AIAA 80-1291R

Propulsion Subsystem for the Multimission Modular Spacecraft (MMS)

R. Finston* and L. M. Spicer†
Hughes Aircraft Company, Space and Communications Group, El Segundo, Calif.

This paper covers the functional design and construction of the propulsion subsystem for the Multimission Modular Spacecraft (MMS), with emphasis on its unique features. The propulsion system for the MMS is capable of providing velocity increments to the spacecraft to remove launch-vehicle injection errors, maintain or change orbital parameters, and provide three-axis attitude control. The design of the system also allows complete functional redundancy with no probable single-point failure modes. Other features of the subsystem include modularized clusters of hydrazine catalytic thrusters that are integrated with the system via mechanical unions, thus providing convenient disconnect and replacement capability. The thrusters used on the system are the HE-55 5-lbf thrust level and the HE-21A 0.2-lbf thrust-level thrusters. The HE-55 unit is identical to the HE-54 model, which has been qualified for and flown on INTELSAT IV A and COMSTAR, with the sole exception of replacing the hard-seat torque-motor valve with a soft-seat solenoid version. The HE-21A unit was developed for the DSCS III program and qualified specifically for the MMS mission. Both thrusters feature constraint-free firing capability without the use of catalyst bed heaters.

Introduction

THIS paper serves to supplement Ref. 1 and is limited to the details of the MMS propulsion subsystem. The MMS is made up of standard subsystem modules that in turn utilize standard components where possible. The basic propulsion module (PM) is designated PM-I and carries a nominal propellant load of 167 lb of hydrazine. A growth version of the module is designated PM-II which would carry approximately 1100 lb of hydrazine for envisioned missions with larger propellant requirements.

In designing the PM-I, requirements were taken into account so that basic elements of the PM, such as the mechanical retention interface, the thruster modules, control electronics and propellant-feed concepts, can be utilized in modules with larger propellant requirements (Ref. 2). The remaining part of the paper will concentrate on the PM-I as it is currently being fabricated and tested for the Landsat-D mission.

System Description

Design Tradeoffs

A number of propulsion-subsystem configurations were studied with respect to operations and reliability. Tradeoffs were conducted to arrive at a preferred configuration for the propulsion elements. The system operation, performance, reliability, and implementation considerations that guided these tradeoffs were the following:

1) Full redundancy for all attitude and orbit control thruster operations, including the safe-hold mode;

2) Three-seat protection to meet the Shuttle two-seat safety requirement for launch and retrieval, with no single-point failure to preclude the latter.

3) Failsafe thruster operation during unattended portions of the orbit (e.g., out of sight of the ground-control center).

4) No single-point failures and minimization of dual failures that could cause the loss of attitude control (about any axis) or orbit control.

5) Full redundancy for all heater operations, including both automatic (thermostatic control) primary and secondary modes subject to ground override.

6) Straightforward attitude-control system (ACS)/PM interfaces that satisfactorily implement all planned uses of the thrusters for attitude control, including periods of orbit control operations.

7) Implementation using existing or proven technology at minimum cost and risk.

Functional Description

The propulsion subsystem consists of all the necessary components and propellant capacity to provide velocity increments to the MMS to accomplish the following:

1) Orbit adjustment including a) removal of launch vehicle injection errors and b) maintenance or change of orbital parameters.

2) Attitude control including a) initial stabilization of the spacecraft, b) torque for reaction wheel unloading, c) restabilization of the spacecraft, d) counteracting roll disturbance torque during orbit adjust firings, and e) course attitude control of the spacecraft while in the safe-hold mode.

The propulsion subsystem provides thrust on demand by supplying MIL-P-26536C-1 hydrazine from the propellant tanks through the various manifolds, filter, and valves to the appropriate thrust-chamber assembly where the hydrazine is catalytically decomposed and expanded in a conical nozzle. The subsystem configuration is shown schematically in Fig. 1.

Propellant is carried in three 16.5-in. diameter titanium tanks located at 120 deg intervals about the spacecraft roll axis (see Fig. 2). The propellant-pressurant interface in each tank is established and maintained by an AF-E-332 elastomeric diaphragm for positive propellant expulsion in a zero-*g* environment. The pressurant in the tanks expands as propellant is expelled and hence the entire system operates in a blowdown mode. The three tanks carry 167 lb of propellant which provides a 3:1 blowdown ratio, from 300 to 100 psia at the valve inlets.

The gas sides of the three tanks have individual manifolds to three fill and vent valves, with titanium tubing of 0.25-in. diam, leading to the gas-servicing location. The propellant sides are manifolded with 0.25-in. titanium tubing to the

Presented as Paper 80-1291 at the AIAA/SAE/ASME 16th Joint Propulsion Conference, Hartford, Conn., June 30-July 2, 1980; submitted Aug. 25, 1980; revision received Feb. 17, 1981.

*Project Engineer, Propulsion Department.

†Manager, Propulsion and Power Systems Laboratory. Associate Fellow AIAA.

propellant-servicing location. The gas and propellant manifolds terminate in titanium fill and vent/drain valves with redundant seals. The gas and propellant fill and vent/drain valves differ only in the line-connection size to preclude inadvertent misconnection.

A titanium feedline tees off the propellant-tank liquid manifold and connects to a 10-μm absolute filter. This titanium filter insures contaminant-free propellant is fed to the latch and thruster valves downstream. Welded to the outlet tube of the filter is a titanium to stainless-steel coextruded diffusion-bonded transition joint. Downstream of the filter, a pressure transducer is welded into the feedline to monitor system pressure. The remainder of the subsystem tubing is of 0.25-in. diam 304L stainless steel which negates the need for any transition joints to weld in the pressure transducer or latch and thruster valves. Six soft-seat bistable latch valves are fed in parallel from the subsystem filter. Two latch valves are used in parallel to isolate the four 5-lbf thrusters. Each of the other four latch valves is used to isolate the three 0.2-lbf thrusters in each rocket-engine module (REM).

The four REMs, each containing three 0.2-lbf attitude-control thrusters and one 5-lbf orbit-adjust thruster, are located at 90 deg intervals about the module as shown in Fig. 2. For easy replacement, each REM is connected to its propellant feedlines by means of two threaded mechanical joints utilizing redundant concentric O-ring and metallic seals. The REM location provides a 21-in. lever arm for the orbit-adjust thrusters and a 22.3-in. lever arm for the roll thrusters. Each thruster within each REM is individually aligned to within 0.1 deg of the required orientation. With REM A and C primary and REM B and D backup, total redundancy is provided for performing station acquisition and orbit-adjust maneuvers and concurrent transverse-axis pitch/yaw attitude control using the 5-lbf thrusters while the 0.2-lbf thrusters provide a redundant capability to execute roll and pitch/yaw torque commands for all attitude-control functions as required. Table 1 illustrates the redundancy achieved with this scheme.

With the exception of the eight mechanical joints discussed previously, all joints and connections in the propulsion system are butt welded. All welding is performed by an automatic tungsten inert-gas (TIG) welding machine and x-ray inspected.

The thermal configuration is driven by the requirements of lowest possible heater power, specified heat leakages to space and the spacecraft, specified solar and planetary heat fluxes at various angles, tight temperature tolerances, and REMs that are thermally independent of the shelf-tank assembly. An insulated system with thermostatically controlled electrical heaters is capable of sustaining the required temperatures throughout the environmental extremes. Thermal blankets over the shelf-tank assembly reduce heat losses in cold conditions and minimize required heater power. By isolating components from solar and planetary heat fluxes, the blankets minimize high temperatures in the hot environments.

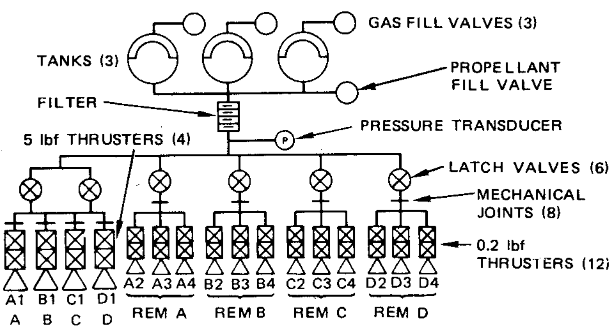


Fig. 1 Propulsion-subsystem schematic.

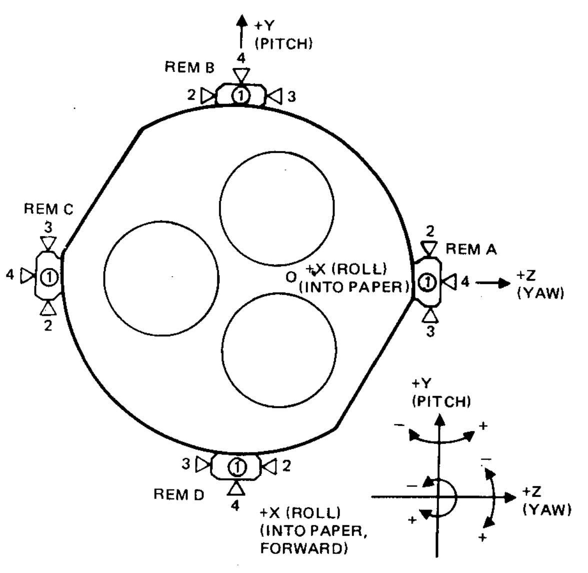


Fig. 2 Propulsion module (bottom view looking forward toward payload).

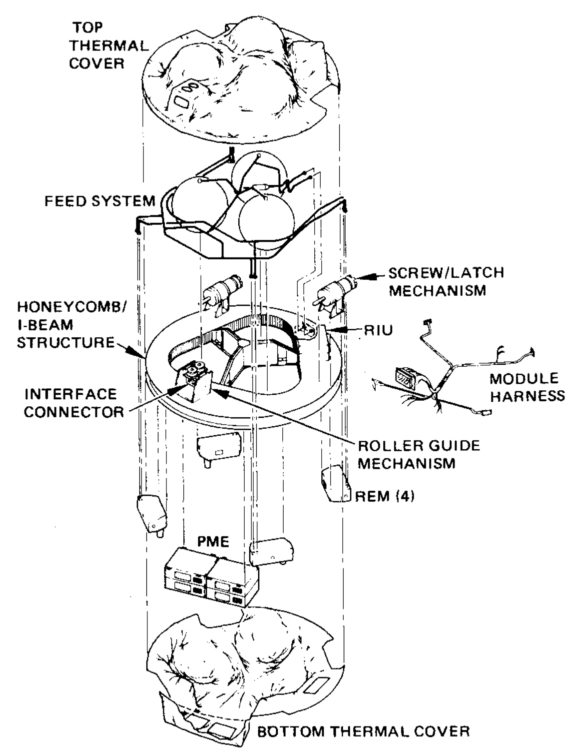


Fig. 3 Propulsion module (exploded view).

Table 1 Thruster redundancy matrix

Thruster	+Roll	−Roll	+Pitch	−Pitch	+Yaw	−Yaw
Primary	A2,C2	A3,C3	C4	A4	A2,C3	A3,C2
Backup	B2,D2	B3,D3	B2,D3	B3,D2	B4	D4

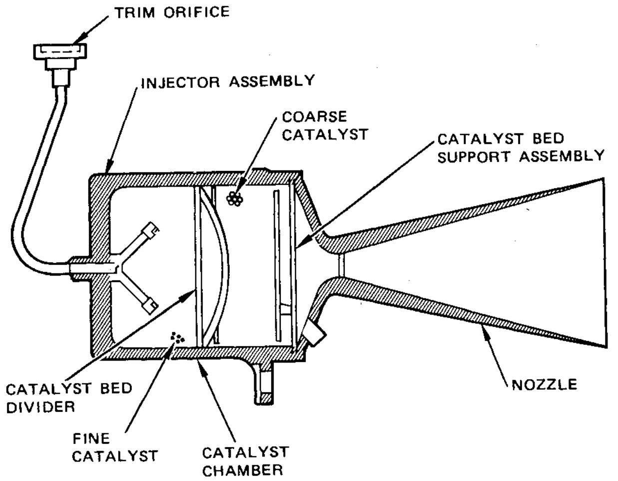


Fig. 4 HE-55 thruster.

Stainless steel, coated on the inside with a low-emittance gold finish, forms the REM insulating enclosure or canister. A black finish is used on the outside in order to provide a durable high-emittance surface. Each thruster also has a separate, low-emittance radiation shield surrounding it. An exploded view of the propulsion module showing the integration of the propulsion subsystem is presented in Fig. 3.

Components

The propulsion components were selected on the basis of low cost, low weight, high reliability, and flight-proven experience. NASA standard components were considered in every case but were not used when a technical advantage or lower cost was achievable with another component.

5-lbf Thruster

The thruster for the orbit-adjust function is the model HE-55, which is identical to the HE-54 thruster except for replacement of the hard-seat, torque-motor operated propellant valve with a series-redundant, soft-seat solenoid-operated valve. The thruster consists of a catalytic thrust chamber, a propellant control valve, and the necessary interface bracket. A cross-sectional sketch of the thrust chamber is shown in Fig. 4. It consists of the following major components: 1) injector assembly, 2) catalyst chamber, 3) catalyst bed divider, 4) catalyst bed support, 5) exhaust nozzle, and 6) a specially processed catalyst.

The HE-54 thruster was developed, qualified, and flown on INTELSAT IV A. Its qualification program (Ref. 3) was extended to encompass the more rigorous requirements of COMSTAR on which it also has flown. Thrusters of this design have demonstrated their ability to perform within all specification requirements after undergoing the following severe testing: 1) random vibration, 29*g* rms, three axes; 2) sine vibration, up to 35*g*, three axes; 3) propellant temperatures, 40-140°F; 4) catalyst bed temperature at start of run, 20-1800°F; 5) valve temperature at start of run, 40-300°F; 6) inlet pressures, 20-350 psia; 7) "on" times, 20 ms to 45 min; 8) cold starts, 900; 9) lbm of propellant consumed, up to 1240 lbm; 10) number of pulses, up to 1,003,501; and 11) seconds of steady-state operation, up to 39,569.

0.2-lbf Thruster

The thruster for the attitude-control function is the model HE-021A‡ (Ref. 4) thrust-chamber assembly. The HE-021A thruster assembly consists of two major subassemblies: a thrust chamber containing Shell 405 catalyst and a series-redundant propellant-control valve. Figure 5 shows the assembly mounted to its REM mount bracket.

‡Patent pending (application filed 1979).

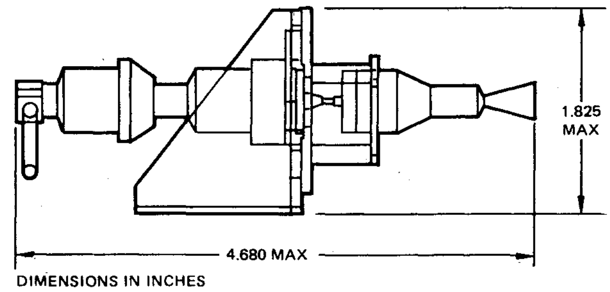


Fig. 5 HE-021A thruster.

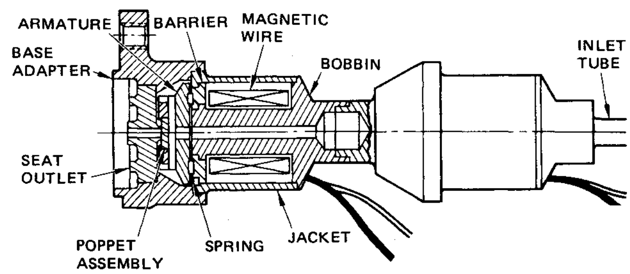


Fig. 6 Propellant valve.

The principles embodied in the design of the HE-021A thruster assembly parallel those embodied in the HE-54 thruster assembly discussed earlier. The thruster chamber is comprised of 1) inlet tube, 2) injector, 3) upstream catalyst chamber, 4) downstream catalyst chamber and catalyst bed divider, 5) catalyst bed support, and 6) an exhaust nozzle having a 100:1 expansion ratio.

Hydrazine flows from the propellant supply as controlled by the propellant valve through the inlet tube to the injector which consists of a single spud (three streams) that penetrates the upstream catalyst bed. The control and distribution of propellant from the single spud, as well as the depth of penetration of the spuds, are designed to minimize hydraulic mining of the upstream catalyst granules and to control the thermal environment of the injector during firing and soakback.

Recently, the qualification program (Ref. 5) for the 0.2-lbf thruster was successfully completed. The thruster is deemed fully qualified to support the MMS mission. Additional verification testing was performed to demonstrate that catalyst fines generated by vibration of new units will not result in plugging or performance degradation for on-orbit use. Three sets of engine parts were used to fabricate, test, dissect, and reassemble ten "new" thrusters that were subjected to the following: 1) acceptance vibration, 2) acceptance hot firing, 3) water flush and vacuum dry, 4) qualification vibration, 5) hot firing (5 units), and 6) flow check (5 units). Additionally, one unit was subjected to acceptance vibration, acceptance firing, water flush and vacuum dry, qualification vibration, and qualification hot firing.

All testing conducted on the HE-021A thruster was accomplished without the aid of a catalyst bed heater, and consequently, the thruster does not contain a catalyst bed heater. The REM will include a heater and a thermal shield for thermal management purposes. The thermal management techniques to be utilized will maintain the catalyst bed temperature above 80°F, while maintaining the valve between +80 and +180°F at all times throughout the mission. A post-fire valve-soakback temperature of 250°F is allowed.

Propellant Valves

The propellant valve used on the HE-55 thruster is a dual solenoid-operated, soft-seat valve of the same design as tested

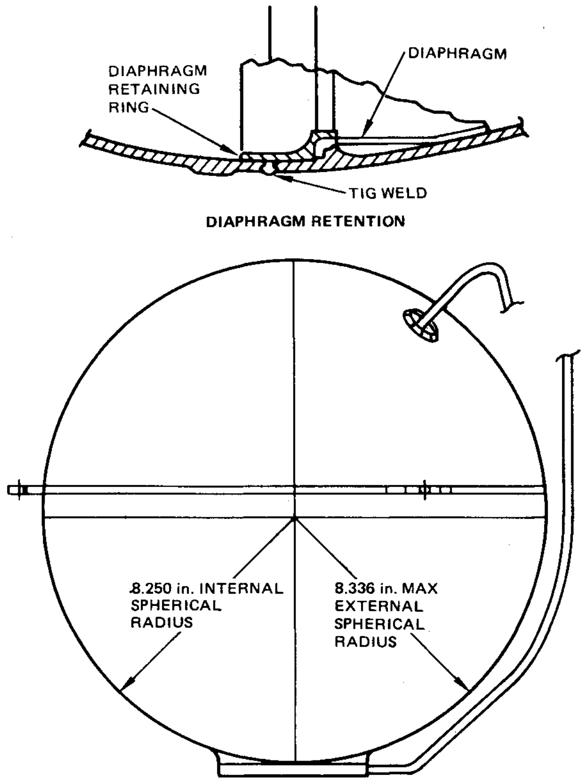


Fig. 7 Propellant tank assembly.

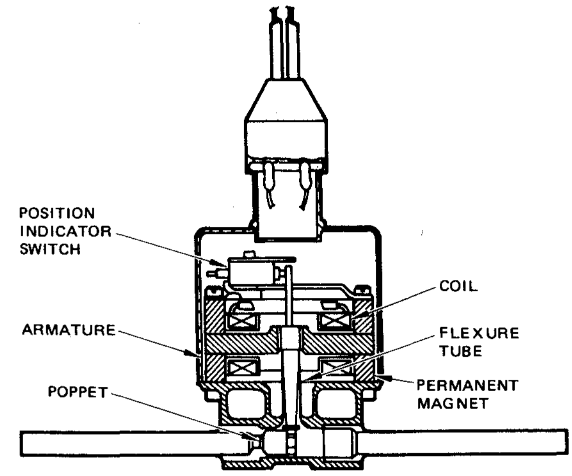
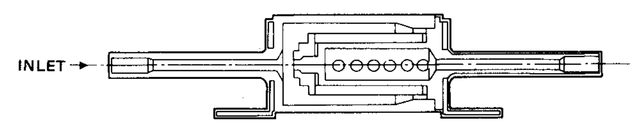


Fig. 8 Latch valve.



- TITANIUM HOUSING
- ELECTROCHEMICALLY ETCHED DISKS
- FILTRATION RATING: 10μ ABSOLUTE
- PRESSURE DROP: <9 psid AT 0.025 lb/sec FLOW RATE AFTER FLOWING 2250 lb OF HYDRAZINE

Fig. 9 Propellant filter.

during the 0.2-lbf thruster development program (Ref. 5). Figure 6 is a cross-sectional view of the downstream seat of the valve. The upstream seat is identical. The propellant valve used on the HE-021A thruster is a scaled-down version of the 5-lbf thruster valve with one difference: the inlet feed tube enters the filter housing of the upstream valve radially rather than axially.

The valve is a clapper-type solenoid in which the actuated member is a flat plate. There are no sliding surfaces or nonworking air gaps as in a plunger-type solenoid; therefore, it is not a contamination generator nor is it sensitive to system-borne contaminants. The clapper-type solenoid offers an efficiency advantage over plunger solenoids in that both air gaps are working, providing actuating force directly to the armature. At a given power consumption, higher forces are generated, resulting in faster response and greater force margins. Sealing material on the upstream and downstream seats is AF-E-411. All other materials in fluid contact are 304L and E-Brite 26-1, electron-beam welded for no leakage and structural integrity.

Both the 5-lbf and the 0.2-lbf thruster valves have been subjected to an extremely harsh development program. The prototype valves have been used in all the MMS vibration, thermal mapping, and hot firing (developmental and qualification) testing performed to date. The generic design has demonstrated capability far in excess of that required for MMS. Additionally, qualification tests were performed on the valves at the component level to include 1) acceptance test, 2) vibration, 3) leak test, 4) cleanliness, 5) operating margin (each coil), 6) endurance test, 7) thermal tests, 8) post-thermal tests, and 9) burst-pressure test.

Propellant Tank

The propellant tank is a spherical titanium-alloy shell containing an AF-E-332 elastomeric diaphragm. It is shown in Fig. 7. The tank assembly is of all welded construction. The diaphragm is retained equatorially between a welded backup ring and a machined lip on the tank. Advantages of the diaphragm include smoothness of propellant flow, repeatability of operation, no severe folding (particularly at the point of propellant depletion), and relative ease of fabrication.

A considerable amount of testing (Ref. 6) has been successfully completed with the AF-E-332 diaphragm material and method of diaphragm retention employed with the baseline configuration. The diaphragm has demonstrated excellent resistance to repeated cycling; the basic tank design during qualification was subjected to 120 cycles without failure. Vibration testing has included partial propellant loads of 50, 75, and 95%, demonstrating the ability to successfully survive a launch in a partially filled condition.

Additionally, the MMS tank has completed supplemental qualification testing. The qualification test sequence consisted of 1) acceptance testing, 2) weight and volume determination, 3) proof-pressure demonstration, 4) leak test, 5) vibration, 6) leak test, 7) expulsion efficiency check, 8) leak test, 9) bulk yield test, and 10) burst test.

Latch Valve

A flight-proven latch valve is used on the PM. This valve has a single poppet, seat, and actuator. The valve is magnetically latched in either the open or closed position following a signal to either the opening or closing coil. The valve will remain latched without power. The seat is made from 304L stainless steel, while the poppet is made from AF-E-411. Materials used in the valve are compatible with all fluids used in the system. It does not contain a bellows or any sliding parts and is of welded construction. A microswitch located in the valve housing indicates its position. Figure 8 shows a cross section of this valve.

Propellant Filter

The filter element consists of approximately 800 chem-milled, stainless-steel, washerlike disks, stacked on a central perforated tubular member and held in tight compression by means of a clamping nut. The chem milling generates radial flow passages of controlled size on the disks. The propellant entering the filter passes through the tortuous radial flow

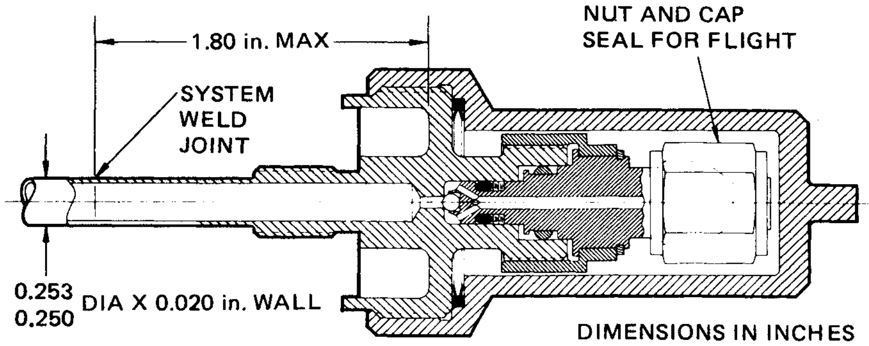


Fig. 10 Fill and drain valve.

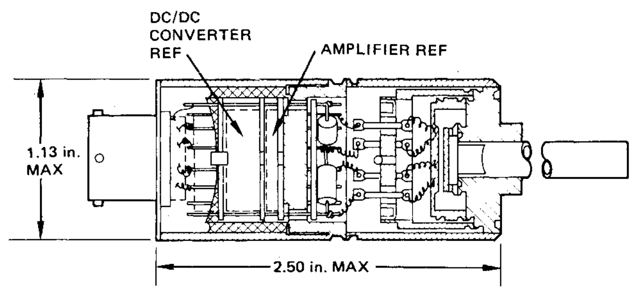


Fig. 11 Pressure transducer.

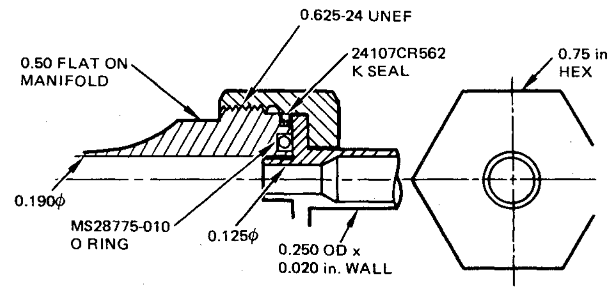


Fig. 12 Mechanical joint.

paths, while any contaminating particles are trapped and held in the disks. The body housing is titanium and is of all welded construction. The filter is illustrated in Fig. 9.

Fill and Drain Valve

The fill and drain valve is used in both the gas and liquid manifolds of the MMS PM. It is illustrated in Fig. 10. The valve is manually operated and direct acting, with the primary seal formed between a tungsten-carbide ball and a titanium seat machined into the valve body. The ball, retained in a stem assembly, is moved on and off the seat without rotation when the locking nut is rotated on the valve body. Due to the small ball size and the large axial loads developed by the locking nut, very low torque is required to provide high seat loading and a leak-tight seal. The final contour of the seal is actually formed by the mating ball, and, since the materials of construction and design permit the application of seating loads when the valve is closed, essentially zero leakage can be repeatedly achieved.

When a system is serviced through the fill and drain valve, the cap seal is removed and an external propellant line or gas line, as appropriate, is connected to the valve inlet port (⅛-in. tube size for gas, ¼-in. for propellant to prevent misconnection). The locking nut is loosened to open the valve and permit propellant or gas flow. When the operation is completed, the locking nut is tightened and lockwired, the external line is disconnected, and the inlet-port cap seal is reinstalled. Before flight, an aluminum closure cap, using a K-seal at its base as an added redundant seal, is screwed down over the complete valve.

Pressure Transducer

This device uses strain-gauge elements mounted on a metallic diaphragm to sense pressure; initiation voltage is provided by a regulated hybrid dc to dc converter. The strain gauge output is amplified by a temperature-compensated hybrid amplifier to the specified level. The transducer is illustrated in Fig. 11.

The pressure transducer senses absolute pressure throughout the range from 0 to 500 psia. The output signal varies from 0- to 5-V dc and is directly proportional to pressures from 0 to 100% of full scale. Provisions to limit the output voltage to −1.0- and +5.0-V dc are incorporated in the integral transducer circuitry. All joints in the transducer sensing cavity and housing are sealed by welding. The total deviation (error) in signal voltage is nominally ±38 mV from the theoretical straightline curve between the end points of the initial static calibration throughout the sensed pressure range from 0 to 500 psia under all combinations of operating conditions within the specified ranges.

Mechanical Joint

Mechanical joints of the type illustrated in Fig. 12 will be used to connect the REMs to the propellant manifold. The joint will be constructed of 304L CRES. It features redundant concentric seals provided by an inner O-ring and an outer K-seal. The design of the joint assures leak-tight service coupled with a convenient disconnect capability for REM replacement if required.

The male end of the joint is an integral part of the REM. There are two joints per REM. One directly feeds the 5-lbf thruster, and the other feeds a manifold common to three 0.2-lbf thrusters. The female end of the joint and the lock nut are on the propellant-feed manifolds, downstream from their respective isolation-latch valves. The lock nut that fastens the male and female ends together is lockwired secure during REM installation.

Lines and Fittings

All manifold joints, with the exception of the mechanical joints, in the propulsion system are made by butt welding by an automatic tungsten inert-gas (TIG) process. No weld fittings are required except for tees, elbows, etc. When used, these fittings will be of the same material as the tubing sections to which they are joined. At the outlet of the system filter, a coextruded, diffusion-bonded, 304L stainless-steel to 6 Al 4 V titanium transition joint will be employed to permit welding of the titanium alloy filter housing to the stainless-steel propellant distribution manifold.

Heaters

Independent primary, backup, and Shuttle survival heaters are located in each REM and on the module shelf. The heaters are a laminated FEP/polyimide patch-type design. The basic construction consists of a 30% iron, 70% nickel (Balco)

Table 2 Weight and power requirements

Component	Unit weight, lb	Quantity	Total weight, lb	Power required per unit
Tank	10.80	3	32.40	–
5-lbf TCA	1.36	4	5.44	20 W during actuation
0.2-lbf TCA	0.30	12	3.60	10 W during actuation
Latch valve	0.60	6	3.60	8 W during actuation
Filter	0.15	1	0.15	–
Transducer	0.50	1	0.50	0.4 W (continuous)
Fill and drain valve	0.30	4	1.20	–
Mechanical joint	0.20	8	1.60	–
Thermistors	0.01	32	0.32	Negligible
Lines and fittings	–	AR	1.81	–
Heaters	0.04	11	0.44	≤40 W total, all heaters
Thermostats	0.01	40	0.40	–
			51.46	

resistance element overlaid with 0.001-in. fusible FEP film and an outer skin of 0.002-in. Kapton polyimide. These are laminated under heat and pressure, with the FEP material then acting as an adhesive to bond the outer skin, resistance element, terminals, and lead-in wires into a single unit.

Thermostats

Separate primary and backup flight heater thermostats and Shuttle survival heater thermostats (parallel-series arrangement) are used in each REM and the PM shelf. These thermostatic switches are high reliability, hermetically sealed units employing Klixon snap acting disks.

Thermistors

Negative-temperature-coefficient type, thermally sensitive resistors are employed to monitor key-system temperatures. These thermistors are used to monitor tank, latch valve, and selected shelf temperatures, as well as downstream propellant-valve coil temperatures in each REM.

Component Summary

Table 2 provides a tabulation of all propulsion-subsystem components, including quantities per module, weight, and power requirements.

Testing

Component Acceptance Tests

Rigorous acceptance tests are required for all propulsion-subsystem components. Typical component-acceptance tests can include, but are not limited to, weight determination, proof test, vibration test, functional checks, calibration, electrical response check, and cleanliness verification. Strict monitoring by unit engineers and rigid quality control insure only flight quality, specification-compliant components are delivered for subsystem itegration.

Subsystem/Module Level Acceptance Testing

The overall subsystem buildup on the PM shelf will proceed concurrently with individual REM assembly. Also, within this same time frame, the 16 thrusters required per spacecraft will be assembled, vibrated on a facility block simulating a REM, and hot fired with a facility valve according to the approved acceptance-test procedure. The thrusters will then be water flushed and vacuum dried. Thruster performance data will be reviewed and thrusters will be assigned to specific REM positions based on thrust matching. The thrusters will then be integrated on the REMs and the REMs integrated to the subsystem. At this point, proof-pressure testing will be performed. PM integration commences at this point and all further testing is accomplished at the module level.

Module-level propulsion-subsystem testing will consist of the following, in the order specified:

1) Pressure transducer calibration
2) Propellant-valve leakage and response tests
3) Latch-valve leakage and operation tests
4) Temperature-sensor and heater checks
5) Sine vibration and acoustic tests
6) Acceleration tests (protoflight only)
7) Cleanliness demonstration
8) Thermal vacuum command response and overall leakage tests
9) Pressure transducer calibration
10) Propellant-valve leakage and response tests
11) Latch-valve leakage and operation tests
12) Diaphragm leak tests
13) Temperature-sensor and heater checks

Conclusion

The PM for the MMS provides a versatile, highly reliable, and low-cost system to supplement MMS capability in all current and future missions. The baseline PM-I embodies the foundation from which the increased capacity PM-II can be derived with relatively little additional development. Furthermore, should the need arise, the self-contained PM could be adapted to support other spacecraft as required.

References

[1] Barker, F.C. and Schreib, R.R., "MMS Propulsion Module Design," AIAA Paper 78-1095, 14th Joint Propulsion Conference, July 1978.

[2] Etheridge and Woodruff, "Analysis and Design Study of the Multimission Modular Spacecraft Hydrazine Propulsion Module," AIAA Paper 78-1094, 14th Joint Propulsion Conference, July 1978.

[3] "Hughes Model HE-54 Thruster Qualification Report for HS 362 Program," Ref. C6226, Hughes Aircraft Co., Sept. 1974.

[4] Ellion, M.E., Spicer, L.M., and Barber, W.R., "Development of a Long-Life 0.2-lbf Heaterless Thruster Without Pulse-Mode Degradation," AIAA Paper 78-1063, 14th Joint Propulsion Conference, July 1978.

[5] "Hughes Model HE-021A 0.2-lbf Thruster Qualification Report," Ref. 41-33-10 Engr. Record 79-3, Hughes Aircraft Co., March 1979.

[6] "Qualification Testing of LMSC Part Number 1462892-1 CCA 2398 Hydrazine Supply Tank Containing an AF-E-332 Rubber Diaphragm," Ref. TR 56-000054, Pressure Systems Inc., July 1973.