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Potential Propellant Storage and Feed Systems for Space Station Resistojet Propulsion Options

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16. Abstract

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ABSTRACT

The resistojet system has been defined as part of the baseline propulsion system for the Initial Operating Capability Space Station. The resistojet propulsion module will perform a reboost function using a wide variety of fluids as propellants. There are many optional propellants and propellant combinations for use in the resistojet including (but not limited to): hydrazine, hydrogen, oxygen, nitrogen, water, carbon dioxide, and methane. Many different types of propulsion systems have flown or have been conceptualized that may have application to use with resistojets. This paper describes and compares representative examples of these systems that may provide a basis for Space Station resistojet system design.

INTRODUCTION

A rebirth of interest in a manned space station brought with it a commitment to place the Space Station in Earth orbit in the 1990's. Some of the technology developed over a decade ago for an earlier attempt to fly a space station was left incomplete, untested, or unused. However, related technology advancements were made in programs developing communications and near-earth orbiting satellites. NASA is supporting an Advanced Development Program aimed at providing propulsion technology for the initial and growth configuration of the the Space Station *1,2*. Since it has been mandated to minimize technology risk, costs, and development time, trade studies are underway to define the appropriate technology options. This paper will focus on Space Station auxiliary propulsion with particular emphasis on propellant storage and feed systems for low-thrust resistojet thrusters.

Propulsion will be required on Space Station for atmospheric drag makeup, correction of large torques, collision avoidance, and backup for control moment gyros. The low thrust system would provide reboost propulsion *3*. The reboost requirement for Space Station may exceed 2 X 10E7 Ns/yr (4.5 X 10E6 lbf sec/yr). A high thrust system would handle the other propulsion requirements. High thrust (110 N, 25 lbf) options for auxiliary propulsion include: hydrazine, hydrogen-oxygen, and storable bipropellants.

The resistojet has been baselined for Space Station auxiliary propulsion because it offers mission benefits associated with low thrust such as nearly constant altitude maintenance and low induced accelerations. The resistojet system is simple reliable, and can use a wide variety of propellants including excess station fluids, both oxidizing and reducing *4*. Waste fluids for propulsion will probably be obtained from the station environmental control and life support system (ECLSS), lab modules, attached payloads, and possibly the Shuttle orbiter. Resistojets can also be used for nonpropulsive venting. By adjusting power settings and operating temperatures, performance can be traded for increased life and reliability. Thruster performance is not a ranking issue in space station propulsion; the technology focus is on long life and multipropellant capability.

Because resistojets are capable of handling many different propellants which may have special properties requiring different storage and feed systems, it is necessary to look at a variety of systems or concepts available to support a resistojet system design effort. Resistojet systems have flown on Vela Spacecraft, Applications Technology Satellites, RCA, and INTELSAT V satellites using nitrogen, ammonia, and hydrazine propellants *5*. resistojet systems using hydrogen or biowaste propellants have no flight history. Current propulsion and fluid management technology options are reviewed in this paper. The focus will be on low thrust resistojet monopropellant storage and feed system concepts which have application to Space Station auxiliary propulsion. Information on representative propellant storage and feed systems for the candidate propellants from various space subsystems will be provided. The selected reference feed systems for the candidate propellants are not necessarily resistojet systems. It is expected that the feed systems discussed will function independently of the type of thruster used. The propellants that will be covered in this report are; hydrazine (N_2H_4); ammonia (NH_3); nitrogen (N_2);

hydrogen (H_2); oxygen (O_2); and biowaste products including water (H_2O), carbon dioxide (CO_2), and methane (CH_4). The most prevalent monopropellant in use is hydrazine and consequently a large number of hydrazine feed system design options will be explored.

DEFINITION OF THE MONOPROPELLANT STORAGE AND FEED SYSTEM

The purpose of the storage and feed system is to receive and store the propellant until needed, then to feed it to the thrusters as required. The storage tank or the accumulator is functionally the beginning of the system. It receives propellant from a supply source or another subsystem. The tank stores the propellant and often provides the pressure to move it through the feed system to the thrusters. The accumulator is used as a reservoir for propellants from another system upstream, or it is used downstream of a tank as a flow dampener or conditioned propellant uptake. The overall system performs other functions in addition to the basic storage and delivery. Components within the system monitor propellant quantities; monitor and control pressure and temperature; filter out contaminants; condition propellants; and isolate or bypass leaks, empty tanks, and failed components.

Storage

The propellants under consideration are stored in one of two states, gas or liquid. Gas propellant tanks are normally simple pressure vessels. The propellant is driven by tank pressure. Propellant quantities are determined by automatic calculation using the gas law equation and transducer readings. Liquid propellants may be stored at subcritical or supercritical temperatures.

Propellants may be stored within the feed system in an accumulator. An autonomous tank storage and feed system may not have an accumulator whereas a system drawing its propellants from another system most likely will.

Propellants may also be stored in other Space Station systems. Such systems include the Environmental Control and Life Support System (ECLSS), lab modules for materials or life sciences, attached payloads, and orbit transfer vehicle tank farms. Purge gases from station platforms or free-flyers may also be available for propulsion. Because of the low propulsion requirements, waste products, boil off, residual propellants, or excess pressurants could be sufficient to meet the propellant needs for orbit maintenance. A significant amount of non-propulsive venting may be required during periods of fluid excess. The quantity of propellant used for drag-makeup propulsion will vary depending on reboost strategy, solar year, altitude, and Space Station configuration.

Propellant Delivery

There are two basic methods of driving propellants through the system to the thrusters: the blowdown method, and the pressure regulated method. In the blowdown system, propellant is pressurized only from the beginning of the system in the tank. Because of fluid incompressibility, liquid delivery systems require some mechanical means of displacing the propellant from the tank and driving it through the system. These systems will have pressurant driven diaphragm, bellows, or surface tension tanks. The tank pressurizing system may essentially be a propellant delivery system in itself. In the case of liquid storage gas feed systems (supercritical and subcritical) the propellant is normally pumped from the tank.

In the pressure regulated system, propellant is pressurized at some point in the system. At a point short of the thrusters the pressure is regulated to the required level. This system accounts for declining tank pressure down to the regulated pressure plus the sum of the pressure drops between the tank and regulator.

By the most basic principle virtually all feed systems are the same. Th propellant is forced out of a storage device to the thrusters. Beyond this the resemblances between feed systems diverge. Locations, numbers, and types of components in a system vary. This is affected by considerations of mission requirements, propellant type, safety and reliability requirements, cost, and manufacturer's preference. Where a function can only be performed practically one way, systems will be similar. Where a variety of methods will work, a variety of systems may be found. The subroutings and components to be discussed here are common to feed systems in general. In the lines near the storage tank or on the tank itself, there is a service valve for fill and drain or manual vent. On the upstream side of a liquid delivery tank is the tank pressurizing system consisting of a pressurant tank and feed subsystem components. In some cases the pressurant may simply be contained in the propellant tank initially at high pressure/low volume. Downstream of, or on the propellant tank, a relief valve and/or rupture disc may be used. The propellant is delivered to the thrusters through lines sized for minimum weight and tolerable pressure drop. En route, the propellant is controlled by valves including isolation, check, relief, and thruster valves driven by solenoids, servo-motors, pyrotechnics, manual levers, or springs. The system could be monitored at any point by pressure or temperature transducers. Liquid delivery systems require line and component heaters in freeze prone areas and gas generators upstream of, or attached to, the thrusters.

Some propellant systems may require special components. Since the ECLSS operates at a pressure of about one atmosphere, biowaste propellants must be boosted to the higher feed system operating pressure by a pump or compressor. Propellants from water electrolysis units may be delivered at pressures as high as 2070 N/cm2 (3000 psia). Some propellants may contain trace contamination such as: gas impurities, water, hydrocarbons, and particulates. Furthermore, in normal operation of mechanical components, motion of parts within the flow stream causes wear. Wear debris causes erosion creating more particulates. Filters may be used in several locations upstream of the thrusters to protect critical components. The service lives of most space systems flown to date are short enough that the missions are completed before the filter fouls to failure. The Space Station has a projected service life of up to ten years. Long term reliability becomes a major issue. The need for long life or on-board replaceable components is important. Relatively short life items such as the filter element must be improved for longer life or made accessible for on-orbit replacement. Certain design options to feed system routing may improve accessibility to inherently short life components. Another option is redundancy. The higher risk and lower service life components or branches of the feed system may be duplicated or triplicated within the system. To compensate for a major failure of a feed system branch or components of the branch, parallel redundancy of the entire branch is commonly employed. For a single failure which would render a component inoperative, identical components can be routed in parallel. In the least serious case, a single failure-operable, duplicate components may be routed in series. An example of this is a valve designed to open in failure, followed by another such valve.

Propellant Conditioning

The final major function of the feed system is propellant conditioning. It is desireable to store and/or deliver some propellants in a different state than they are used in the thruster. All of the liquids must be vaporized or decomposed into gaseous products before injection into the thruster chamber. Ammonia is usually stored as a liquid and delivered to a vaporizer in the form of liquid, vapor, or a mixture of both. The ammonia may be vaporized in the tank as needed and delivered to the thrusters by its own vapor pressure *6*. Hydrazine is normally stored and delivered as a liquid and decomposed to gas products in a catalyst bed or electrothermal decomposer at the thruster. It could prove desirable to decompose the hydrazine in a single catalyst bed and deliver gas from a central accumulator to the thrusters. Water has yet to be used as a propellant in a space flight application; but, in concept, it would be handled in a similar manner to hydrazine using an electrothermal vaporizer. Water may also be dissociated to hydrogen and oxygen by electrolysis *4*. In the resistojet system either hydrogen or oxygen may be used as a propellant. Hydrogen or oxygen may be scavenged from boil-off of cryogenic storage systems which are dedicated to Orbit Transfer Vehicle propellant storage. It would be necessary to thermally condition the boiloff propellant in the feed system to avoid the special handling problems associated with cryogenic gases.

PROPELLANT SYSTEM DESCRIPTIONS

Hydrazine

Hydrazine was initially baselined as the propellant for the Space Station orbit maintenance propulsion system *7*. Nine tanks supply hydrazine to 36 thrusters arranged in four triply redundant clusters, Fig. 1. Symbols are defined in Appendix A. The thrust level is approximately 200 N (45 lbf) per thruster. The specific impulse of hydrazine is about 220 seconds. The technology for hydrazine storage and feed systems for propulsion has been developed over the last two decades. Hydrazine is stored and delivered as a liquid, it must be protected from freezing, and must be gasified before it is injected into the thrust chamber. The liquid hydrazine is usually expelled from the tank by displacement pressurization using a gas pressurant and a diaphragm or bladder in the tank.

Hydrazine propellant feed system data is the most common due to its wide scale use in satellites, orbiters, and explorer spacecraft. To illustrate how feed systems may differ for the same propellant the hydrazine storage and feed systems are the logical choice.

A representative example of hydrazine system is TRW's Fleet Satellite Communications Spacecraft (FLTSATCOM) reaction control system (RCS). FLTSATCOM is a series of Department of Defense communications satellites designed for a minimum of seven years in equatorial geosynchronous orbit. The first of the series was launched Feb. 9, 1978 *8,9*. The spacecraft's RCS uses sixteen 4.4 N (1.0 lbf) high level thrusters (HLT) and four 0.4 N (0.1 lbf) low level thrusters (LLT). Following transfer orbit injection and launch vehicle separation the HLTs are used to spin stabilize the spacecraft, precess the spin axis, inject to geosynchronous orbit, despin, then point the spacecraft. On orbit coarse positioning is also handled by the HLT's. Reaction wheels and thrusters combined provide an orbit control in normal operation, with LLT's providing the roll/yaw control. Duty cycles of all thrusters, on orbit, normally are low enough to permit return to prefire temperatures. For a seven year mission total impulse is 26,400 Ns (5940 lbf sec) for the attitude control allocation and 131,580 Ns (29600 lbf sec) for the orbit maintenance allocation. Average specific impulse (Isp) is 209 sec. The total mass of hydrazine propellant allocated for the seven year mission is 14.7 Kg (32.4 lbm) for attitude control and 62.4 Kg (137.6 lbm) for orbit maintenance. The minimum overall cycle life is 100,000; the number of catalyst bed starts required by design per thruster.

The dual level of redundancy for FLTSATCOM is indicated in Fig. 2. There are essentially two storage and feed systems, A and B, with a single crossover, joined at a single point to the manifold connecting the thruster modules. There are eight modules, each containing a redundant pair of HLT's and two modules each containing two LLT's. The satellite's propellant tank pressurizing and delivery method is the simple blow-down mode. The displacement fluid, gaseous nitrogen (GN2), is highly compressed and separated from the fill of N2H4 by an elastomeric diaphragm in the tank. As the propellant is used up tank pressure diminishes, or "blows down" from 241 to 124 N/cm2 (350 to 180 psia).

Electrically operated components in the feed system include 15 VDC (regulated) 2.0 W and 2.5 W catalyst bed heaters for the HLT's and the LLT's, respectively; 28 VDC (regulated) 0.2 W pressure transducer and 4.5 W thruster valves; and 18 to 38 VDC (unregulated) 10 W isolation valves. Unregulated voltages from 20 to 70 VDC provide 0.25/2.5/3.3 W for line/thruster valve/tank heaters sized for 100% duty cycle at minimum voltage and coldest environment (-37 C, -35 F). The total average on orbit power allocation for the entire propulsion system is 14.5 W. The overall component count includes: two heated tanks, four service valves, two pressure transducers, two 10 micron filters, seven latching isolation valves with 50 micron integral filters, twenty heated thruster valves with 15 micron integral filters, twenty catalyst bed thrusters, and twenty two thermisters associated with the tank and valve heaters. Lines are heated by thermostatically controlled dual element heat wraps. The component count, supplier source, and mass for the FLTSATCOM Spacecraft RCS is given in Table I.

To show how feed systems may resemble each other the Communications Technology Satellite (CTS) Reaction Control system, developed by

Hamilton Standard, was selected as an example. The CTS preceeded the FLTSATCOM on orbit by two years. Like the FLTSATCOM the CTS was designed with three axis control for a geosynchronous communications mission, though in a research role *10*. With the exception of the isolated crossover of the FLTSATCOM and the position of the pressure transducer relative to the filter on both, the systems are identical in configuration to short of the header for the thrusters, Fig. 3. The CTS feed system operates in the blowdown mode. Perhaps a significant reason for the differences between the two systems is the two year mission of the CTS compared to the seven year minimum mission of the FLTSATCOM. The additional safety of the crossover may have been considered unnecessary for the short mission. Like FLTSATCOM, the CTS propulsion system was not designed for a north-south station keeping requirement (though it is capable of it). Operational specific impulse ranges are as follows: 223 to 235 sec. for the two 22 N (5 lbf) high thrust engines and 97 to 230 sec. for the 16 0.4 N (0.1 lbf) low thrust engines. The overall component count of CTS is similar to that of FLTSATCOM: two heated tanks, four service valves, two 10 micron filters, two pressure transducers, seven latching isolation valves with heaters and position indicators, eighteen heated thruster valves, eighteen catalyst bed thrusters, and at least fourteen temperature sensors associated with heaters. As an interesting contrast to the FLTSATCOM, the CTS system uses sixteen low level thrusters and two high level thrusters. Differences in orbit injection and on orbit maneuvers may have influenced the design philosophy that resulted in selection of opposite numbers of high and low level thrusters. The CTS propulsion system suffered latch valve anomalies caused by high surge flow. However, it was concluded that this was a component level problem- an inherent instability in the valve itself.

The Applications Technology Satellite 6 (ATS 6) is one of a series of experimental communication satellites. The ATS 6 propulsion system was designed and fabricated by Rocket Research for a five year mission in geosynchronous orbit. It was launched in May 1974. The propulsion system is capable of providing three axes of control for orbit correction, station keeping, station transfer, and inertia wheel backup or unloading *11*. The ATS 6 is an example of a dual redundant hydrazine system, Fig. 4. There are two complete identical feed subsystems linked by a crossover, isolated by a latching valve. The system operates in the blowdown mode. The tanks are the diaphragm type using nitrogen as the pressurant. Total system capacity is 49.1 Kg (108.2 lbm) propellant plus 0.8 Kg (1.8 lbm) pressurant. Pressurant volumes are not crossfed. At the tank exit a thermister measures temperature. Downstream of the tank is a pressure transducer and a service valve, beyond that the propellant is filtered. All of the seven latching valves also have integral inlet filters. Each feed subsystem has eight 0.4 N (0.1 lbf nominal) catalyst bed thrusters. Actual thrust range is 0.586 to 0.22 N (0.125 to 0.053 lbf) over the nominal blowdown pressure range of 258 to 92 N/cm2 (375 to 134 psia). Specific impulse is 220 sec at the nominal 0.1 lbf thrust. Thrusters are designed for 50 hours accumulative operation at up to 100,000 cycles. The total impulse for the system is 86,600 Ns (19,500 lbf sec). As a point of reference, the ATS propulsion system total impulse capability is about two orders of magnitude lower than that required annually for Space Station reboost. A list of major system components resembles those of the CTS and FLTSATCOM: two tanks with temperature sensors, four service valves, two pressure transducers, two filters, seven latching isolation valves with integral inlet filters, sixteen filtered thruster valves-half with thermal control, and sixteen catalytic thrusters with temperature sensors and catalyst bed heaters. A more complete component count with masses is given in Table II. The ATS 6 experienced some anomalies within its first four years on orbit including failures of varying degrees in eleven of the sixteen thrusters, and heater failures. The cause of the thruster failures is not known but at least some of the failures have been attributed to contamination in the propellant including, possibly, products of tank diaphragm degeneration. Heater failures were a component level design or operational proceedure problem. The other unexplained anomalies were not necessarily caused by the system design layout.

The INTELSAT V propulsion feed system is an example of total redundancy. Like the ATS 6 system, it is dual redundant. There are essentially two separate feed systems. The INTELSAT V system however has duplicate crossovers. Failure of a crossover valve to open would not affect a normally operating system. In the case of a single crossover, though, it would prevent an emergency crossfeed. INTELSAT V is one of a series of geosynchronous communications satellites. The satellite's propulsion system uses resistojets for north-south station keeping. The first of the V generation was launched in 1980 *12,13,14*. The system operates in the blowdown mode, Fig. 5. Two surface tension tanks contain a total of 213 Kg (470 lbm) of hydrazine. Each tank feeds a complete redundant set of thrusters, and crossfeeds the other subsystem through on of the two redundant isolated crossovers. Each set of thrusters consists of two 0.44 N (0.1 lbf) and five 2.7 N (0.6 lbf) catalyst bed thrusters, and two 0.3 N (0.071bf) resistojet thrusters. Specific impulse for the resistojets is 304 sec. The total component count includes: two tanks, two pressure transducers, four service valves, four latching isolation valves, two filters, twenty thruster valves, and twenty thrusters. The dry mass of the system is 16.0 Kg (35.3 lbm).

An example of another level of redundancy is the International Ultraviolet Explorer (IUE) propulsion system manufactured by Hamilton Standard. The IUE is a celestial observer satellite launched into inclined elliptical geosynchronous orbit January 26, 1978 *15*. Its propulsion system also operates in the blowdown mode, Fig. 6. Matched pairs of tanks are connected by triply redundant feed lines. The tank pairs are diametrically opposed to maintain spacecraft balance. Because of the balance requirement, the system is only triply redundant in spite of triple parity of tanks. The ratio of high thrust to low thrust is similar to CTS. There are four 22 N (5 lbf) and eight 0.9 N (0.2 lbf) thrusters. Stabilization on orbit is achieved by 3 axis thrust and by momentum wheels. Estimates of the annual on-station total impulse, specific impulse, and propellant consumption are 583 Ns (131 lbf sec), 225.3 sec, and 0.33 Kg (0.74 lb) respectively. The overall component count includes the following: six tanks, nine service valves, three 10 micron filters, three pressure transducers, seven latching isolation valves with position indicators, twelve filtered thruster valves, and twelve thrusters with thermocouples. Two of the four thruster group lines are heated.

All of the systems described so far are liquid fed with gas generators attached to each thruster; the liquid hydrazine is decomposed to gaseous propellant at the thruster. Another method of delivering hydrazine is to decompose it upstream of the thrusters in a single larger capacity gas generator. An example of this is a satellite system demonstrated for the Air Force by TRW. The system is a hybrid of this concept using liquid fed high thrust and gas fed low thrust *16*. Two 0.057 m3 (3500 in3) blow down tanks, each containing 63.5 Kg (140 lbm) hydrazine, supply two vernier velocity thrusters, two high level thrusters, and a gas generator/accumulator subassembly that in turn feeds eight low level thrusters, Fig. 7. The two tanks are nitrogen pressurized. Because the satellite is spin stabilized, elastomeric diaphragms for pressurant/propellant separation and separate pressurant fill lines are unnecessary and were omitted from the design. The four large thruster assemblies are conventional in that they receive liquid hydrazine at 345 to 138 N/cm2 (500 to 200 psia, the blow down range of the tanks) and decompose it in their integral gas generators. Feed pressure to the low level thrusters is controled by accumulator filling strategy. The amount of hydrazine delivered to the gas generator and decomposed will determine the pressure in the accumulator. Design total impulses for the thrusters are 11,558 Ns (2,600 lbf sec) for the high level AC thrusters, 93,351 Ns (21,000 lbf sec) for the vernier thrusters, and 5,779 Ns (1,300 lbf sec) for the low level thrusters. The overall component count includes: two tanks, two service valves, two liquid filters, one gas filter, one pressure transducer, one gas generator/accumulator assembly, two isolation valves, twelve thruster valves, and twelve thrusters.

Hydrazine systems for satellite propulsion have been demonstrated in many forms and applications. Propellant masses up to 213 kg have flown on INTELSAT V. With the exception of redundancy requirements, as yet undefined for Space Station auxiliary propulsion, some existing hydrazine feed systems may prove applicable to a resistojet system with only performance and dimensional scaling required.

Ammonia

Ammonia is not a likely candidate propellant for Space Station propulsion but is a potential propellant for electrothermal thrusters with satellite application. Ammonia has handling properties similar to hydrazine and is in fact one of the products of hydrazine decomposition. Ammonia has a lower freezing point than hydrazine and requires only thermal conditioning. Ammonia systems are usually driven by their vapor pressure requiring only a tank heater/vaporizer.

The Applications Technology Satellite IV propulsion system provides an example of a simple ammonia resistojet feed system. The ATS IV was an ancestor of the ATS 6 described earlier. The system was designed to provide east-west station keeping during a three to six year mission in geosynchronous orbit. A booster failure during the August 1968 launch injected the satellite into a decaying elliptical orbit, and shortened the mission to two months *17*. The feed system was designed with little redundancy, Fig 8. A single tank feeds a double accumulator referred to as a pre-plenum and plenum through redundant lines. Flow into the pre-plenum is regulated by a pressure regulating valve in each line controlled by redundant pressure switches on the preplenum. The propellant is vaporized in part by the heaters located at the valve inlets. Both valves must be capable of handling liquid or gaseous ammonia, and regulate plenum pressure to 6.9 N/cm2 (10 psia). The pre-plenum and the plenum are separated by a series of orifices. This double accumulator system was designed to dampen the pressure variations that result from feeding both gaseous and liquid ammonia. There is a pressure transducer on the pre-plemun. At the exit of the plenum the line splits to two thruster lines. Each line has one pyrotechnic normally open isolation valve, one solenoid thruster valve, one porous flow control device, and one nominal 178 uN (40 ulbf) resistojet thruster. The flow control devices control thruster inlet pressure to 0.7 N/cm2 (1 psia). The overall system mass is 7.3 Kg (16 lbm) including 1.4 Kg (3 lbm) ammonia. During the short two months of the modified mission 35% of the propellant was depleted in 825 hours of operation. Total impulse was 1778 Ns (400 lbf sec). Total power was 11 W for the system. Specific impulse was 125-135 sec. Cold jet specific impulse was 80 sec.

Another example of a simple ammonia system is the Lincoln Experimental Satellite (LES) 8 and 9. The LES 8 and 9 are geosynchronous military communications demonstrators. The ammonia system was selected because of its compatibility with the mission's low thrust requirement and low temperature on orbit environment. The propulsion system adds two axes of control to the third axis provided for by the momentum wheel *18*. The tank is pressurized by the propellant's vapor pressure which varies from 62 to 155 N/cm2 (90 to 225 psia) with temperature. The tank has a fill capacity of 34 Kg (75 lb). Ullage is 8.5 percent at 25 C (77 F). From the tank the propellant is filtered, then passes through two series redundant pressure control valves and enters the vaporizer, Fig 9. The vaporizer is heated by the tank, supplemented by a 1 W heater. Propellant leaves the vaporizer at 20 to 24 N/cm2 (29 to 35 psia). On the line from the vaporizer is an accumulator opposed by two parallel redundant pressure control tranducer units. Downstream of the vaporizer and accumulator the propellant is again filtered before delivery to the ten thrusters. The attitude control thrusters are arranged in two groups of four. Each group alone is capable of performing all required pitch and yaw manuevers. The thruster assemblies are heated as required to prevent propellant condensation. The LES 8 and 9 propulsion system was designed for a five year service life with a total impulse of 28,000 Ns (6300 lbf sec). The thrusters generate a maximum of 0.04 N (0.01 lbf). Peak system power usage is 25 W. The system mass is 68 Kg (150 lbm) maximum. Because of system simplicity the component count is low: One heated tank, one service valve, one pressure transducer, two 10 micron filters, one pressure control valve with dual redundant pressure control units, one heated vaporizer, one accumulator, four latching isolation valves, ten thruster valves, and ten thrusters in two heated units.

Nitrogen

An example of a nitrogen system is the gas propellant feed system of the Manned Maneuvering Unit (MMU). The MMU, designed by Martin Marietta Corporation, is a one person, self contained, free flying space vehicle *19,20*. Because of this, safety of flight is a prime consideration. The doubly redundant propulsion system consists of two completely independent storage, feed and thruster subsystems linked by a single crossover with two manual isolation valves, Fig. 10. Between the manual valves is a pair of quick disconnects. These couple with the feed system of the Flight Support Station during docking for propellant resupply. Each subsystem is capable of independantly meeting the full propulsion requirements. The operating pressure range of the tanks is 2067 to 172 N/cm2 (3000 to 250 psia). Propellant flow to the thrusters is pressure regulated 146 N/cm2 (212 psig). Relief valves, integral to the regulators, protect the low pressure half of the system downstream of the regulator from regulator failure. Twelve 7.6 N (1.7 lbf) cold jet thrusters in each subsystem provide six degrees of freedom for maneuvering. An important feature of the MMU propulsion system not noted in any of the prior mentioned systems is its reusability. The MMU was designed for a minimum service life of twelve years including 100 flights with 600 hours flight time. The total component count for the propulsion system includes: two quick disconnects, two toggle valves, two pressure gauges, two tanks, two motor driven isolation valves, two pressure regulator/relief valves, one service valve, one 10 micron filter, one pressure transducer, and eight "triad" assemblies each consisting of three solenoid valves and three thrusters. The regulator and the isolation, toggle, and thruster valves have integral filters. The component count and mass is given in Table III.

The Defense Meteorological Satellite Program (DMSP) RCS propulsion module uses a unique mixed mode nitrogen and hydrazine feed system. The RCS provides attitude control and apogee trim during ascent and backup to the reaction wheel control system on orbit *21*. The second version of the DMSP (Block 5D-2) is shown in Fig. 11. Its load of 15.9 kg (35 lbm) of hydrazine is displaced from two tanks by pressure regulated gaseous nitrogen and blows down to a simple and more or less conventional feed subsystem and four 378 N (85 lbf) thrusters. Two 1.1 kg (2.5 lbm), 3100 N/cm2 (4500 psia) nitrogen tanks feed to a single line, through a single stage regulator to pressurize the two hydrazine tanks to 320 N/cm2 (465 psia). The most interesting feature is the branch from this line that feeds eight 8.9 N (2 lbf) cold jet nitrogen thrusters. Heaters with individual thermostats maintain a minimum temperature in the regulator, latching isolation valve and nitrogen thrusters. Four of the nitrogen thrusters provide roll control, two each of the nitrogen and hydrazine thrusters provide pitch control. The remaining two each provide yaw control. Specific impulse values for the thrusters are 225 sec for hydrazine and 69 sec for nitrogen. The propulsion system component count and mass is given in Table 4.

Hydrogen/Oxygen

There are two basic strategies for the acquisition of hydrogen or oxygen, as propellants, for Space Station auxiliary propulsion: the gases can be derived from the electrolysis of water, or they can be removed from cryogenic (liquid) storage. A very simple example of an electrolysis system is shown in the Boeing concept, Fig. 12. *22*. Water from a tank is pumped into the electrolysis unit. Water vapor is separated from the hydrogen and the oxygen and returned to the tank. The dried propellant gases are stored at pressure in a tank for each. Pressure regulated hydrogen feeds the resistojet(s) and the primary thruster. Pressure regulated oxygen feeds the primary thruster. Balance oxygen is tapped off the valve at the oxygen tank inlet for use in the ECLSS. The figure shows no redundancy though an actual Space Station system would almost certainly have at least dual redundancy through most of the system.

In the early seventies H-O propulsion was an option for the Space Shuttle orbiter. The McDonnell Douglas High Pressure Auxiliary Propulsion System concept is representative of the proposed H-O systems *23*. A simplified schematic is given in Fig. 13. The fuels are stored in liquid state. Pressure regulated Helium displaces each fuel from the tank to where it is pumped through the heat exchanger. The fuel is stored in the gaseous state in an accumulator. From there it is pressure regulated and distributed to the thrusters or to power the pumps and heat exchangers. Hydrogen is fed through a gas generator where it is is oxidized. The hydrogen rich propellant drives the turbine which in turn drives the liquid fuel pump. The propellant exiting the turbine is further oxidized in another gas generator and enters the heat exchanger in counter flow to the liquid fuel. The spent propellant is vented from the system through thrusters. The actual system concept specifies triply redundant turbopumps, heat exchangers, gas generators, and regulators for both the hydrogen and the oxygen halves of the system. There are four venting thrusters in two sizes for each half as well. If such a system was applied to Space Station, the H-O thrusters would provide main propulsion. The reacted propellant would be fed to the resistojets for auxiliary propulsion.

In a Martin Marietta concept, hydrogen and oxygen fuel the primary thrusters and hydrogen is used for resistojet auxiliary propulsion Fig. 14, *24*. The system is highly symmetrical and the resistojets could just as easily be fed oxygen instead of hydrogen. Like the early Space Shuttle concept, this concept calls for liquid storage of the hydrogen and oxygen. The schematic shows dual redundant tanks for each propellant with dual redundant filters and valves for each tank. There is a pump and motor for each tank exit line and the motors may be coupled. The tank service lines are redundant with an isolated crossfeed for each tank pair. These sub-systems feed through single heat exchangers, check valves, an into a single accumulator for each propellant. Once again there are dual redundant filters and valves at the exit of each accumulator. The oxygen line feeds directly into the primary thruster module. The hydrogen line feeds the resistojet modules and the primary thruster module. There is a pressure transducer and an EVA service valve/disconnect at the exit of each tank and accumulator, and before the inlet of each heat exchanger. There is a relief valve on or near each tank and accumulator. All of the hydrogen/oxygen systems described are engineering concepts; none have flown. Though H-O systems have flown, individual use of either hydrogen or oxygen in a low thrust system has not been applied. Development effort is needed in the area of components. It would be necessary to adapt or develop an electrolysis unit, a small water pump, and gas dryers for the low thrust space application. Some technological development is needed for the cryogenic boiloff feed system. For instance, the system described requires small cryogen pumps. Other system concepts may require small compressors capable of handling cryogenic gases. Both the pump and the compressor need development.

Biowaste

No biowaste propellant system is known to have flown. All system design information available is conceptual. McDonnell Douglas has generated concepts for biowaste propellant feed system designs in support of the Manned Orbiting Research Laboratory program *25,26*.

The illustrated McDonnell Douglas concept, Fig. 15, is a segment of a combined carbon dioxide, methane, and water system. In this case the Sabatier process is used for carbon dioxide reduction. In the system water is used to supplement the CO2 or methane propellants during periods when the thrust requirement exceeds the capability of CO2 or methane alone.

CO2 from the ECLSS is stored in an accumulator. From there it is fed to a compressor and on to higher pressure storage. The propellant is then pressure regulated to the thrusters. CO2 from the ECLSS accumulator may alternately be reduced in a Sabatier unit to oxygen, methane and water. The methane is blown from the Sabatier unit to an accumulator, from there the methane feed subsystem parallels the CO2 feed subsystem. From the Sabatier unit water is stored in an accumulator. From there water is boosted by a pump to the vaporizer and on to the thrusters or an accumulator. Pressure regulated CO2 is used as a pressurant to expell the water from the second accumulator. The water, methane, CO2 and CO2/methane lines each crossfeed to identical subsystems.

Other Propellant Options

One way to simultaneously avert problems of resupply and reliability is to combine the use of different propellants. This is exemplified by the McDonnell Douglas concept though the idea is certainly not limited to biowaste propellants. Carefully conceived, such a system would not be required to rely on a resupply of any one of its constituent propellants or function of its feed subsystems. Unfortunately, the technology for this attractive concept is relatively undeveloped or undemonstrated. Technology for the subsystems may well be developed. If nitrogen is to be one of the propellants for example, the nitrogen feed subsystem could resemble a pressurant system from a hyrazine propulsion system. However, from where this feed subsystem merges with the other feed subsystems, all components must be capable of handling all of the propellants including mixtures and possibly different pressures. A requirement for the development of new components or the demonstration of existing components for multipropellant capability is likely. Examples of components that may require development include: line valves, selector valves, and thrusters. The largest concern is with seat and seal material compatibility for the valves.

The propellants and their feed systems covered so far are those currently considered candidates for Space Station auxiliary propulsion or are of particular interest. There are a number of other fluids that can be used as propellants not currently under consideration for Space Station. A number of inert gases, for instance, may have properties that could ultimately prove ideal or, at least, more desirable than the current candidate propellants. A feed system for an inert gas propellant might resemble a proven gas feed system such as that of the MMU or the DMSP. Helium, for instance, has been used as a pressurant as nitrogen has. A pressurant subsystem is essentially a feed system by itself. A list of optional propellants might include: helium, argon, krypton, and neon.

SYSTEM COMPARISON AND ANALYSIS

Examples of propulsion systems with flight heritage and system concepts have been individually described and examined. Tables V and VI provide an overall comparison of those systems that have flight heritage. Table V compares the systems by major component counts and by system dry mass. The FLTSATCOM, CTS, ATS 6, and INTELSAT V are similar in layout appearance. With the exception of the catagories of heaters and temperature sensors their component counts are comparable. The CTS has the highest total major component count at 149. In spite of similarities in appearance, the dry masses for these four systems differ by as much as 133 percent. Of these systems with available dry mass data, the ATS 6 is the most massive at 37.4 Kg. The most massive of the ten systems is that of the MMU at 47 Kg. The MMU mass penalty is due, in part, to high pressure gas storage. The system of the least components and mass is that of the ATS IV, with thirteen major components at 6.0 Kg. This system, however, was designed only for east-west station keeping which is a considerably simpler and lighter propulsive requirement. The most common number of tanks in a system is two. Pressurant tanks, regulators, relief valves, and accumulators are not widely used. A common number for pressure transducers and line filters is two or three. It should be noted that in some cases, with filters for example, some of the systems mentioned may have a number of filters greater than that noted in Table V. It is common for some types of components, such as valves, to have integral filters. These are functionally not separate components and are therefore not noted as such. In another case, gas generators are noted as separate components.

Table VI compares the systems by their usage. From the data available, the most efficient system dry mass to total spacecraft mass ratio is 0.015 for the INTELSAT V. The FLTSATCOM runs a close second with a ratio of 0.016. The least efficient system in this respect is that of the MMU with a ratio of 0.15. It is noteworthy that the MMU is the only spacecraft system described by the table that is reusable and has a crew safety concern. Most of the systems described are not reusable. The total propellant throughputs are no greater than the single total propellant load. The INTELSAT V propellant load of 213 Kg of hydrazine was calculated to be sufficient for all required maneuvers for at least seven years in geosynchronous orbit. The Space Station is expected to orbit at approximately 400 Km for ten years. In a nominal year of high solar activity that 213 Kg would provide Space Station with less than a month and a half of drag makeup propulsion alone. From the standpoint of propellant throughput, none of the described systems that have flown come close to meeting Space Station requirements. An increase in throughput is associated with an increase in required component cycle life. The difference between the nominal seven year mission of the INTELSAT V and the anticipated ten year mission of the Space Station is not significant. However, the total propellant throughput for ten years of Space Station orbit maintenance with hydrazine could be 1000 times that of the INTELSAT V in seven years. The differences in component cycle life requirements between the two space systems are therefore significant. The high cycle life requirement is not a great concern for some Space Station components. Fittings should not be affected by pressurization cycles. With a 90 day resupply schedule, service valves may be cycled as infrequently as 40 times in the ten year nominal service life of the station. By the same consideration, propellant storage tanks would experience only 40 fill and drain cycles. Line and thruster valves have been qualified with cycle lives in the millions. The thruster valves on the LES 8/9 were qualified for two million cycles, for example. For some components duty cycle time is more the driving factor. Hydrazine catalytic gas generators have yet to demonstrate long service lifetimes required for Space Station propulsion. Some components are unaffected by cycle life or system service life requirements, but carry different longevity concerns. In a system with perfectly clean propellant a filter could last indefinitely. Because no propellant is perfect, and contamination levels may be difficult to predict, filter element life may also be difficult to predict. For instance, a component failure upstream of a filter could release enough wear debris contamination to saturate the element.

Some component development will be necessary to adapt the satellite propulsion system concepts to the long life and crew safety requirements of the Space Station. Filters capable of removing more contaminiation before saturating will be needed. If low thrust hydrazine is to be used, longer life gas generators will have to be developed.

The propulsion system concepts described each present a means of handling different propellants or propellant combinations. The concepts bare little resemblance to the systems with flight heritage or to each other. These systems provide base line information for Space Station resistojet feed system design. Some of the concept systems require special components not common to the systems that have flown. Components such as the biowaste gas compressor, the small water pump, and the water boiler have not been developed and demonstrated in a space propulsion system. These components would have to be developed.

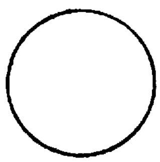
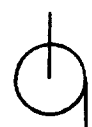
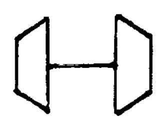
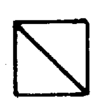
CONCLUDING REMARKS

There are many feed systems that may have application to resistojet propulsion for Space Station. Representative examples of these systems with flight heritage or in the conceptual stage have been described and examined. Some of the system types described have been well demonstrated on orbit with mission lifetimes over seven years. Other system types are engineering concepts. For the satellite systems described, feed system dry masses ranged from around 1.5% of total spacecraft mass for hydrazine, to around 15% for nitrogen. A typical feed system component count is in the 100 to 200 range. A propellant load of about 200 Kg is large for a representative hydrazine satellite system. A Space Station auxiliary propulsion system may compare to a satellite system by schematic appearance, but component requirements would be more demanding for Space Station because of higher propellant throughputs. A Space Station hydrazine auxiliary propulsion system might have a total throughput up to 1000 times of the maximal satellite described. Relatively short lived components such as filters and gas generators will likely need development to adapt a satellite propellant feed system schematic to Space Station use.

There are many possible feed system concepts that may have application to Space Station or other space systems. Each has unique advantages and disadvantages. It is therefore necessary for the propulsion system designer to be familiar with all of the candidate system concepts.

Appendix

SYMBOLS

	CONNECTOR
	QUICK DISCONNECT
	TANK/ACCUMULATOR
	FILTER
	PRESSURE TRANSDUCER/GAUGE
	TEMPERATURE TRANSDUCER
	SERVICE VALVE
	LINE VALVE
	RELIEF VALVE
	CHECK VALVE
	THRUSTER VALVE
	PRESSURE REGULATOR
	POSITION INDICATOR
	ORIFICE
	FLOW CONTROL
	PRESSURE SWITCH
	PRESSURE CONTROL
	COMPRESSOR/PUMP
	TURBO PUMP
	ELECTRIC MOTOR
	GAS GENERATOR
	HEATER
	HEAT EXCHANGER
	THRUSTER

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<(*)>**<(*)>****<(*)>****<(*)>****<(*)>****<(*)>****<(*)>****<(*)>**

Note:

Where numbers are surrounded by asterisks they are reference notes. At the time of writing it was not known how to superscript in TEDIT. For example *3,4* means references numbers 3 & 4.

Scientific notation was written as follows (for the same reason):

1 X 10E7 - is one times ten to the seventh power (ten million)

Because it also was not known how to subscript, chemical compounds such as CO2 and H2O should actually have subscripted 2's.

<(*)>**<(*)>****<(*)>****<(*)>****<(*)>****<(*)>****<(*)>****<(*)>**

Table I

Component Count and Mass for the FLTSATCOM Spacecraft RCS

Component	Quantity	Total Mass kg (lb_m)	Supplier
Propellant Tank Assy	2	15.2 (33.5)	Pressure Systems, Inc.
Service Valves	4	0.3 (0.6)	TRW
Pressure Transducer	2	0.4 (0.8)	Statham
Filter	2	1.0 (2.2)	Wintec
Latching Isolation Valve	7	1.8 (3.9)	HR Textron
Thruster Valves	20		Parker Hannifin & Allen Design
HLT's and LLT's	20		TRW
Catalyst Bed Heaters	20		Tayco
Thermisters	20		Fenwal
Thermostats	20		Sundstrand
Dual Thruster Modules	10	7.7 (17.0)	
Line Heaters & Misc. Hardware		1.9 (4.1)	Tayco (heaters)
Total System Dry Mass		28.0 (61.9)	TRW

Table II

Component Count and Mass for the Applications Technology Satellite-6 Propulsion System

Component	Quantity	Total Mass kg (lb_m)	Supplier
Propellant Tank	2	8.12 (17.90)	Pressure Systems
Service Valves	4	0.40 (0.88)	Rocket Research
Pressure Transducer	2	0.16 (0.35)	Dyna Sciences
Filter	2	0.10 (0.23)	M/S Filters (Vacco)
Latching Isolation Valve	7	1.91 (4.20)	Carlton Controls
Thruster Valves	16		Parker Hannifin
Thruster Assemblies	16	4.72 (10.40)	Rocket Research
Temperature Sensors	34	0.11 (0.25)	Fenwal, Rosemont Eng., American Standard
Thermal Control		10.43 (23.00)	Clayborn Labs
Lines & Fittings		1.37 (3.01)	Aeroquip (fittings)
Structure, Hardware & Wiring		10.06 (22.18)	
Total System Dry Mass		37.38 (82.40)	Rocket Research

Table III

Component Count and Mass for the Manned Maneuvering Unit Propulsion System

Component	Quantity	Total Mass kg (lb_m)	Supplier
Propellant Tank	2	25.40 (56.00)	Structural Composites Industries
Quick Disconnect	2	0.28 (0.62)	Symetrics
Toggle Valve	2	0.89 (1.96)	Carleton Controls
Pressure Gage	2	0.15 (0.32)	HTL
Isolation Valve	2	2.40 (5.30)	Carleton Controls
Regulator/Relief	2	0.73 (1.60)	Sterer Engineering
"Triad" Thruster Assy	8	7.62 (16.80)	HR Textron
Welded Assemblies, Brackets, Hardware		9.57 (21.10)	
Total System Dry Mass		47.04 (103.70)	Martin Marietta

Table IV

Component Count and Mass for the Defense Meteorological Satellite, Block 5D-2 Mission Propulsion System

Component	Quantity	Total Mass kg (lb_m)	Supplier
Pressurant Tank	2	3.33 (7.34)	Airite
Propellant Tank	2	3.40 (7.50)	TRW
Regulator	1	0.91 (2.00)	Marotta
Pressure Transducer	2	0.38 (0.84)	Gould
Service Valves	3	0.54 (1.20)	Pyronetics
Filters	15	0.06 (0.14)	Wintec
Isolation Valve	2	0.91 (2.00)	Pyronetics
Latch Valve	1	0.61 (1.35)	HR Textron
Relief Valve	1	0.18 (0.40)	Carleton Controls
Manifold, Nitrogen High	1	0.33 (0.72)	RCA
Manifold, Nitrogen Low	1	1.21 (2.68)	RCA
Manifold, Hydrazine	1	2.27 (5.00)	RCA
Thruster Valves	12		
Nitrogen Thruster Assy	4	2.00 (4.40)	Wright
Hydrazine Thruster Assy	8	5.30 (11.68)	Marquardt
Total System Dry Mass		21.43 (47.25)	RCA

Table V

Major Individual Component Count and System Dry Mass Comparison

Spacecraft / Component	FLTSATCOM	CTS	ATS 6	INTELSAT V	IUE	TRW System	ATSIV	LES 8&9	MMU	DMSP
Pressurant Tank	-	-	-	-	-	-	-	-	-	2
Propellant Tank	2	2	2	2	6	2	1	1	2	2
Service Valve	4	4	4	4	9	2	-	1	2	3
Pressure Transducer	2	2	2	2	3	2	-	1	2**	2
Line Filter	2	2	2	2	3	3	-	2	-	15
Regulator *	-	-	-	-	-	-	2	2	2***	1
olation Valve	7	7	7	4	7	2	2	4	2	3
Relief Valve	-	-	-	-	-	-	-	-	***	1
Accumulator	-	-	-	-	-	1	2	1	-	-
Gas Generator	-	-	-	-	-	1	-	1	-	-
Temperature Sensor	20	14	18	NA	12	NA	-	NA	-	NA
Heaters	NA	82	44	NA	NA	11	2	5	-	18
Thruster Valves	20	18	16	20	12	12	2	10	2	4****
Thrusters	20	18	16	20	12	12	2	10	24	12
Total Major Components	77+	149	111	54+	64+	48+	13	38+	58	63+
Total System Dry Mass Kg (lbm)	28.0 (61.9)	NA	37.4 (82.4)	16.0 (35.3)	26.4 (58.1)	NA	6.0 (13.0)	20.7 (45.6)	47.0 (103.7)	21.4 (47.3)

* includes regulator valves ** gage ***relief integral with regulator ****N_2 thruster & valves integral

Table VI

Propulsion System Usage Comparison

Spacecraft / Component	FLTSATCOM	CTS	ATS 6	INTELSAT V	IUE	TRW SYSTEM	ATS IV	LES 8&9	MMU	DMSP
System Dry Mass Kg (lbm)	28.0 (62)	NA	37.4 (82.4)	16.0 (35.3)	26.4 (58.1)	NA	6.0 (13.0)	20.7 (45.6)	47.0 (103.7)	21.4 (47.3)
Propellant Type	N_2H_4	N_2H_4	N_2H_4	N_2H_4	N_2H_4	N_2H_4	NH_3	NH_3	N_2	N_2/N_2H_4
Propellant Mass Kg (lbm)	122 (268)	24.8 (54.7)	49.1 (108.2)	227 (500)	27.3 (60.2)	64 (140)	1.4 (3)	34 (75)	11.5 (25.4)	2/16 (5/35)
System Wet Mass Kg (lbm)	150 (330)	NA	87.3 (192.4)	343 (756)	53.7 (118.3)	NA	7.3 (16)	55 (121)	58.6 (129.1)	40 (88)
Total Spacecraft Mass, Kg (lbm)	1788 (4100)	346 (763)	1361 (3000)	1035 (2282)	NA	NA	NA	494 (1088)	310 (685)	NA
Mission Length, Years	7	2	5	7	NA	NA	(2 mo.)	5 minimum	(6 hrs.)	NA
Cumulative Thruster firing time, hrs	NA	NA	NA	NA	289/yr	NA	825	NA	NA	NA
Total Firings	2.6×10^5	9043 + 28300 per year	NA	NA	6800 + 3.38×10^6 per year	NA	NA	NA	NA	NA
Approx Power Usage W	14.5	NA	45	NA	NA	NA	11	25	42	NA
Design Total Impulse Ns (lbf sec)	157,980 (35,540)	NA	86,600 (19,500)	NA	47,500 (10,700) estimated	110,700 (24,900)	1778 (400)	28,000 (6,300)	NA	36,500 (8,200) estimated

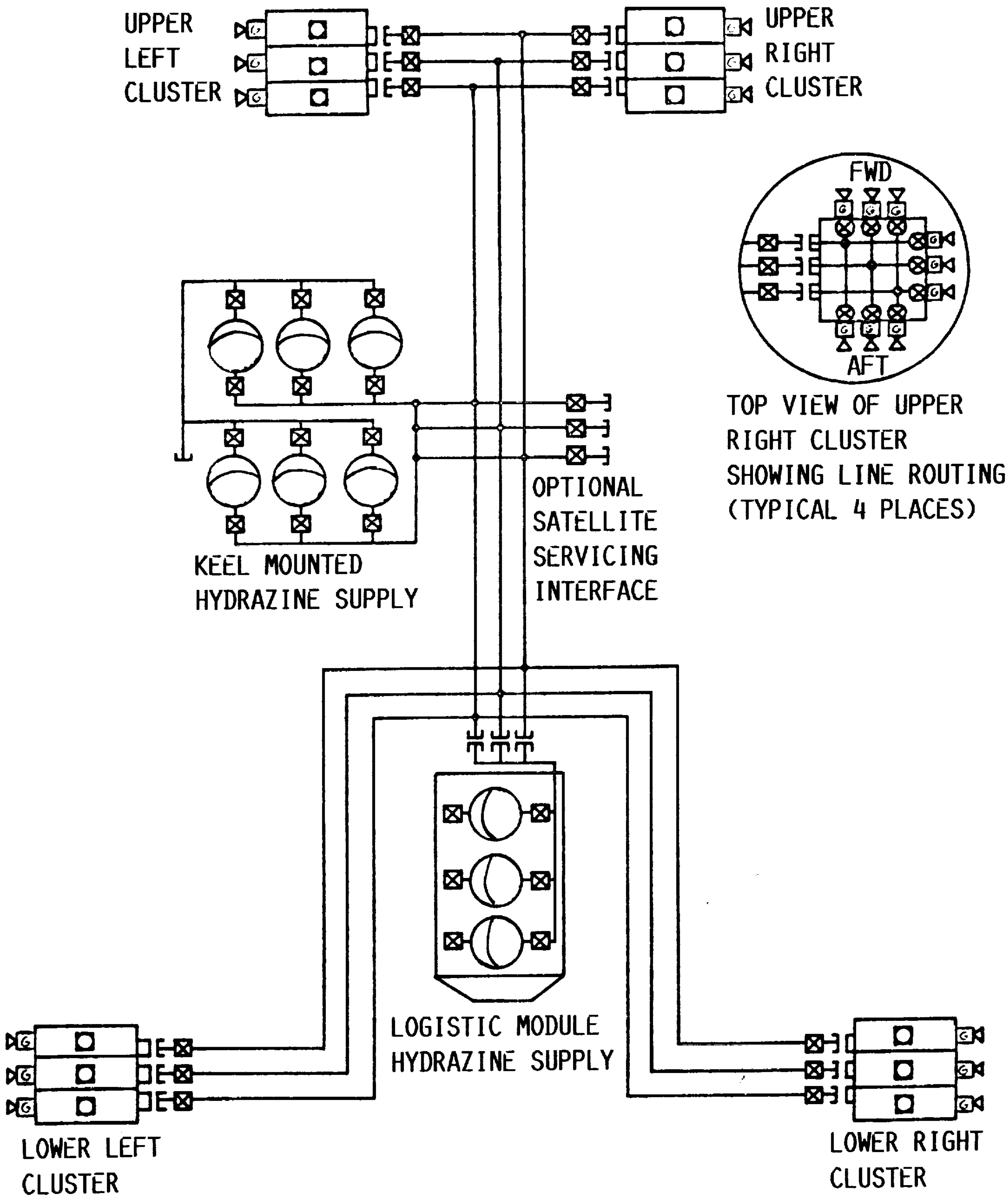

FIGURE 1.- SPACE STATION PROPULSION SYSTEM REFERENCE CONFIGURATION 1984.

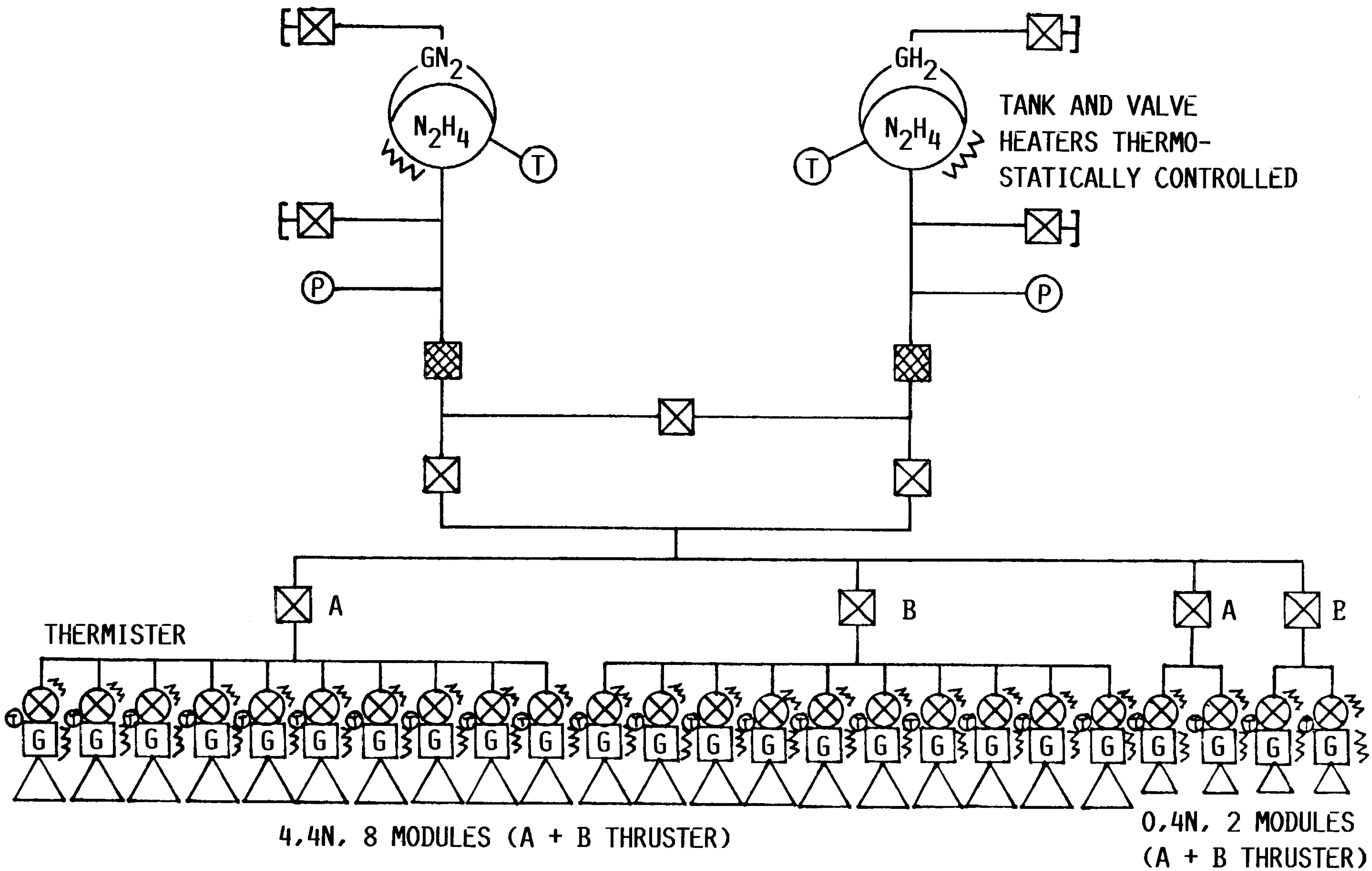

FIGURE 2.- FLEET SATELLITE COMMUNICATIONS (FLTSATCOM) REACTION CONTROL SYSTEM (RCS) SCHEMATIC.

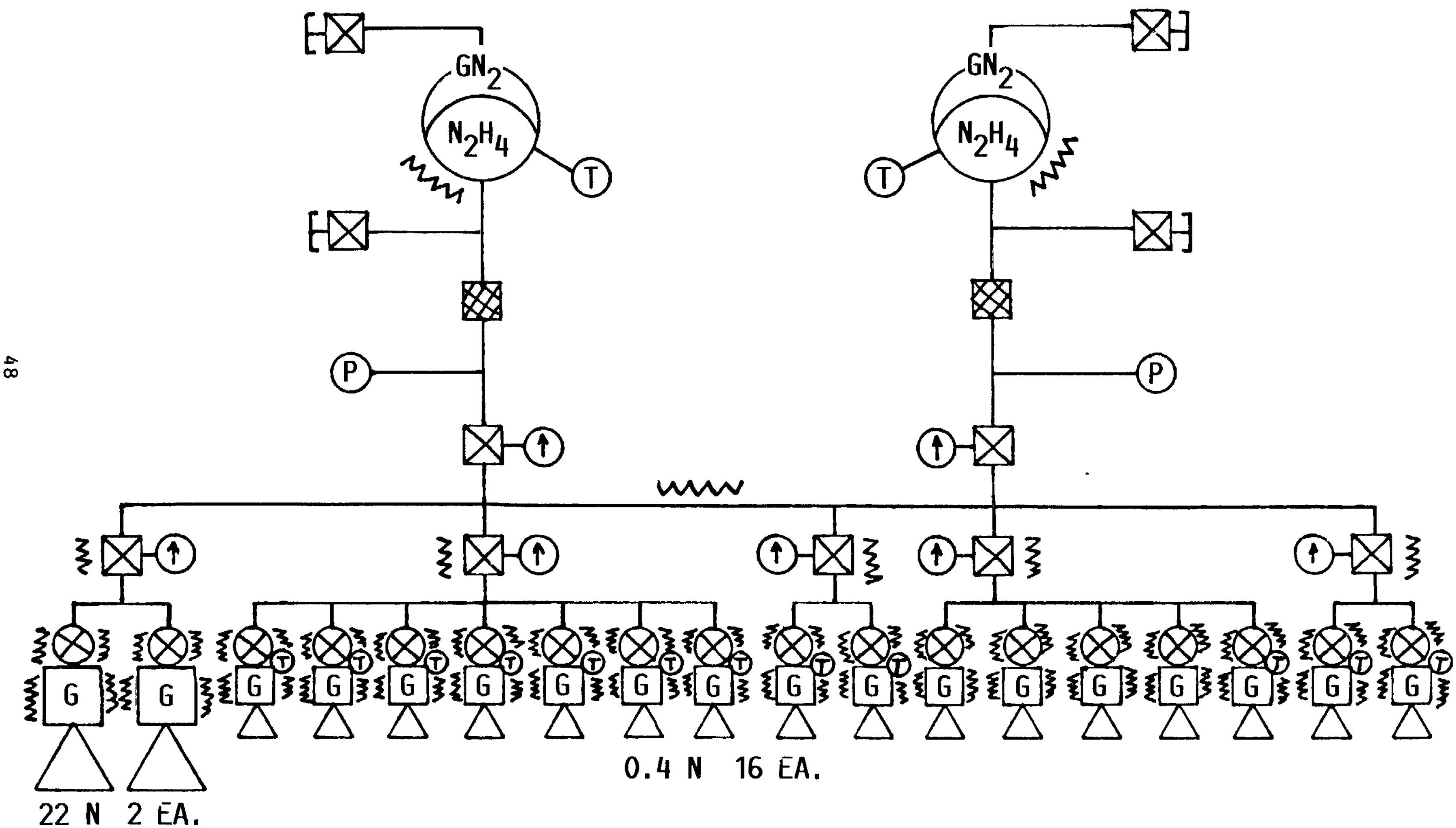

FIGURE 3.- COMMUNICATIONS TECHNOLOGY SATELLITE (CTS) REACTION CONTROL SYSTEM (RCS) SCHEMATIC.

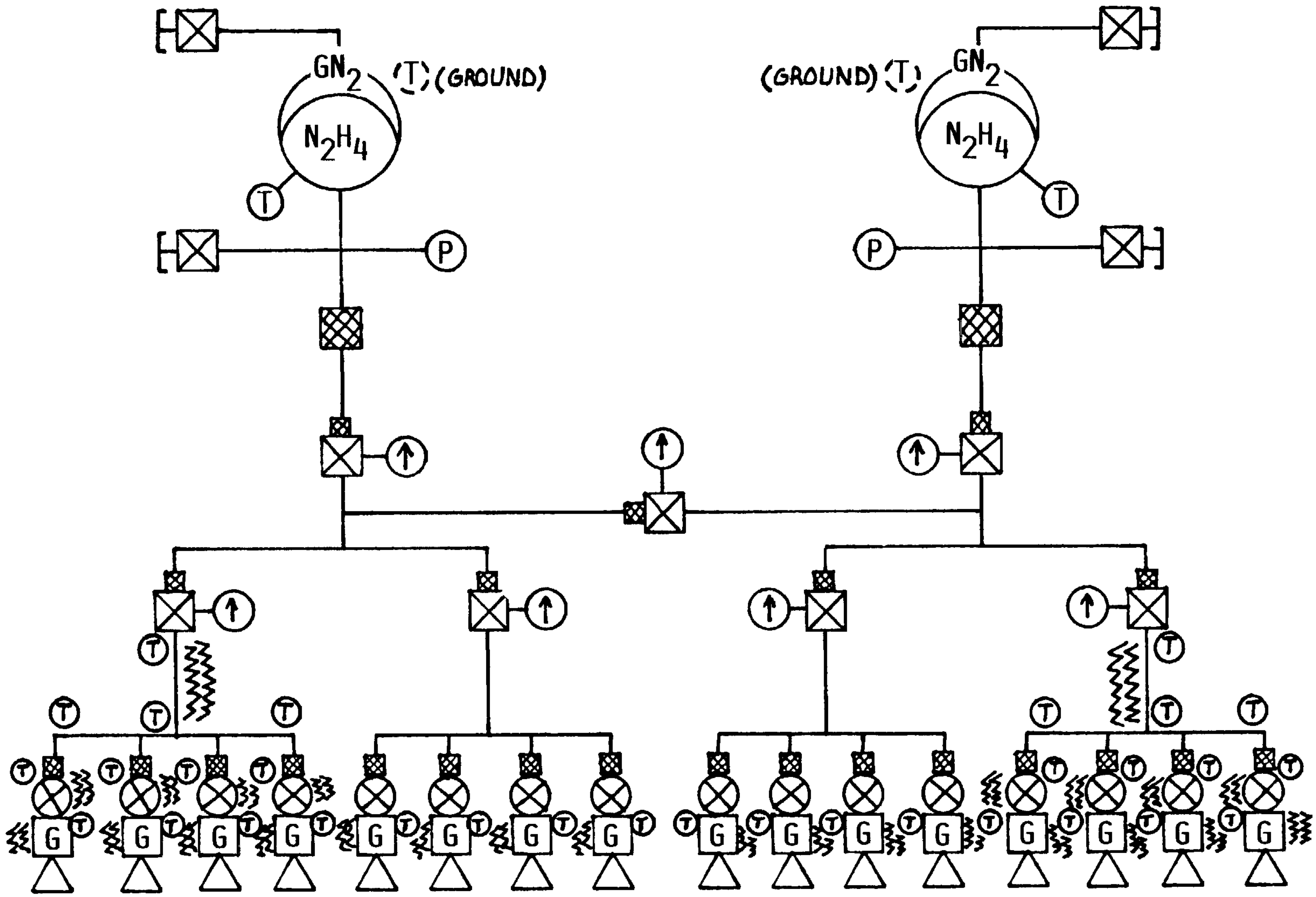

FIGURE 4.- APPLICATIONS TECHNOLOGY SATELLITE (ATS 6) PROPULSION SYSTEM SCHEMATIC.

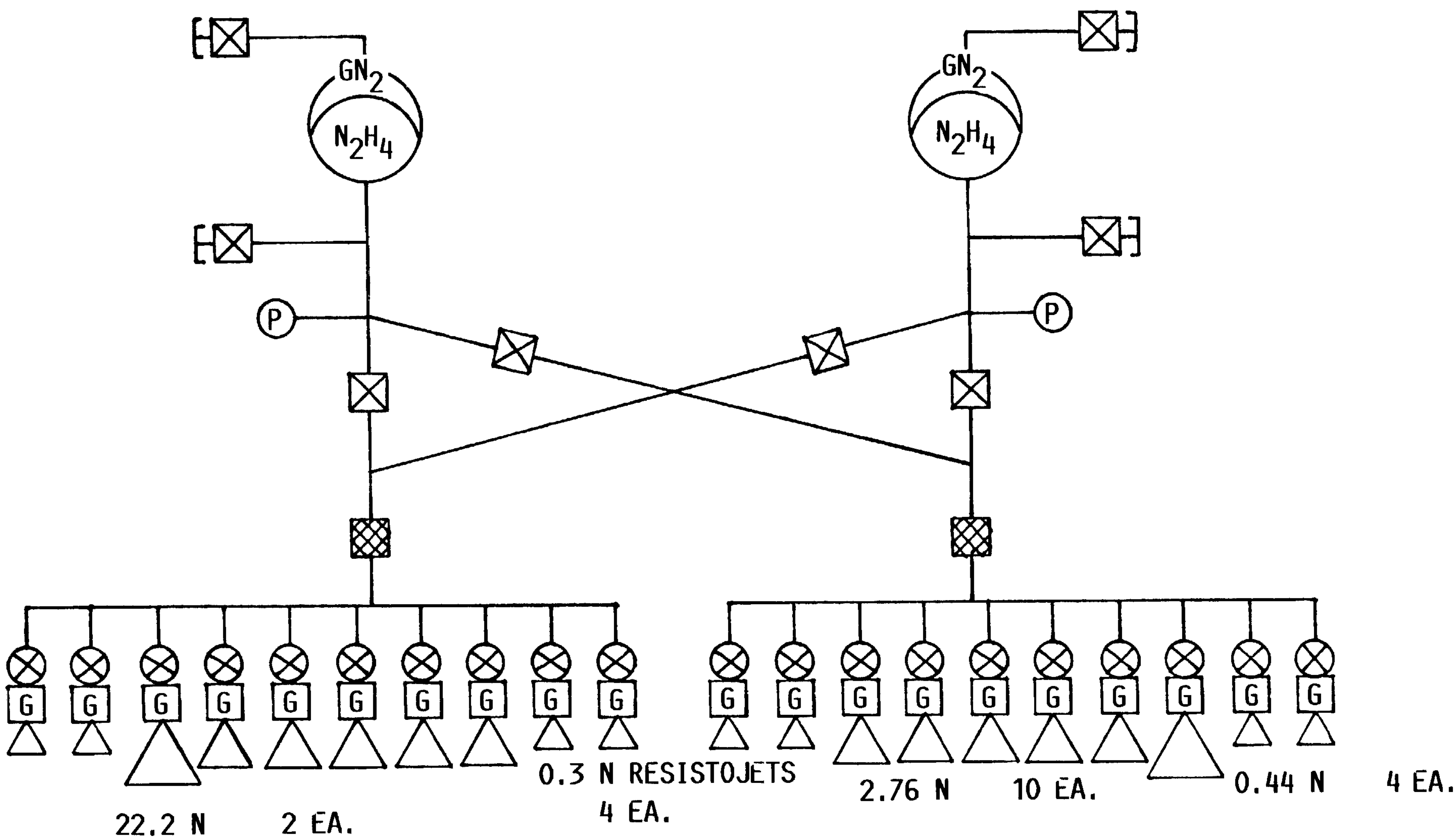

FIGURE 5.- INTELSAT V PROPULSION SYSTEM SCHEMATIC.

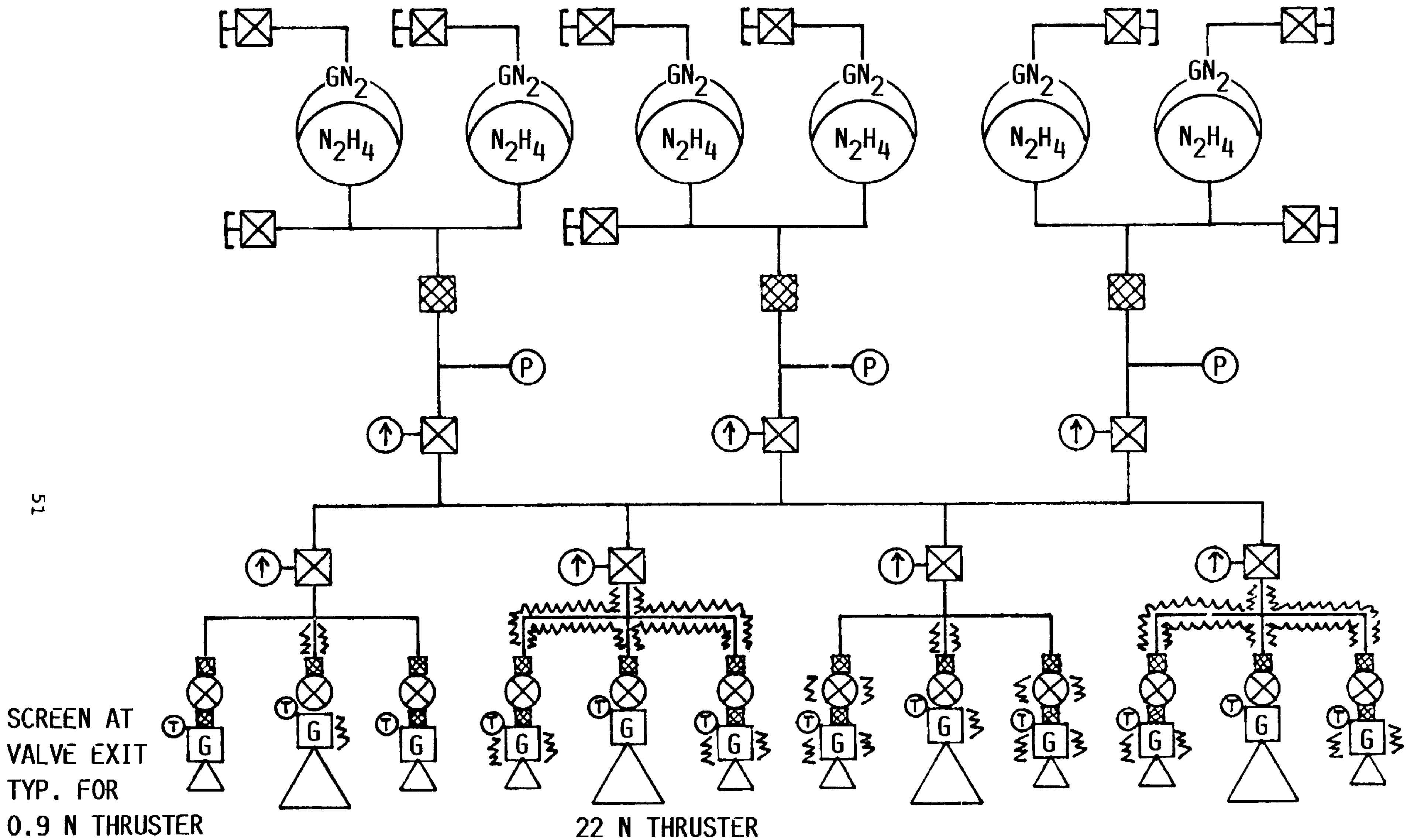

FIGURE 6.- INTERNATIONAL ULTRAVIOLET EXPLORER (IUE) HYDRAZINE AUXILIARY PROPULSION SYSTEM (HAPS) SCHEMATIC.

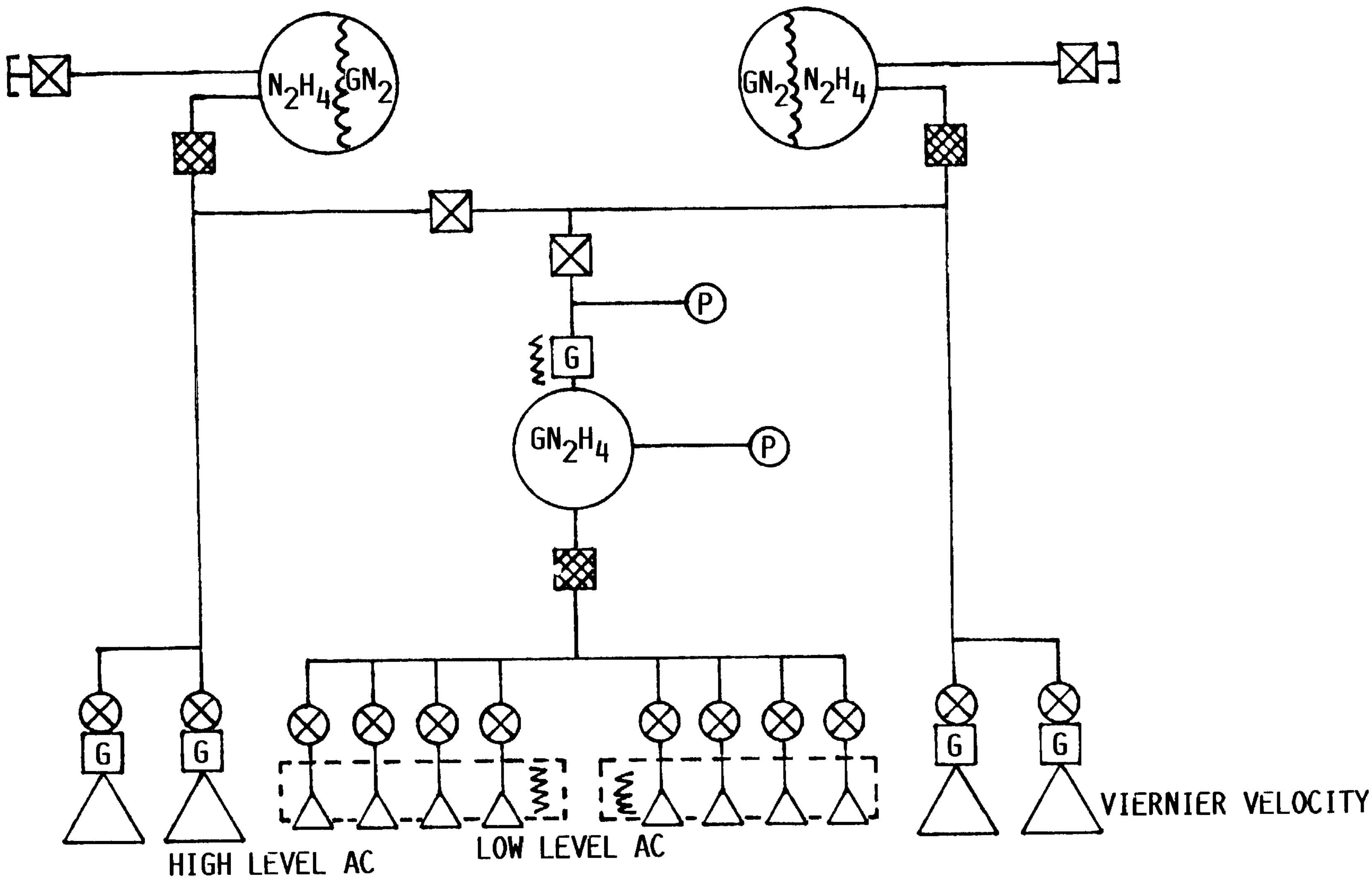

FIGURE 7.- TRW SATELLITE PROPULSION SYSTEM SCHEMATIC.

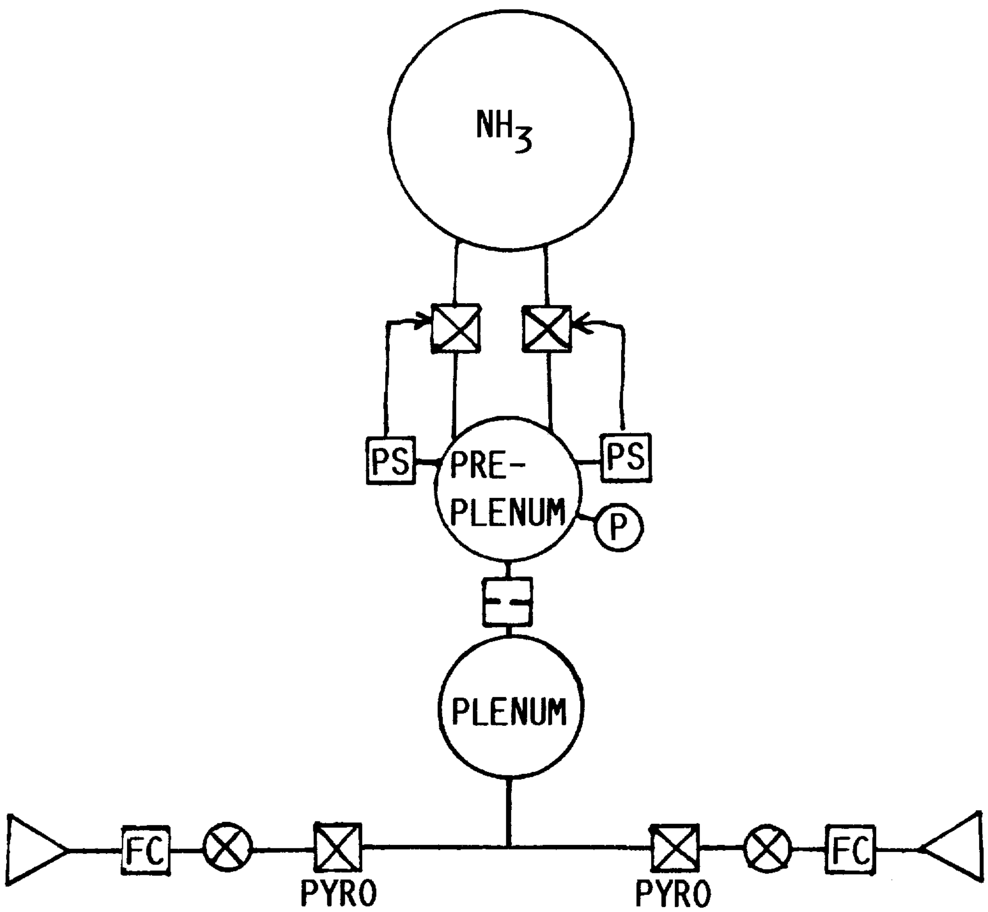

FIGURE 8.- APPLICATIONS TECHNOLOGY SATELLITE (ATS IV) AMMONIA RESISTOJET PROPULSION SYSTEM SCHEMATIC.

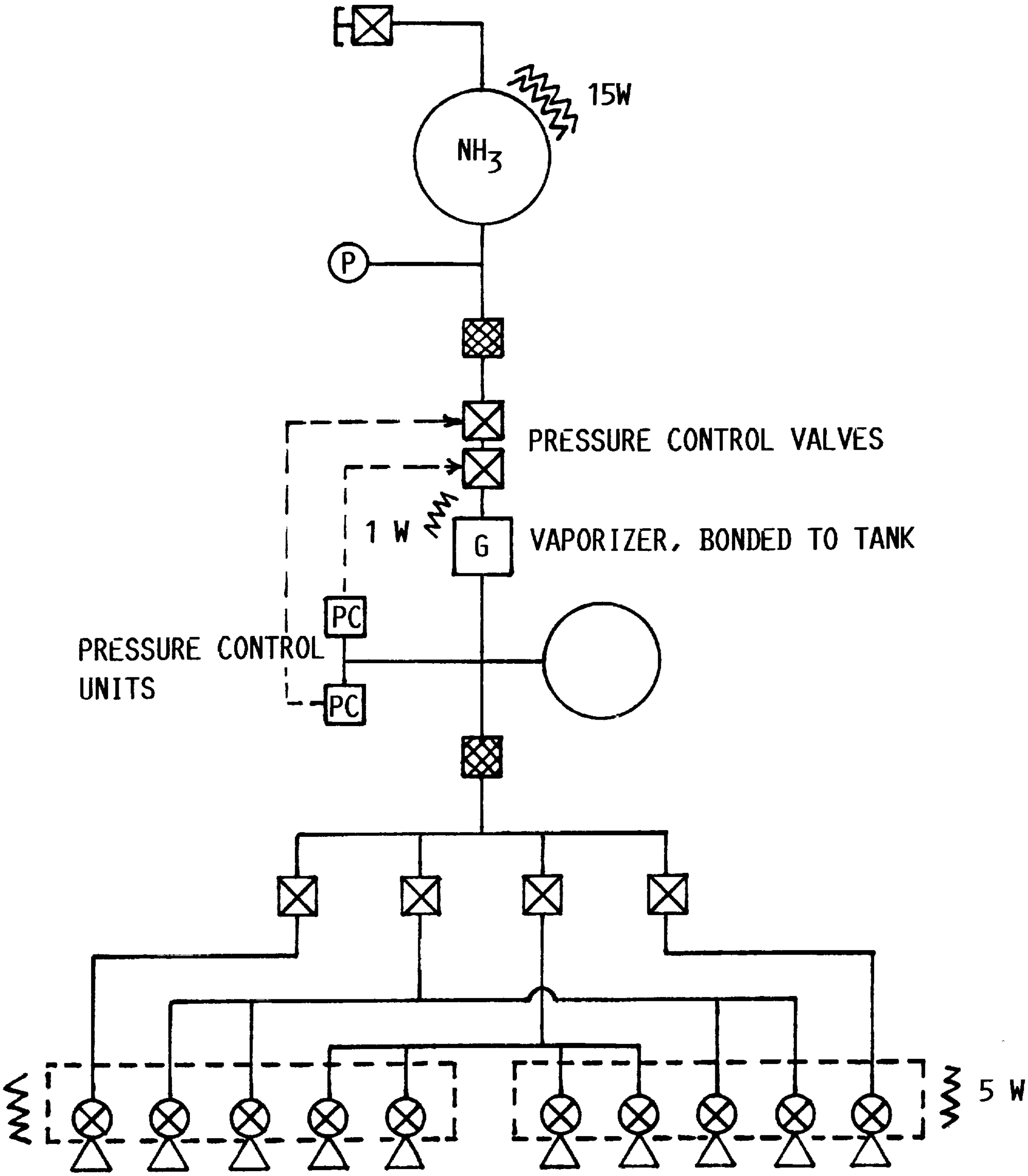

FIGURE 9.- LINCOLN EXPERIMENTAL SATELLITE (LES 8/9) PROPULSION SYSTEM SCHEMATIC.

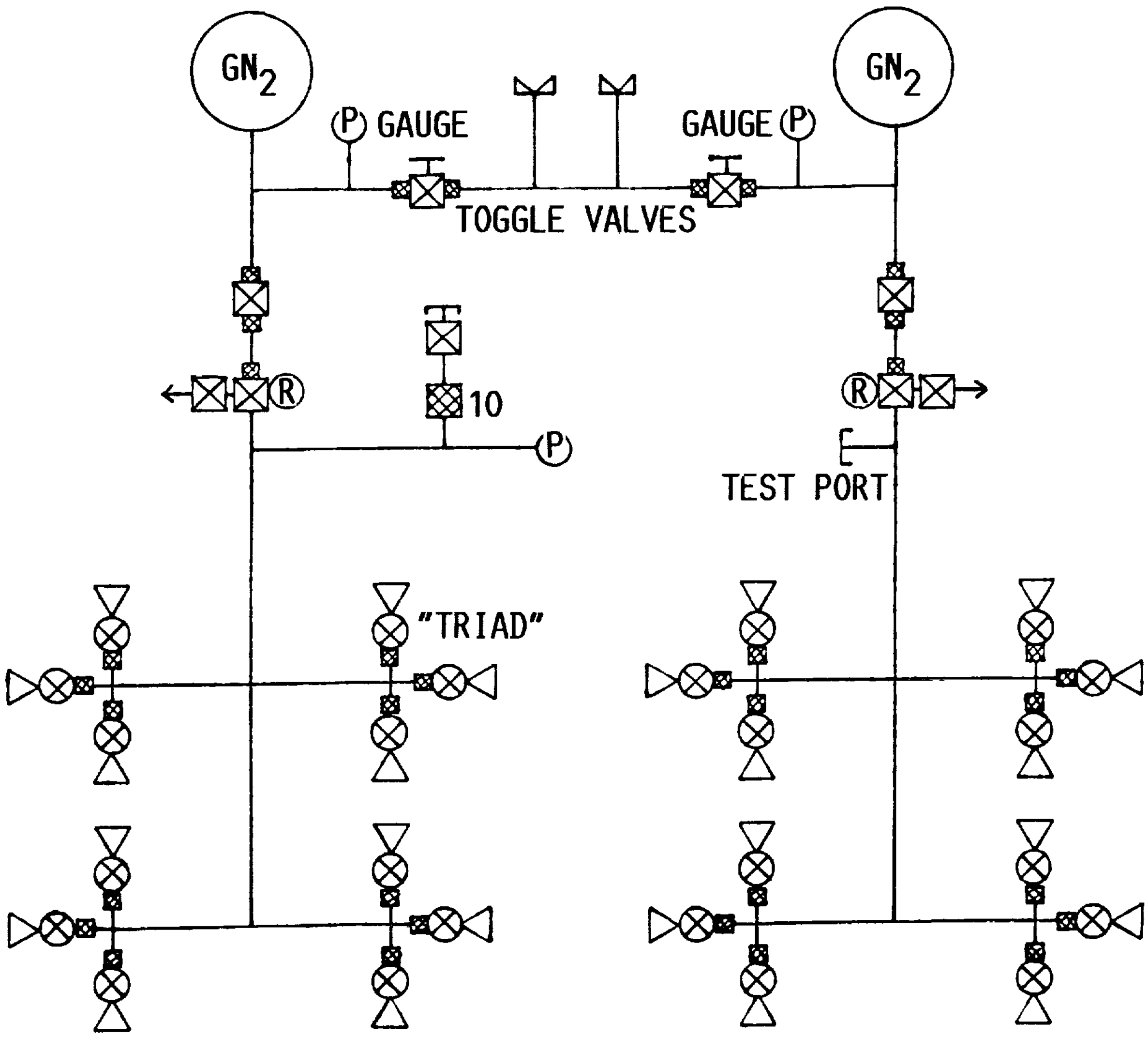

FIGURE 10.- MANNED MANEUVERING UNIT (MMU) PROPULSION SYSTEM SCHEMATIC.

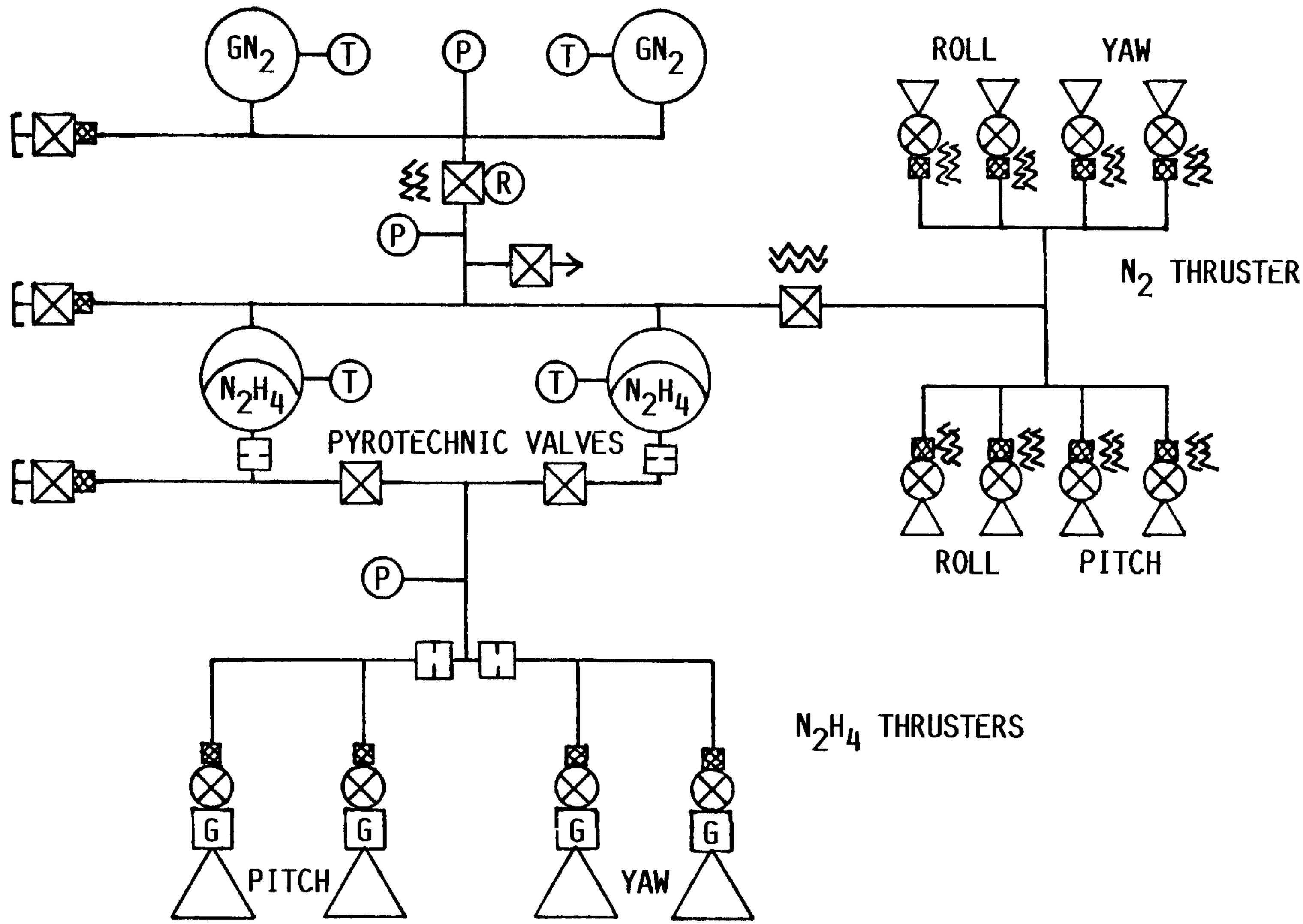

FIGURE 11.- DEFENSE METEOROLOGICAL SATELLITE PROGRAM (DMSP) BLOCK 5D-2 PROPULSION SYSTEM SCHEMATIC.

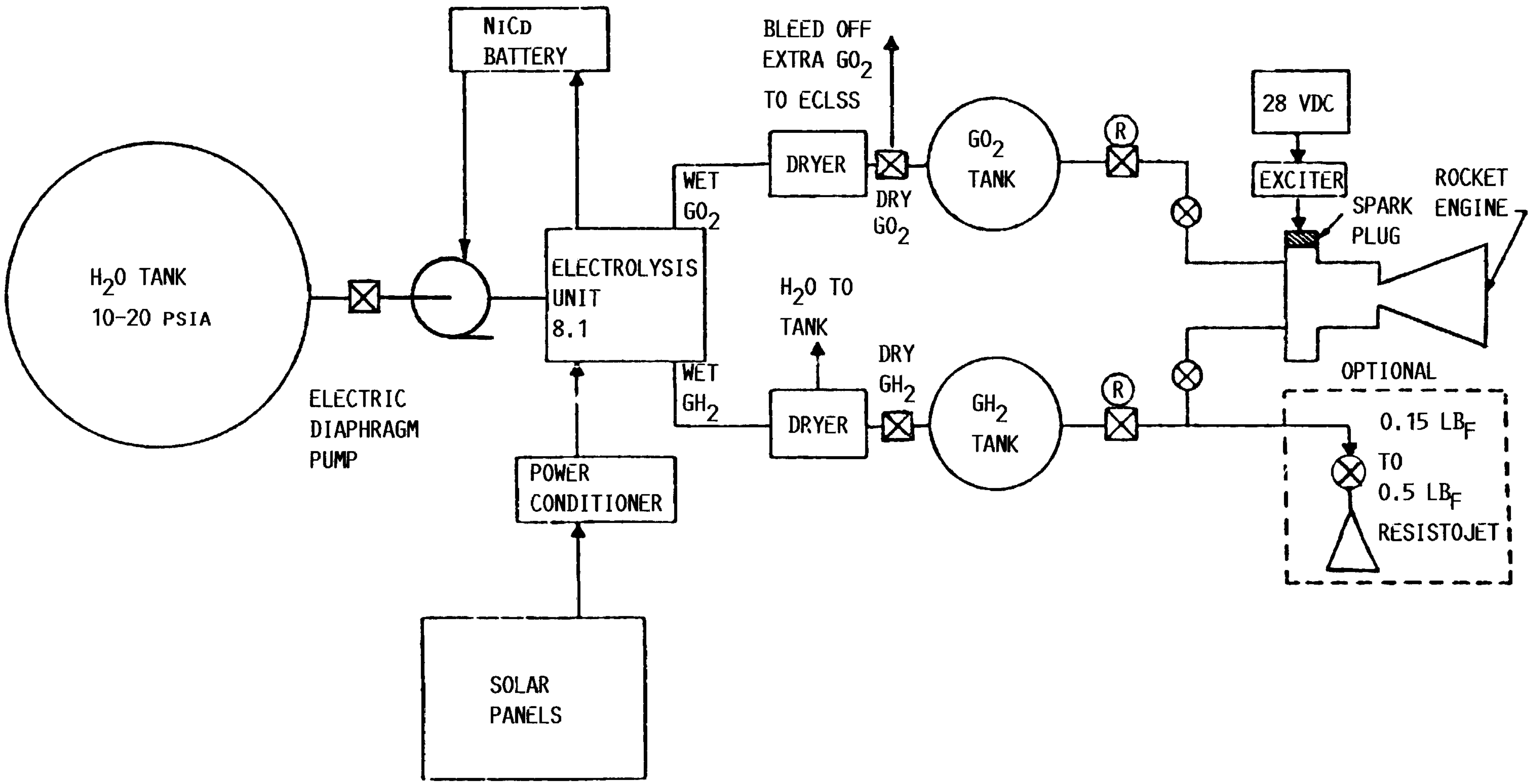

FIGURE 12.- BOEING PROPULSION SYSTEM CONCEPT.

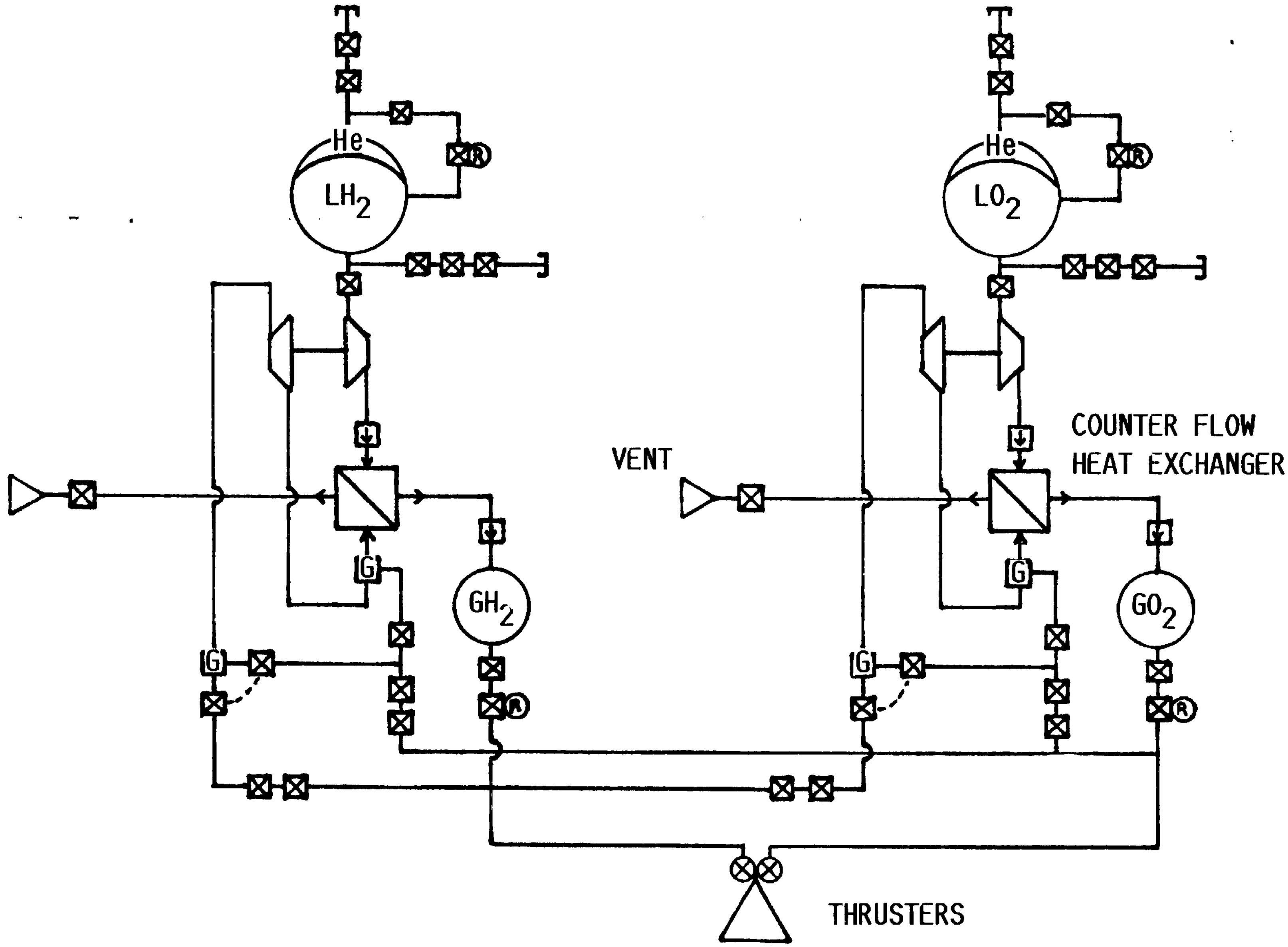

FIGURE 13.- McDONNELL DOUGLAS SPACE SHUTTLE AUXILIARY PROPULSION SYSTEM CONCEPT (SIMPLIFIED).

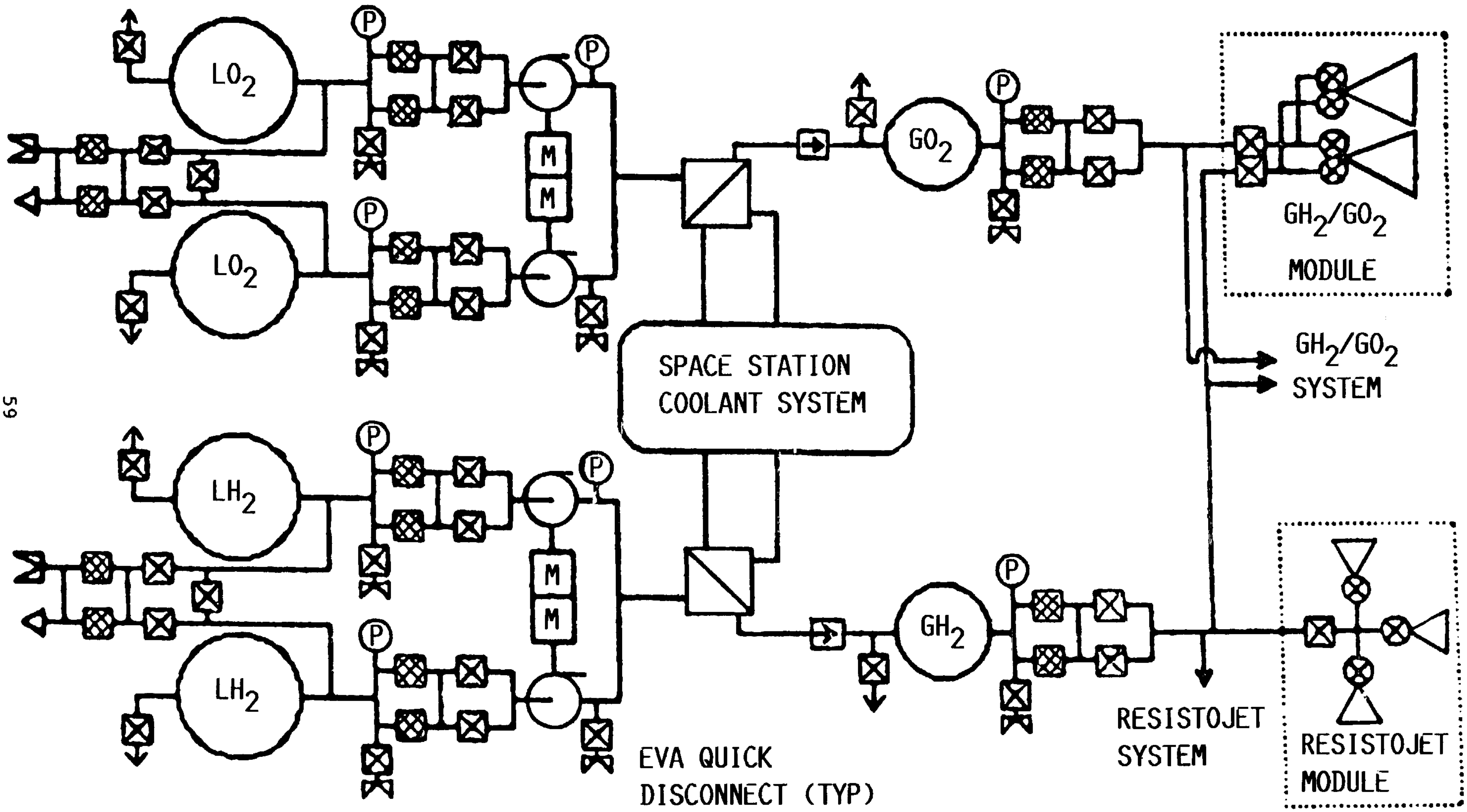

FIGURE 14.- MARTIN MARIETTA PROPULSION SYSTEM CONCEPT.

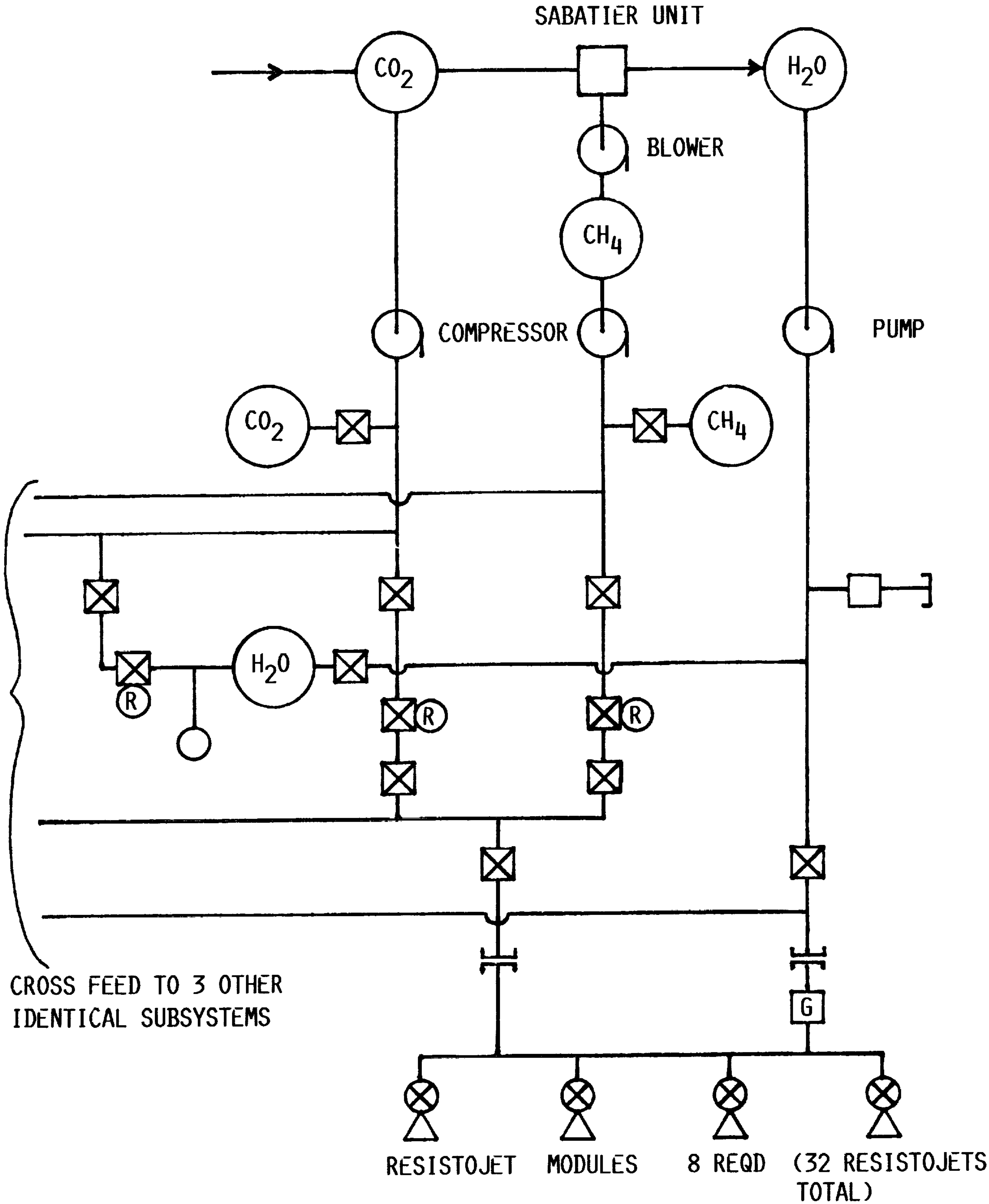

FIGURE 15.- McDONNELL DOUGLAS BIOWASTE PROPULSION SYSTEM CONCEPT.

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15. Supplementary Notes

Project Manager, James Sovey, Spac^ Propulsion Technology Division, NASA Lewis Research Center.

16. Abstract

The resistojet system has been defined as part of the baseline propulsion system for the Initial Operating Capability Space Station. The resistojet propulsion module will perform a reboost function using a wide variety of fluids as propellants. There are many optional propellants and propellant combinations for use in the resistojet including (but not limited to): hydrazine, hydrogen, oxygen, nitrogen, water, carbon dioxide, and methane. Many different types of propulsion systems have flown or have been conceptualized that may have application to use with resistojets. This paper describes and compares representative examples of these systems that may provide a basis for Space Station resistojet system design.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
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