conditions occur). These data originate at sensors and position switches in the RCS, 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.



RCS Control Diagram

The 28-volt d-c and 115-volt a-c primary power required by the RCS is furnished by the Electrical Power Subsystem. Interconnect plumbing between the RCS thruster propellant manifolds and the ascent propulsion section tanks permit the RCS to use propellants from the Main Propulsion Subsystem (MPS) during certain phases of the mission.

Control of the RCS is provided by the GN&CS. Modes of operation, thruster selection, and firing duration are determined by the GN&CS.

FUNCTIONAL DESCRIPTION

THRUSTER SELECTION, OPERATION, AND CONTROL

The GN&CS provides commands that select thrusters and fire them for durations ranging from a short pulse to steady-state operation. The thrusters can be operated in an automatic mode, attitude-hold mode, or a manual override mode.

Normally, the RCS operates in the automatic mode; all navigation, guidance, stabilization, and steering functions are initiated and commanded by the LM guidance computer (primary guidance and navigation section) or the abort electronics assembly (abort guidance section).

The attitude-hold mode is a semiautomatic mode in which either astronaut can institute attitude and translation changes. When an astronaut displaces his attitude controller, an impulse proportional to the amount of displacement is routed to the computer, where it is used to perform steering calculations and to generate the appropriate thruster-on command. An input into the DSKY determines whether the computer commands an angular rate change proportional to attitude controller displacement, or a minimum impulse each time the controller is displaced. When the astronaut returns his attitude controller to the neutral (detent) position, the computer issues a command to maintain attitude. For a translation maneuver, either astronaut displaces his thrust/translation controller. This sends a discrete to the computer to issue a thruster-on command to selected thrusters. When this controller is returned to neutral, the thrusters cease to fire.

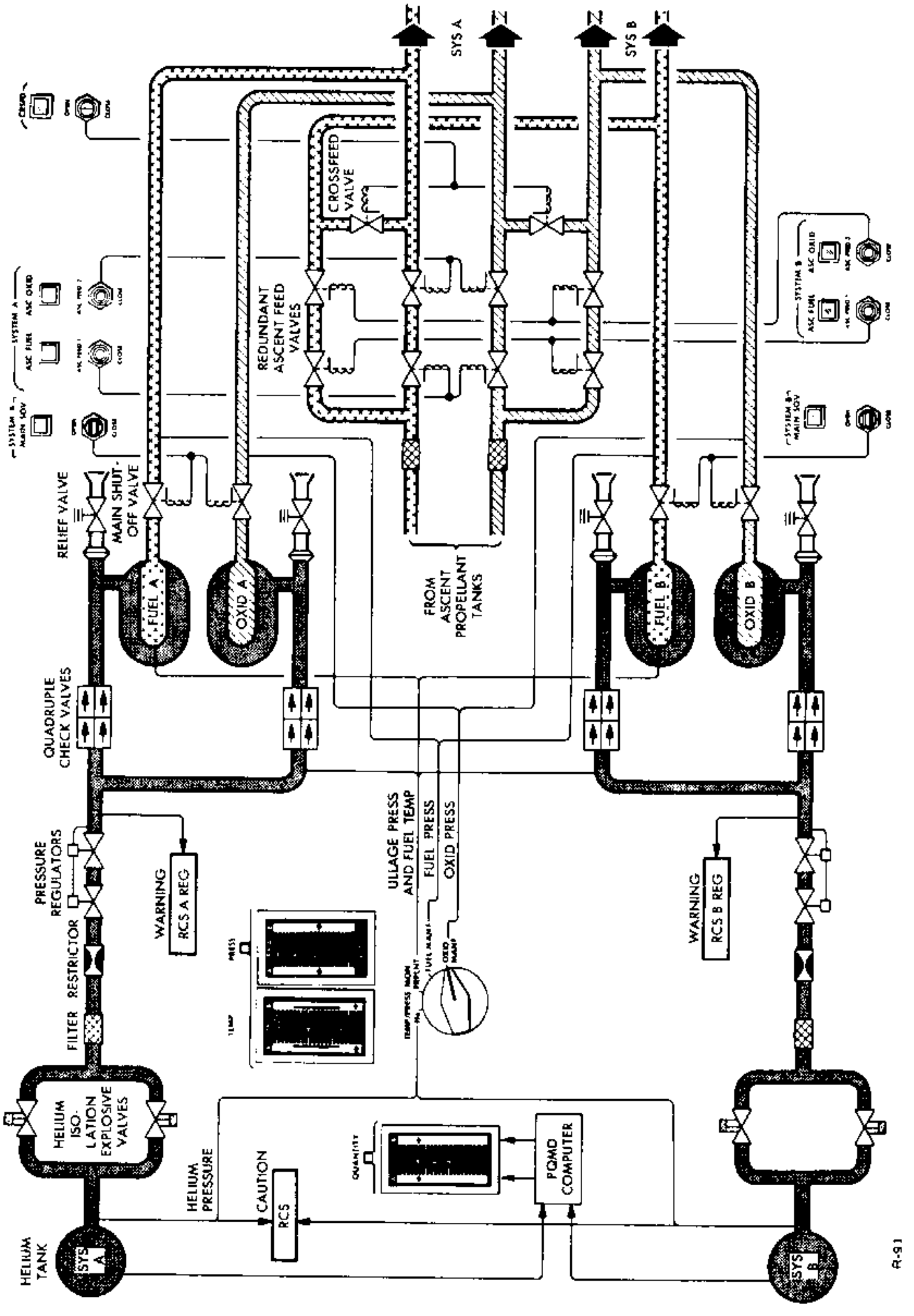
If the abort guidance section is in control, attitude errors are summed with the proportional rate commands from the attitude controller and a rate-damping signal from the rate gyro assembly. The abort guidance equipment uses this data to perform steering calculations, which result in specific thruster-on commands. The astronauts can select two or four X-axis thrusters for translation maneuvers, and they can inhibit the four upward-firing thrusters during the ascent thrust phase, thus conserving propellants. In the manual mode, the four-jet hardover maneuver, instituted when either astronaut displaces his attitude controller fully against the hard stop, fires four thrusters simultaneously, overriding any automatic commands.

For the MPS ullage maneuver, the astronauts select whether two or four downward-firing thrusters should be used. Depending on which guidance section is in control, the astronauts enter a DSKY input (primary) or use a 2-jet/4-jet selector switch (abort) to make their selection. Under manual control, a +X-translation pushbutton fires the four downward-firing thrusters continuously until the pushbutton is released. Firing two thrusters conserves RCS propellants; however, it takes longer to settle the MPS propellants. Before stage separation, all four +X-axis thrusters may have to be fired because thermal infringement on the descent stage skin limits the operating time for downward-firing thrusters to 15 seconds.

RCS OPERATION

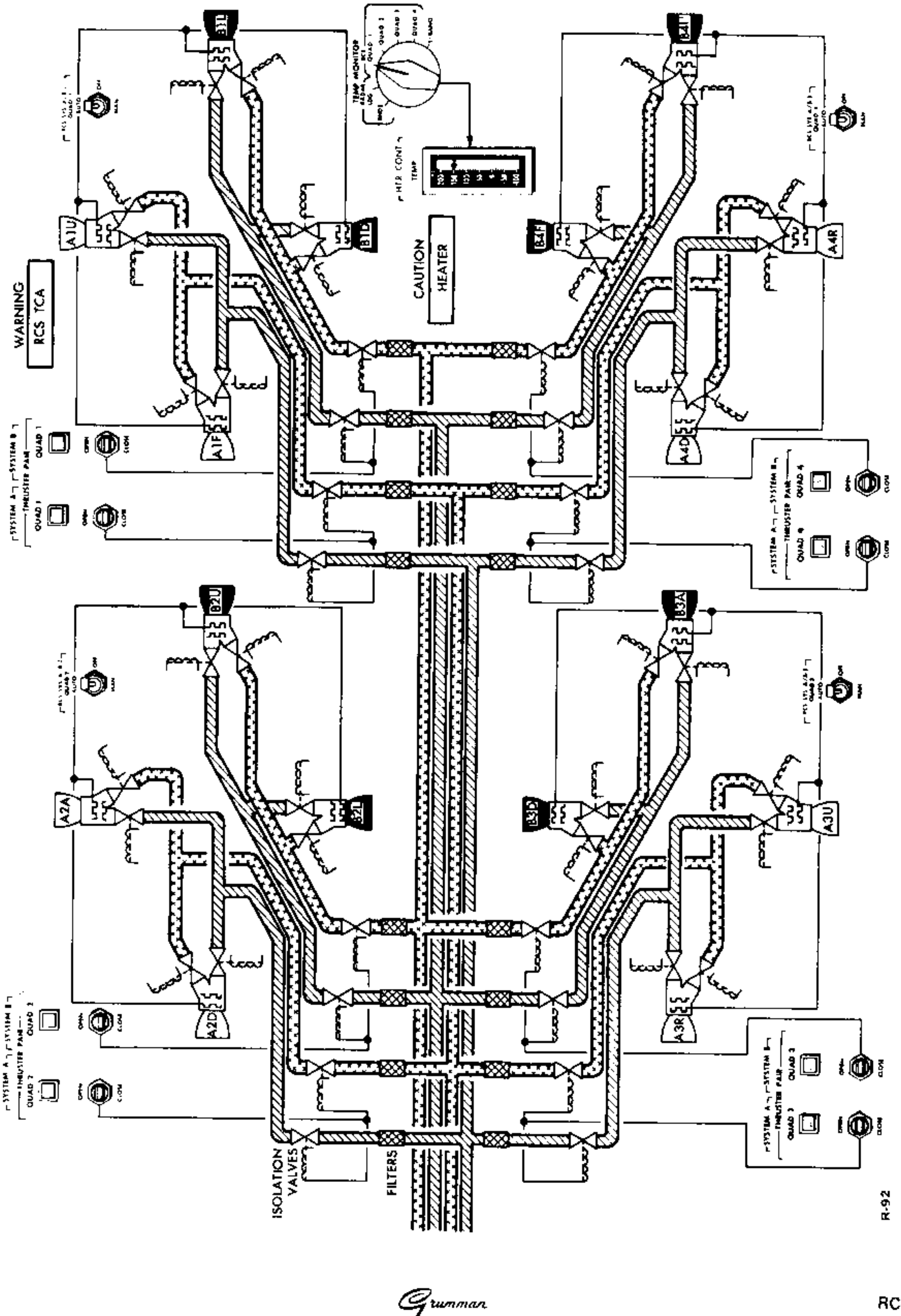
Functionally, the RCS can be subdivided into pressurization sections, propellant feed sections, and thruster sections. Because RCS systems A and B are identical, only one system is described.

Fuel and oxidizer are loaded into bladders within the propellant tanks and into the manifold plumbing that extends from the tanks through the normally open main shutoff valves up to the isolation valves leading to the thruster pairs. Before separation of the LM from the CSM, the astronauts set switches on the control panel to preheat the thrusters, open the isolation valves to permit the propellants to flow right up to the thrusters, and fire explosive valves to pressurize the propellant tanks. Gaseous helium, reduced to a working



Helium Pressurization and Propellant Feed Sections Flow Diagram

"ApolloNewsRef LM J.RC06.PICT" 322 KB 1999-02-07 dpi: 360h x 366v pix: 2662h x 3835v



Propellant Lines and Thrusters Flow Diagram pressure, enters the propellant tanks and forces the fuel and oxidizer to the thrusters. Here, the propellants are blocked by fuel and oxidizer valves that remain closed until a thruster-on command is issued. As the selected thruster receives the fire command, its fuel and oxidizer valves open to route the propellants through an injector into the combustion chamber, where they impinge and ignite by hypergolic action. The astronauts can disable malfunctioning thrusters by closing appropriate switches on the control panel. Each of these switches is connected to a fuel and an oxidizer isolation valve so that both propellant supplies to one thruster pair are shut off simultaneously. Talkbacks above the switches inform the astronauts of the status of all RCS propellant line valves.

PRESSURIZATION SECTION

The RCS propellants are pressurized with high-pressure gaseous helium, stored at ambient temperature. The helium tank outlet is sealed by parallel-connected, redundant helium isolation explosive valves that maintain the helium in the tank until the astronauts enter the LM and prepare the RCS for operation. When the explosive valves are fired, helium enters the pressurization line and flows through a filter. A restrictor orifice, downstream of the filter, dampens the initial helium surge.

Downstream of the restrictor, the flow path contains a pair of pressure regulators connected in series. The primary (upstream) regulator is set to reduce pressure to approximately 181 psia. The secondary (downstream) regulator is set for a slightly higher output (approximately 185 psia). In normal operation, the primary regulator is in control and provides proper propellant tank pressurization.

Downstream of the pressure regulators, a manifold divides the helium flow into two paths: one leads to the oxidizer tank; the other, to the fuel tank. Each flow has quadruple check valves that permit flow in one direction only, thus preventing backflow of propellant vapors if seepage occurs in the propellant tank bladders. A relief valve assembly protects each propellant tank against overpressurization. If helium pressure builds up to 232 psia, the relief valve opens to relieve pressure by venting helium overboard. At 212 psia, the relief valve closes.

PROPELLANT FEED SECTION

Fuel and oxidizer are contained in flexible bladders in the propellant tanks. Helium routed into the void between the bladder and the tank wall squeezes the bladder to positively expel the propellant under zero-gravity conditions. The propellants flow through normally open main shutoff valves into separate fuel and oxidizer manifolds that lead to the thrusters. A switch on the control panel enables the astronauts to simultaneously close a pair of fuel and oxidizer main shutoff valves, thereby isolating a system's propellant tanks from its thrusters, if the propellants of that system are depleted or if the system malfunctions. After shutting off one system, the astronauts can restore operation of all 16 thrusters by opening the crossfeed valves between the system A and B manifolds.

During ascent engine firing, the astronauts may open the normally closed ascent propulsion section/RCS interconnect lines if the LM is accelerating in the +X-axis (upward) direction; closing the interconnect lines shortly before ascent engine shutdown ensures that no ascent helium enters the RCS propellant lines. Control panel switches open the interconnect valves in fuel-oxidizer pairs, for an individual RCS system, or for both systems simultaneously.

Fuel and oxidizer manifolds in each RCS system feed propellants to two thrusters in each cluster. Each of these thruster pairs is controlled by a normally open pair of fuel and oxidizer isolation valves, permitting isolation of only two thrusters rather than disabling an entire system. When a thruster pair switch is in the closed position, it issues a signal informing the LM guidance computer that the related isolation valves are closed and that alternate thrusters must be selected.

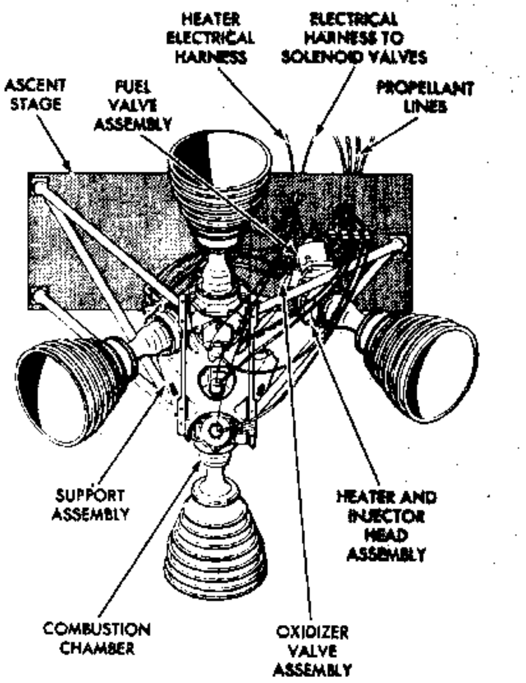
Transducers in the propellant tanks sense helium pressure and fuel temperature. Due to the proximity of the fuel tank to the oxidizer tank, the fuel temperature is representative of propellant temperature. Quantity indicators for system A and B display the summed quantities of fuel and oxidizer remaining in the tanks.

THRUSTER SECTION

Each of the four RCS clusters consists of a frame, four thrusters, eight heating elements, and associated sensors and plumbing. The clusters are diametrically opposed, evenly distributed around the ascent stage. The frame is an aluminum-alloy casting, shaped like a hollow cylinder, to which the four thrusters are attached; the entire cluster assembly is connected to the ascent stage by hollow struts. The vertical-firing thrusters are at the top and bottom of the cluster frame, the horizontal-firing thrusters are at each side. Each cluster is enclosed in a thermal shield; part of the four thruster combustion chambers and the extension nozzles protrude from the shield. The thermal shields aid in maintaining a temperature-controlled environment for the propellant lines from the ascent stage to the thrusters, minimize heat loss, and reflect radiated engine heat and solar heat.

The RCS thrusters are radiation-cooled, pressure-fed, bipropellant rocket engines that operate in a pulse mode to generate short thrust impulses for fine attitude corrections (navigation alignment maneuvers) or in a steady-state mode to produce continuous thrust for major attitude or translation changes. In the pulse mode, the thrusters are fired intermittently in bursts of less than 1 second duration – the minimum pulse may be as short as 14 milliseconds – however, the thrust level does not build up to the full 100 pounds that each thruster can produce. In the steady-state mode, the thrusters are fired continuously (longer than 1 second) to produce a stabilized 100 pounds of thrust until the shutoff command is received.

Two electric heaters, which encircle the thruster injector, control propellant temperature by conducting heat to the combustion chamber and the propellant solenoid valves. The heaters maintain the cluster at approximately +140° F, ensuring that the combustion chambers are properly preheated for instantaneous thruster starts. An out-of-tolerance temperature (less than +119° F or more than +190° F) in any cluster activates a caution light. The astronauts then determine, by use of a temperature indicator and a related selector switch, which cluster requires temperature correction and select the appropriate heater switch to restore the cluster temperature.



NOTE:
THE CLUSTER IS SHOWN WITH
THE THERMAL SHIELD REMOVED.

R-93

Thrust Chamber Cluster

Propellants are prevented from entering the thrusters by dual-coil, solenoid-operated shutoff valves at the fuel and oxidizer inlet ports. These valves are normally closed; they open when an automatic or a manual command energizes the primary or secondary coil, respectively. Seven milliseconds after receiving the thruster-on command, the valves are fully opened and the pressurized propellants flow through the injector into the combustion chamber where ignition occurs. By design, the fuel valve opens 2 milliseconds before the oxidizer valve, to provide proper ignition characteristics. Orifices at the valve inlets meter the propellant flow so that an oxidizer to fuel mixture ratio of 2 to 1 is obtained at the injector.

As the propellants mix and burn, the hot combustion gases increase the chamber pressure, accelerating the gas particles through the chamber exit. The gases are expanded through the divergent section of the nozzle at supersonic velocity, eventually building up to reach a reactive force of 100 pounds of thrust in the vacuum of space. The gas temperature within the combustion chamber stabilizes at approximately 5,200° F. The temperature at the nonablative chamber wall is maintained at a nominal 2,800° F by a combined method of film cooling (a fuel stream sprayed against the wall) and radiation cooling (dissipation of heat from the wall surface into space).

When the thruster-off command is received, the coils in the propellant valves deenergize, and spring pressure closes the valves. Propellant trapped in the injector is ejected and burned for a short time, while thrust decays to zero pounds.

When a thruster-on signal commands a very short duration pulse, engine thrust may be just beginning to rise when the pulse is ended and the propellant valves close. Under these conditions, the thrusters do not develop the full-capacity thrust of 100 pounds.

A failure-detection system informs the astronauts should a thruster fail on (fires without an on command) or off (does not fire despite an on command). Either type of failure produces the same indication: a warning light goes on and the talkback related to the failed thruster pair changes from the normal gray to a red display. The astronauts then disable the malfunctioning thruster pair by closing the appropriate isolation valves. To offset the effects of a thruster-on failure, opposing thrusters will automatically receive fire commands and keep firing until the failed-on thruster has been disabled. A thruster-off condition is detected by a pressure switch, which senses combustion chamber pressure. When a fire command is received, the solenoid valves of the thruster open, resulting in ignition and subsequently in pressure buildup in the combustion chamber. When the pressure reaches 10.5 psia, the switch closes, indicating that proper firing is in process. When a very short duration fire command is received (a pulse of less than 80 milliseconds), the combustion chamber pressure may not build up enough for a proper firing. Short pulse skipping does not result in a failure indication, unless six consecutive pulses to the same thruster have not produced a response. In this case, the warning light and the talkback inform the astronauts that they have a nonfiring thruster, which must be isolated.

EQUIPMENT

EXPLOSIVE VALVES

The explosive valves are single-cartridge-actuated, normally closed valves. The cartridge is fired by applying power to the initiator bridgewire. The resultant heat fires the initiator, generating gases in the valve explosion chamber at an extremely high rate. The gases drive the valve piston into the housing, aligning the piston port permanently with the helium pressurization line.

PROPELLANT QUANTITY MEASURING DEVICE

The propellant quantity measuring device, consisting of a helium pressure/temperature probe and an analog computer for each system, measures the total quantity of propellants (sum of fuel and oxidizer) in the fuel and oxidizer tanks. The output voltage of the analog computer is fed to an indicator and is displayed to the astronauts on two scales (one for each RCS system) as percentage of propellant remaining in the tanks.

The propellant quantity measuring device uses a probe to sense the pressure/temperature ratio of the gas in the helium tank. This ratio, directly proportional to the mass of the gas, is fed to an analog computer that subtracts the mass in the helium tank from the total mass in the system, thereby deriving the helium mass in the propellant tanks. Finally, propellant tank ullage volume is subtracted from total tank volume to obtain the quantity of propellant remaining. Before firing the helium isolation explosive valves, the quantity displayed exceeds 100%, so that, after the valves are opened and the gas in the helium tank becomes less dense, the indicated quantity will be 100%.