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The MARK-II Propulsion Module

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The development of a large, modular, general purpose propulsion subsystem is proceeding. It is compatible with the other NASA multimission modular spacecraft subsystems and has been designated the MARK-II propulsion module (PM) by Goddard Space Flight Center. The PM has a propellant capacity of 5500 lb of hydrazine operating at a maximum pressure blowdown of 5:1. Axial thrust is provided by four 100-lbf thrusters and reaction control is provided by twelve 5-lbf thrusters. The PM has integral command and telemetry electronics which can operate in either the digital or analog mode to provide the spacecraft's orbit adjust and attitude control functions. The PM is designed for multiple reuse on long duration, Shuttle launched missions in low Earth orbit.

Introduction

IN response to needs for a large, standard propulsion system, the development of the multimission modular spacecraft (MMS) MARK-II propulsion module (PM) is proceeding. The MARK-II PM is designed to satisfy a wide variety of propulsion requirements for low Earth orbiting spacecraft beyond the mid-1980s such as upper atmospheric research satellite (UARS), materials processing satellites, teleoperator maneuvering system (TMS), and others. The multitank configuration illustrated in Fig. 1 provides a range of hydrazine propellant weights from less than 2000 lb to greater than 6000 lb. The four-tank configuration is currently in the final design phase.

The MMS Spacecraft

The MMS program has developed a standardized spacecraft to meet a range of applications tailored to user requirements. Numerous articles and papers have devoted discussions to the MMS in general and to areas of specific interest. In the latter category, Ref. 1 discussed the propulsion options available to MMS users ranging from the PM-I (Ref. 2) to the MARK-II. This range of propulsion capability satisfies all currently identified low energy orbit transfer requirements to the year 2000.

The MMS consists of these basic modules: the modular power subsystem (MPS), the modular attitude control subsystem (MACS), the communications and data handling subsystem (C&DHS), and the propulsion module (PM). A core structure can be user-supplied or the Landsat-D module support structure (MSS) is available. A configuration using existing hardware is illustrated in Fig. 2. A Shuttle optimized concept for a MARK-II spacecraft is illustrated in Fig. 3. This concept uses the advantage of the cargo bay diameter to provide a minimum length spacecraft bus which could accommodate a variety of user payloads.

Functional Description

The MARK-II PM is a complete subsystem requiring only external sources of power and commands to perform its functions of orbit adjust and attitude control. Figure 4 schematically illustrates the subsystem and its functional relationships to the other MMS modules. Electrical power at 28 V dc nominal is supplied by the MPS. Commands initiated by a ground station or by the onboard computer (OBC) are fed from the C&DHS via the standard remote interface unit (RIU). Telemetry data originating within the PM are returned to the C&DHS through the RIU for downlink (D/L). In the event of OBC or other major spacecraft failures, the PM will accept analog control signals directly from the MACS in the safe-hold mode. All power distribution, command decoding, and telemetry processing are handled within the PM by the propulsion module electronics (PME) as illustrated in Fig. 4.

The primary function of the PM is to provide spacecraft thrust control to accomplish 1) orbit adjust, which consists of orbit transfer for altitude and minor inclination changes as well as orbit maintenance; and 2) attitude control, which consists of spacecraft initial stabilization and sensor acquisition, attitude hold control (limit cycling), roll control during orbit adjust maneuvers, momentum management, and attitude maneuvers.

Capability is provided to perform all of the above functions by OBC control or autonomously by analog signals derived from the MACS. Pitch and yaw control is maintained by modulating the orbit adjust thrusters in an off-pulsing manner. The attitude control thrusters provide control about the roll axis.

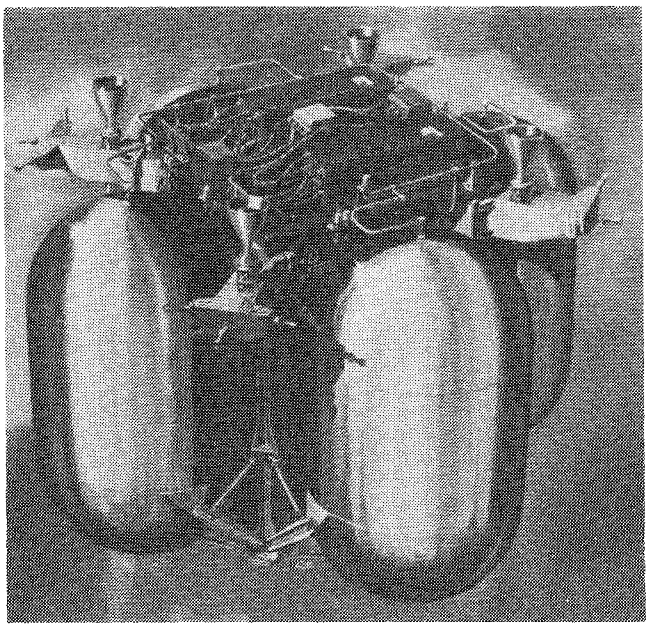

Fig. 1 MARK-II propulsion module.

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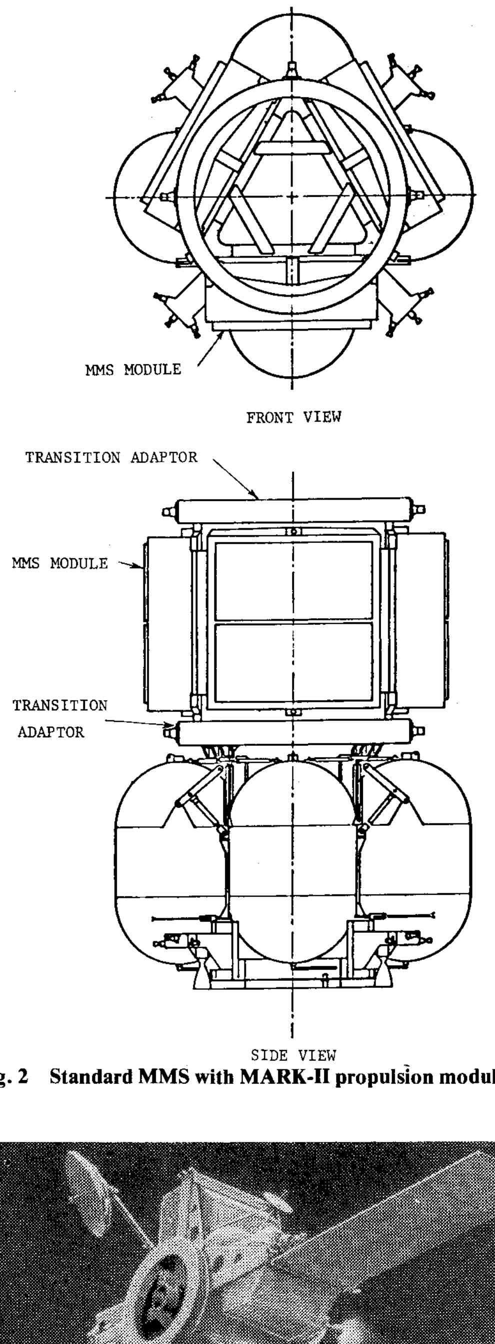

Fig. 2 Standard MMS with MARK-II propulsion module.

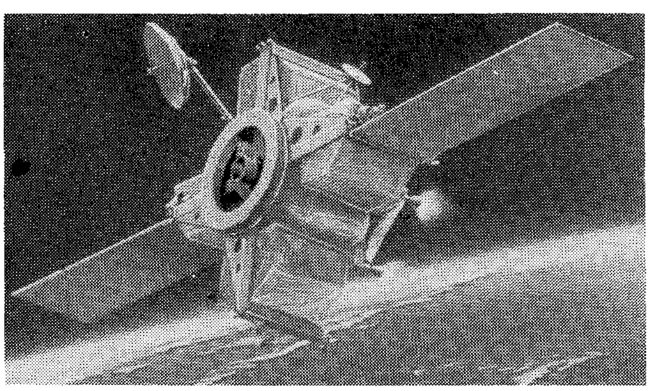

Fig. 3 Shuttle optimized MMS MARK-II spacecraft (concept).

The propulsion fluid system is schematically illustrated in Fig. 5 for the four-tank configuration. Hydrazine propellant and nitrogen pressurant are stored equally in each tank at an initial operating pressure of 350 psia. The system operates in the blowdown mode at a maximum ratio of 5:1. The ullage volumes of each tank are manifolded during loading operations to equalize presure but are separated during orbital operations. Press/vent valves with triple-redundant seals are used to interface with the ground system for pressurization loading. The tanks are manifolded in pairs and each pair has a fill/drain valve and pressure transducer. Propellant expulsion is achieved by capillary screened channels at each tank outlet.

The tank outlet lines connect to redundant filters which are cross-strapped to redundant latching isolation valves. The latch valves provide isolation of tank pairs and pressure isolation from the common manifold. The manifold has a pressure transducer and a purge valve used for system decontamination and drying. The tubing from the tanks to the manifold is all 304L stainless steel and all joints within the PM are Astro-Arc welded. A single line connects each rocket engine module (REM) to the manifold. Within each REM are three 5-lbf thrusters and one 100-lbf thruster. Each thruster has independent dual thrust chamber valves providing a total of three mechanical inhibits required by Shuttle safety regulations. The REMs can be operated in redundant pairs (i.e., A-C or B-D) or can be operated simultaneously depending upon the option selected through the PME. The fluid line components are all mounted to a baseplate referred to as the propellant control assembly (PCA). The REMS each mount to thermal standoff plates at each corner of the PCA.

The electronic packages and interconnecting wire harness are all mounted to a common shelf. The electronic shelf electrically interfaces to the PCA with two standard MMS blind connectors to enhance assembly, test, and refurbishment. The use of the electronic shelf and the aft location of the servicing valves enhance future on-orbit servicing considerations.

Active thermal controls are illustrated in Fig. 5. Each heater is redundant and each has series redundant thermostats of the same set point. The primary heater set points are generally 16°C and the backup are 12°C providing adequate margin to preclude freezing without excessive heater power usage. Thermostatically controlled heaters are located on each propellant tank, the PCA electronic shelf, and each REM. Individual components are not heated except for the tanks. A thermal blanket of multilayer insulation over the entire module in a "cocoon" fashion minimizes heat losses and maintains the enclosed environment between 10 and 40°C. Redundant catalyst bed heaters provided on each thruster are commandable on/off to maximize thruster life. The PM is a thermally independent module with respect to the remainder of the spacecraft with specified minimum conductance leaks.

Analog telemetry is provided to monitor subsystem performance. Redundant thermistors are provided at each tank (three locations), the PCA (six places), and each REM. In addition, each thrust chamber is provided with a thermistor.

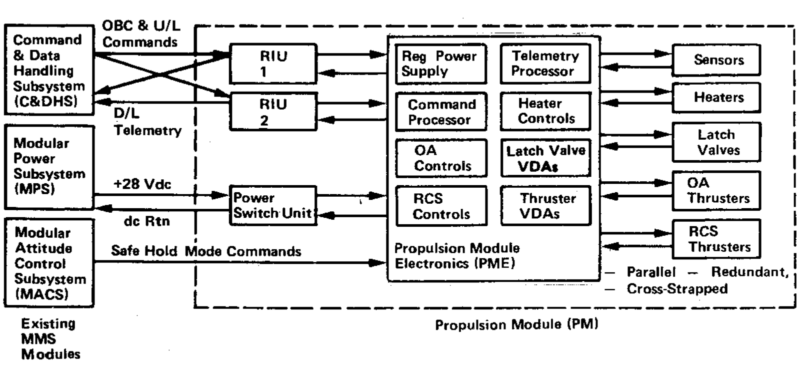

Fig. 4 Propulsion module electrical functional schematic.

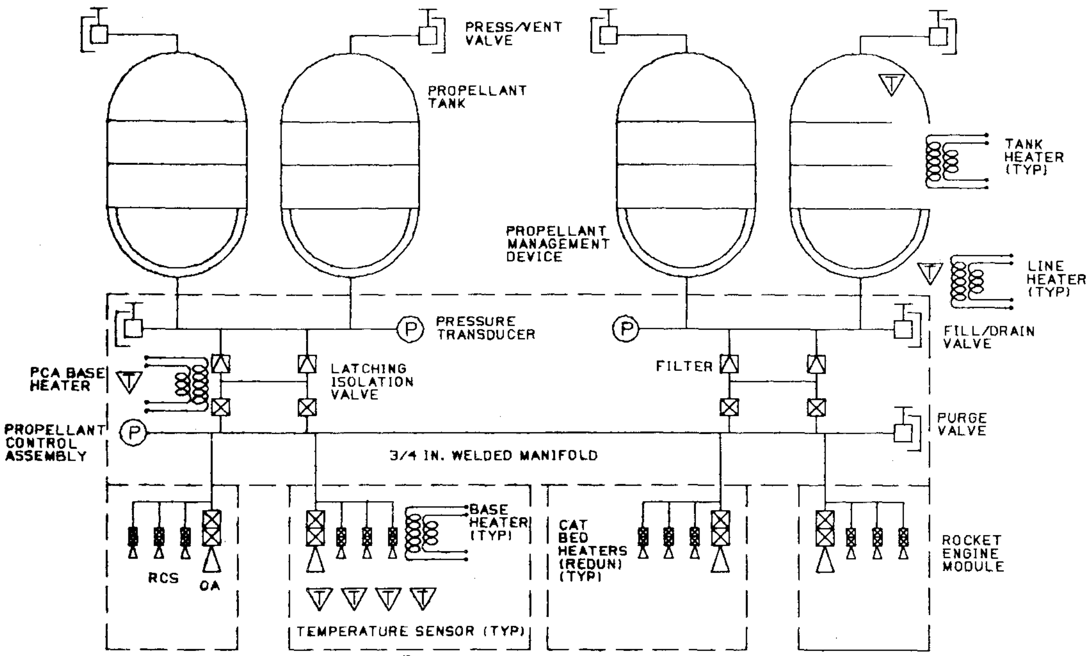

Fig. 5 MARK-II PM fluid schematic.

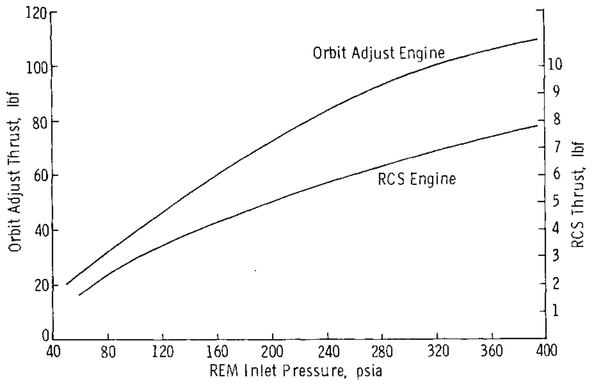

Fig. 6 Rocket engine assembly thrust.

Pressures are measured at each tank pair and at the manifold. Position switches on each latch valve provide both open and closed indications. Serial-digital and bilevel telemetry are provided to monitor command status.

Performance

The propellant capacity of the four-tank configuration in the blowdown mode at a 5:1 ratio is 5500 lb. A lower propellant load could be selected with a correspondingly lower blowdown ratio. Growth options are available to carry up to 6200 lb of propellant by adding an external pressurization source. The existing PM structure has dedicated volume for pressurant spheres which could be used in either the recharge or regulated mode to increase the usable propellant capacity or provide constant thrust. The PM tanks and structure have been designed to accommodate the higher loads.

The steady-state specific impulse of the orbit adjust (OA) thrusters is estimated to be 234 s, with an estimated overall average of 228 s throughout a typical mission life. The steady-state specific impulse of the reaction control system (RCS) thrusters is approximately 232 s, with an estimated overall average of 200 s or less depending on pulsing duty cycle.

Thrust performance for both engines as a function of system pressure is illustrated in Fig. 6. These curves are steady-state nominal values and the allowable variation in both cases is $\pm 5\%$ for each thruster. The OA and RCS thrusters have minimum pulse width requirements of 0.040 and 0.020 s, respectively. The RCS minimum impulse bit (at greater than 100°C) is approximately 0.05 lbf-s with the 0.022-s command from the PME.

A weight and power summary of the PM is given in Table 1. Note that the total dry weight may be reduced by 320 to 1070 lb by deletion of the antislosh baffles to the propellant tanks.

Mechanical Components

Propellant Tank

Adaptation of the multitank configuration allowed the use of the basic 36-in.-diam Viking Orbiter '75 shell, which is made of 6Al-4V titanium. The tank domes are joined to the barrel section by locking girth welds following the insertion of the propellant acquisition device.

The tank is designed to an ultimate stress of 165 ksi (157 ksi at 60°C) with a minimum factor of safety on burst of 2.0 at the Shuttle landing abort condition of 400 psia and 60°C. It is capable of withstanding internal vacuum conditions at sea level with a factor of safety greater than 1.25. The tank is designed by fracture mechanics for a sufficient number of cycles to account for more than four refurbishment operations. Proof test of the tank shell is performed by cryoproof and at the ambient temperature (20°C) proof limit of 600 psia.

The propellant management device (PMD) for the initial MARK-II application contains two parts: 1) an antislosh baffle section, and 2) a screen-channel acquisition device. The antislosh baffles are a series of perforated plates arranged to form a multiple layer, labyrinthine "egg crate" which occupies most of the barrel section of the tank. The screened channels are of conventional design like those used in the Shuttle RCS and Intelsat V tank systems. In this instance, the acquisition system channels are needed only in the lower dome owing to the presence of the baffle assembly. Most users will not require the degree of slosh control provided by the baffles and would save weight by the use of a universal screen-channel device which uses four channels running from the pressure inlet to the propellant outlet.[3]

Table 1 Weight and power summary

Description	Weight, lb	Power, W[a]
Tanks (with Propellant management device) (4 each)	768 [a]	
Rocket engine module (4 each)	76	
Prop. control assy	87	2.1
Propulsion module electronics (2 each)	92	52.7
Remote interface unit (2 each)/Expanded Unit (1 each)	12	4.2
Thermal controls	15	53.3
Structure	246	
Plumbing, cabling, miscellaneous	94	
Total	1390[b]	112.3
Propellant, maximum	5500	
Pressurant	40	
Total loaded	6930	

[a]Orbital average excluding transients. [b]May be reduced by 320 by deleting slosh baffles.

Table 2 REM requirements

Parameter	OA		RCS
Thrust, nominal lbf	100		5
Specific impulse, minimum at 250 psia, s	231		228
Operating pressure, psia	400 to 70		
Proof pressure, psia	990		990
Back pressure relief, psia	325		325
Pulse width, minimum, ms	40		20
Operating voltage, V dc	19 to 35		
Opening force margin at 19 V dc, minimum %	50		50
External leakage, maximum	5×10^{-5}	standard cubic centimeters	
Alignment, deg	±0.5		±1.0
Firing life, lbf-s	600,000		50,000

Rocket Engine Module

The REM is comprised of three 5-lbf and one 100-lbf catalytic thrusters and the associated plumbing, wiring, structure, instrumentation, and thermal controls. Some of the major design drivers for the REM are provided in Table 2.

The OA thruster has been developed[4] based on previously qualified Teleoperator and IUS designs. A flight configuration engine (REA 20-4) was successfully tested to greater than 1,000,000 lbf-s at representative duty cycles in combination with qualification-level vibration tests. The development configurations featured a single-seat valve qualified and flown on Voyager. Shuttle safety requirements dictated that a dual-seat configuration be provided on the MARK-II, so the valve has been modified to accommodate the dual seats. In conjunction with the design modification, the coil was uprated to provide a greater opening force margin (50% minimum) at a wider voltage range (19-35 V dc). The valve assembly was requalified prior to the REM qualification tests. Catalyst bed heaters are provided to warm the thrust chamber prior to firing to enhance thruster life.

The RCS thruster is a minor variation of the flight proven REA 23 known as the REA 39. This thruster was successfully tested by the Rocket Propulsion Laboratory to over 1,000,000 pulses. This thruster also features a dual seat torque-motor value with nonsliding fit parts. The valve assembly has been modified to provide greater force margins over the wide ranges of voltage.

The thrusters are rigidly mounted to the REM structure following their alignment. The REM structure provides a very simple mechanical, fluid, thermal, and electrical interface to the propellant control assembly. The thrusters are aligned relative to the REM interface plane, and the final OA thruster alignment is verified at the PM assembly level. The plumbing lines, fittings, and valves are all welded or brazed construction. The REM is heated by redundant, thermostatically controlled heater plates shunted to the thruster valves. Multilayer insulation and thermal coatings are used to minimize heater power consumption. Thermistors are provided to monitor REM enclosure and thrust chamber temperatures.

The REM will receive comprehensive environmental and performance qualification testing. Firing tests will be conducted to further characterize pulsing performance of the OA engine and to demonstrate life margin following a refurbishment demonstration. For acceptance, each REM will be proof/leak tested, environmentally tested (random vibration and thermal vacuum), vacuum fired, and electrically functioned. Refurbishment of the REM will involve removal of each unit for a repack of the catalyst beds and replacement of the bed screens. Reacceptance of the REMS will be essentially in accordance with the original procedures.

Pressure Transducer

The pressure transducer utilizes four strain-gage elements vacuum deposited onto a bending beam. Pressure in the sensing cavity causes the displacement of a diaphragm to deflect the bending beam. An additional pressure cavity is provided by the design of the all-welded housing, resulting in redundancy of sealing. The solid-state power supply and amplifier sections of the electronics provide a 0-5 V dc output signal.

Filter

The filter utilizes a stainless steel screen to provide a 20-μ absolute rating. The filter is of high capacity, and either filter in the parallel arrangement can handle two tank loads of propellant. Primary filtering is provided by the screens in the propellant tank lower PMD.

Pressurization/Vent Valve

The selected press/vent and purge valve is a 0.25-in. valve used originally on the Viking Lander and subsequently on many other programs. The valve uses a manually operated ball-screw race to actuate the unit. Previous versions of this valve offered either a cap at the valve inlet or an outer cover of the valve body. The MARK-II version will feature both types of caps to provide a higher degree of sealing reliability since the backup seals are untestable. A separate entry filter/valve assembly is attached to the press/vent valve during subsystem buildup and remains in place until completion of final servicing operations. This device ensures a clean entry to the system and minimizes cycles on the flight valve.

Fill/Drain Valve

The fill/drain valve is a scaled-up version of the original 0.25-in. valve and operates on the same principal. Dual caps to back up the primary seal will be provided on this unit and removable entry filters will also be used.

Latching Isolation Valve

The latching valve is a 0.75-in. line diameter valve that uses a combination of bellows, trim springs, and permanent magnets to retain the poppet in either the closed or open position. The valve is actuated to either position using electromagnetic coils. A position indicating switch monitors both positions of the valve. The valve features an internal, high capacity filter and back pressure relief capability (at 450-500 psia).

Lines and Fittings

The propellant lines used to interconnect the components are principally 0.75 in. in diameter. The tubing sections are joined by machined fittings of 304L using all automatic welding—there are no mechanical joints in the lines. Removal of components for refurbishment or problems is easily accomplished with proven techniques. Proof, leak, x-ray, and dye penetrant checks are made as the lines and components are assembled and a final proof test is conducted on the fully welded assembly.

Structure

The core structure is semimonocoque construction as illustrated in Fig. 7. The machined frames, longerons, stringers, and tank struts are all made of 7075-T73 aluminum and the skin panels are 7075-T6. The structure is designed for factors of safety on ultimate and yield of 1.5 and 1.2, respectively, and is static proof tested at 1.1 limit loads. The design is analyzed for fatigue and fracture control for four lives. The NASTRAN finite-element model has verified positive margins of safety for all critical design loading conditions.

Electronic/Electrical Components

Propulsion Module Electronics

As discussed earlier, the PME is the central controller for all PM functions. It interfaces with the other MMS modules via the RIUs or could be modified to operate from other user-supplied command and power sources. The PME performs these basic functions: 1) processes commands, 2) drives the thruster valves, 3) drives the latch valves, 4) controls power switching, and 5) conditions and transmits telemetry.

Redundancy is provided by two separate units, either of which can control the entire PM. Internal redundancy is provided such that no single PM component failure could cause an inadvertent thruster firing. More than three electrical inhibits as required by Shuttle safety regulations are necessary to operate a thruster.

In the normal computer mode, thrust pulses are internally generated in multiples of 22 up to 66 ms. Continuous firings are achieved by commanding 66-ms pulses in every computer word, which are repeated at 64-ms intervals. In the analog mode, rate and position error signals from the MACS are transformed into the PM control axes, and RCS thruster commands are issued as required. Rate gains and axis transformations are readily modified to satisfy mission unique requirements. The logic is also available in the PME to interpret reaction wheel tach signals and autonomously desaturate the wheels with the RCS thrusters when required.

Timers are available in the PME to initiate and time-out an orbit adjust burn in the analog mode or as a backup to the OBC in the normal digital mode. The valve drivers use series HEXFET switches commanded from two independent paths to operate a given thruster. Voltage suppression of the valves is accomplished by ziner diodes in the PME.

Remote Interface Unit

The RIU is a NASA standard unit which provides two-way communication between the PMEs and the C&DHS via the multiplex data bus. The RIU accepts discrete or serial digital commands which originate from the ground or the onboard computer. It also accepts and processes telemetry inputs from the PM in one of four types: analog, analog passive, bilevel, and serial digital. An expander unit (EU) is optional to add additional multiplex capability externally to the RIUs. The MARK-II utilizes two redundant RIUs and an EU which are cross-strapped to the PMEs for command redundancy.

Electrical

The PM electrical interface connector is a standard MMS connector and contains spare pins for user peculiar additions. Standard harnessing interconnects the RIUs, PMEs, and the various electrically actuated components and heaters. A separate fuse unit is provided so that fuse replacement is readily accessible without entry into either PME. The design of the PCA is such as to allow totally free access to all of the electronic packages for troubleshooting or replacement in the field if necessary.

Module Assembly

Additional details and pertinent dimensions of the assembled module are provided in Figs. 8 and 9.

Testing

It has been determined that the only new component qualification testing required is for the propellant tank assembly, rocket engine module, and propulsion module electronics. Each of these components has had extensive development testing to minimize risk. Qualification testing or qualification by similarity will be substantially in accordance with the test matrix, Table 3. Specific exceptions for purely mechanical or electronic components are not noted in the matrix. The test matrix also indicates the testing to be accomplished at the major subassembly and final module level.

Electrical functional testing at the module level can be accomplished in two ways: 1) by a vehicle simulator at the PM interface, or 2) by electrical aerospace ground equipment (EAGE) at the test connector. The vehicle simulator is the method used when end-to-end checkout from the interface

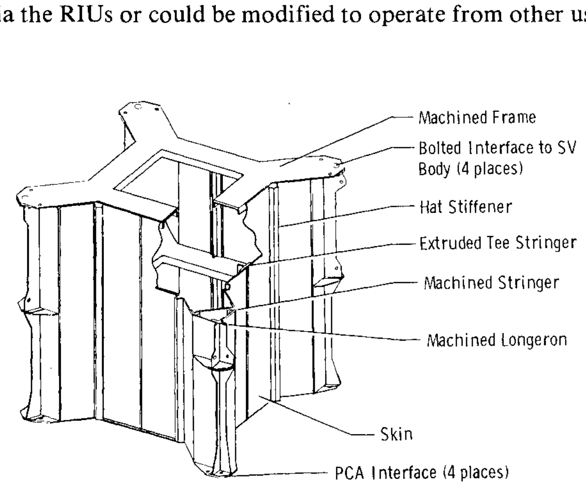

Fig. 7 Propulsion module core structure.

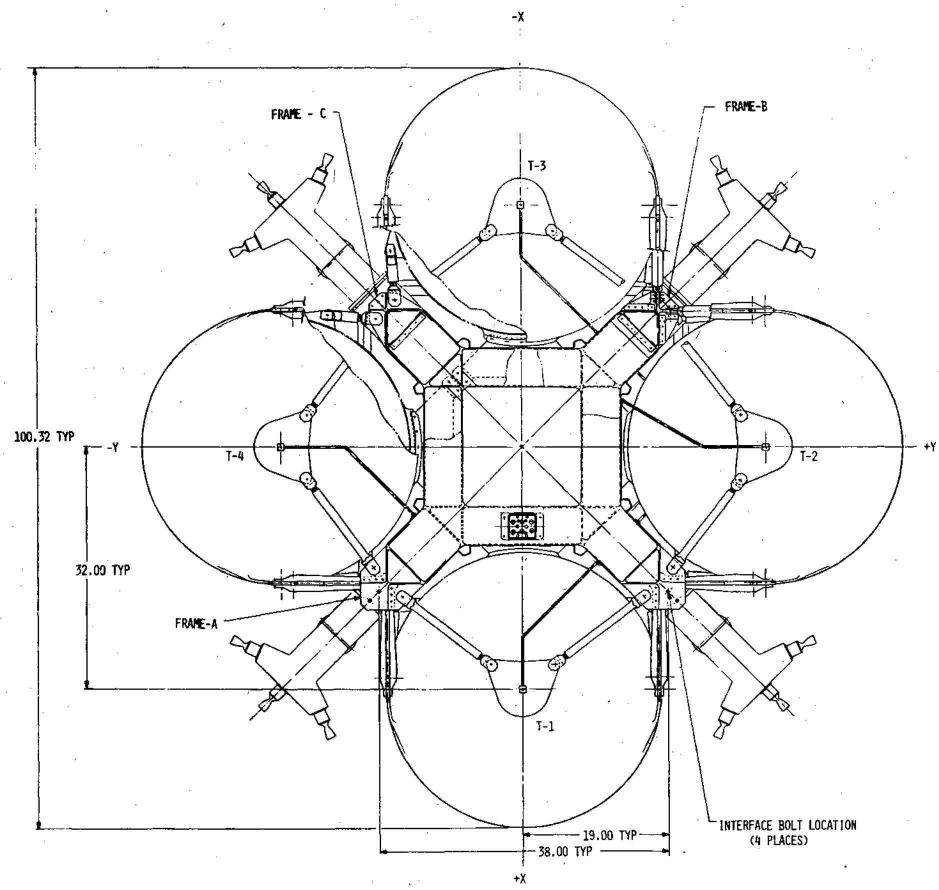

Fig. 8 Propulsion module view looking aft.

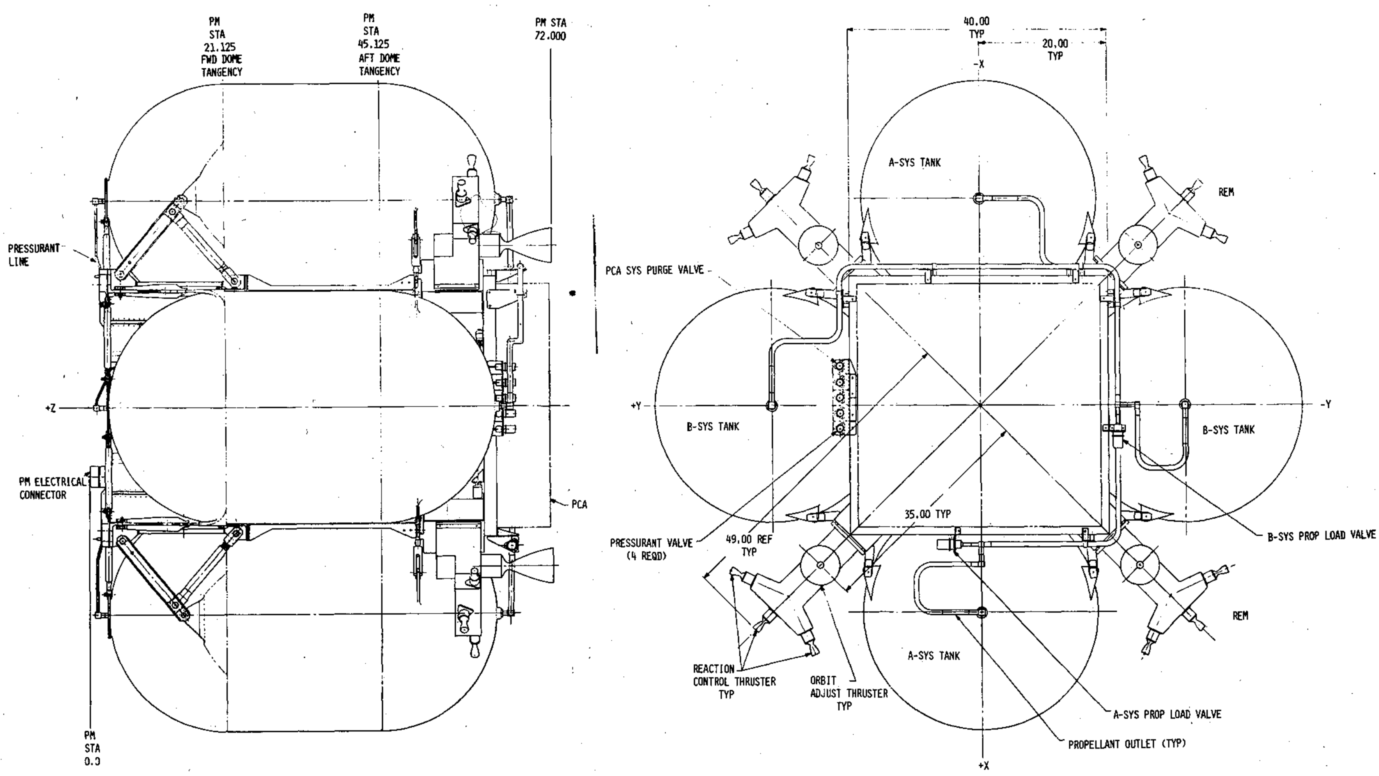

Fig. 9 Propulsion module side and forward views.

connector to the component is required. In this case, the commands simulate the flight computer or analog attitude signals and the PME decodes the commands and stimulates the proper component(s). An EAGE test set is provided so that testing can be performed on the components independently of the vehicle or vehicle simulator. The EAGE also allows testing of the electronics (RIU/PME) without stimulating the components. A test connector is provided in the harness downstream of the PME to which the EAGE test unit may be connected. This connection interrupts the normal command flow. Component simulators in the EAGE can be functioned to check out the electronics, and hardwire signals

Table 3 Test matrix

Test	Component[a]	Subassembly/ module[b]
Performance/functional	A, Q	A, C, Q
Thermal vacuum	A, Q	A, C, Q
Thermal cycling	A, Q	A, Q
Thermal balance		C, V
Random vibration	A, Q	A, Q
Acoustics	A, Q	C, V
Pyroshock	Q	Q, V
Burn-in	A	A
Electromagnetic		C, V
Static proof	Q	C
Pressure/leakage	A, Q	A, C, V

[a] A = acceptance, Q = qualification.
[b] C = combined acceptance and qualification, V = vehicle level verification.

to the components can be issued from the test set. A flight plug at the test connector is installed following final EAGE checks.

Operations and Refurbishment

New portable handling and servicing equipment is provided for the PM, including a portable propellant loading unit capable of handling hydrazine, pressurants, and solvents. It will provide an accurate loading by mass and pressure as well as control normal or contingency propellant offload or venting operations. Propellant loading and final pressurization will take place in the payload test cell at either launch site. Initial bleed-in of the flight system up to the thrust chamber valves (downstream of the tank isolation valves) will be accomplished during loading operations. The PM is configured to meet Shuttle safety regulations during the launch/deployment phase in either the power-on or power-off mode.

During the Shuttle rendezvous and retrieval operations, the OA system can be safed at the prescribed safe separation distance and the RCS thrusters left active up to the allowable Orbiter separation distance. No venting or dumping of fluids is required and the PM can be returned powered-on or with power off at the user's option. Provisions for in-flight servicing have not been provided in the initial configuration, although the design is such as to allow for a simple retrofit of berthing and fluid connections.

Refurbishment of the PM begins after the spacecraft has been removed from the cargo bay and placed in its vertical test cell. Venting and propellant residual removal is followed by flush, purge, and vacuum drying operations dependent on user requirements. A final decontamination sequence of purging and drying is performed at the factory upon receipt of the PM. A postretrieval baseline functional test series is performed prior to any equipment removal. The routine removal of the thermal insulation, electronics and REMs is performed. The electronics are thoroughly bench-tested and any failed piece parts are replaced prior to their reacceptance test. The REMs are returned for catalyst repack and a complete checkout of the units prior to their reacceptance. The philosophy of refurbishment will be to perform the retest and reacceptance of the remaining components in place to the maximum extent. This philosophy will be tendered with conservatism, however, until the operation is proven and routine. Module level reacceptance will be performed in the same manner as an initial acceptance test sequence.

Conclusions

The MARK-II PM is designed to provide considerable capability for growth and user unique options. The use of redundant and highly reliable hardware will ensure long mission life. Ease of servicing and refurbishment enables the full use of Shuttle's capabilities to recover and reuse valuable systems.

The final design of the MARK-II PM is proceeding toward initial system availability in the late 1980s. This large PM will provide MMS and other users with a versatile, cost effective propulsion capability for current and future needs.

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