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ABSTRACT

This paper describes the work completed on the Orbital Spacecraft Consumables Resupply System (OSCRS) for the Johnson Space Center (JSC) under Contract NAS9-17586. The study objective was to provide a concept to NASA for supplying earth storable liquids and gases to a variety of orbiting vehicles, including Space Station, OMV and other satellites in orbits compatible with Shuttle resupply. The design developed by the Fairchild Space Company was driven by life cycle cost.

The design is based on a cylindrical propellant tank optimized for transporting liquids in the Orbiter bay. The tank is polar mounted with the attachment fittings configured as Orbiter sill trunnions. The pressurant tanks provide support between the sill and keel fittings. Two potential spacecraft interface mechanisms were investigated.

Continuing OSCRS effort will be directed toward further standardization studies, adapting the design to the Space Station Servicing Bay and investigating the possibilities of using ELV launchers.

INTRODUCTION

Because it is so expensive to build, launch and operate spacecraft, on-orbit refueling and reservicing represent real economic opportunities essential to expanding the viability of space activities. The Orbital Spacecraft Consumables Resupply System (OSCRS) represents a fundamental shift in our concept of what can be done in space and in our approach to how things are accomplished there.

The impact of OSCRS is potentially enormous. Resupply of consumables will greatly extend the lifetime and productivity of spacecraft. By making resupply an economically attractive alternative, OSCRS has the potential to extend the useful life of many classes of spacecraft. Because most spacecraft operate in orbits that are not economically accessible, spacecraft repair and maintenance, instrument upgrade, product harvesting and payload change-out are uneconomical. The OSCRS will allow free flying spacecraft to perform an essentially unlimited number of maneuvers to change their orbit from an operational one to a shuttle or Space Station accessible one and back. Increased spacecraft mobility will allow for greater utilization of the servicing capabilities and result in longer, more productive spacecraft lives.

The demand for OSCRS already exists; in fact, the user community is assuming that a resupply capability will be available. But until the relevant interfaces are defined there will be understandable reluctance to incorporate resupply into spacecraft designs. The level of latent demand lends an element of urgency to the OSCRS program.

Because OSCRS is not simply an isolated piece of hardware or a relatively independent satellite, there are important economic considerations that can only be evaluated on the basis of OSCRS' role as part of a system. The design of system interfaces will proceed from an understanding of how the OSCRS will function within the system, and for this reason requires a systems approach.

Early standardization of spacecraft and vehicle interfaces and refueling/ reservicing operations will simplify the compatibility requirements, reducing the number of mission-specific interfaces/operations and the associated development efforts. Standardization should be addressed in a user community forum such as a series of conferences; it probably cannot be achieved unilaterally.

OSCRS will, for the foreseeable future, be transported to and from orbit in the Orbiter bay. The initial mission, GRO refueling, is planned to take place in the payload bay. Space Station (SS) basing of the OSCRS is part of its long range role. The SS would function as a central servicing facility, using OSCRS in the servicing bay. Use as an on-orbit propellant depot is also potentially a part of the SS scenario. Use of OSCRS with the OMV or OTV as a short term option for in-situ servicing of spacecraft not in shuttle accessible orbits is also part of OSCRS' long range role. While SS and OMV/OTV interfaces are not yet defined, the operating scenarios generate broad requirements for the OSCRS. Modularity, for example, would allow space basing of the storage components of OSCRS on the SS.

The technology challenge is certainly important, but OSCRS' status as an integral part of space infrastructure through 2010 and beyond adds another dimension to the challenge. In addition to the systems engineering issues discussed above, management and marketing will be critical ingredients in the success of OSCRS. Management is a key aspect because programmatic decisions will affect both OSCRS' cost and its utility, and therefore its viability. Running the OSCRS program will require unique responsiveness on the part of management to elements outside the program. Marketing is also important. In order to achieve its potential, OSCRS must be promoted, defined and explained to the user community. Prospective users need to be aware of OSCRS' availability and capabilities. Marketing efforts will also provide the interface with users that will make OSCRS responsive to user needs. Finally, users will require assurance of a programmatic commitment to OSCRS.

STUDY METHODOLOGY

The Fairchild approach to the OSCRS study has been to maximize the versatility and growth potential of the OSCRS design to capture a larger market while minimizing both initial procurement and life cycle costs. The LCC process, illustrated in Figure 1, allows a comprehensive technical and economic examination of all facets of the program from development through operations, maintenance, and transportation. Because the LCC analysis focuses on budget and cost as a planning tool, technical drivers for the subsystem design are established on a cost basis.

Traffic Model

To make objective life cycle cost comparisons between candidate configurations, the study required a traffic model of potential resupply missions. Fairchild contracted this task to Scientific Applications International Corporation (SAIC), a specialist in this field, who identified 20-year, high and low traffic models of 406 and 301 events respectively. This traffic model was used in the initial life cycle costing. Ultimately, with input from JSC and the other two OSCRS contractors, a composite traffic model of 165 refueling events over the 20-year period was developed. The composite model was used in the final LCC analysis.

The survey clearly indicated that the number of missions that could benefit from refueling is significant. Using a variety of mission models in the life cycle costing revealed an important phenomenon; the size and nature of the models made no difference in the design selection. Whether the model includes 165 or 406 events, launch costs (and consequently flight weight) remain the most important factor in determining life cycle costs. Within the limits of start-up affordability, any design that results in a moderate weight savings relative to another design will more than compensate for the cost to develop it.

Configuration Analyses

The initial LCC analysis, LCC I, analyzed four configurations derived from the initial configuration, an across-the-bay structure supporting up to four propellant tanks, eight pressurant tanks, a berthing platform, and grapple fixture. The initial design is shown in Figure 2. The four variations of this design analyzed for LCC I are shown in Figure 3. They provided a range for analysis in total weight and in degree of modularity. The results of the analysis using a 48-mission model are also summarized in Figure 3. The foremost conclusion implicit in the results is that flight weight is overwhelmingly the most important factor affecting OSCRS lifetime cost. Also, comparing the bottom line for configurations 2 and 3 against that for configuration 1, it can be seen that tailoring OSCRS propellant carrying capacity to spacecraft requirements is more economical than carrying a fixed capacity.

Having new insight into the problem as a result of the first cost analysis, Fairchild re-examined OSCRS to see if the designs being offered were the most effective, specifically, if they were the lightest and least complex. This evaluation resulted in changing the OSCRS concept from the traditional "tanks mounted on a structure" design to a single propellant tank directly supported by the Orbiter sills. A pumped propellant delivery system was also incorporated and the pressurant tanks were used to attach the main tank to the keel fitting.

Using this new design, called "Trigon" (three sides), shown in Figure 4, a similar LCC analysis was performed. A cost comparison of the Trigon against the initial configuration showed an average savings of about $5.8 million per flight. Additionally, modularity enables incremental expansion of capabilities. By phasing investment to match evolving user demand, an economical program for maximizing the impact of funds is achieved. To expand capacity in parallel with user demand is the most promising way to optimize the flexibility and usefulness of the OSCRS. The modular approach to the Trigon OSCRS is shown in Figure 5.

Because non-recurring development costs can represent a formidable start-up hurdle, any means of sharing costs over a number of programs will reduce their impact. Commonality between the monopropellant and bipropellant programs means that both will benefit from the same development funds. The benefits of commonality will extend to include sharing of costs for mechanical aerospace ground equipment, electrical ground equipment, software, and the design of fluid systems ground equipment. The use of common elements in the monopropellant and bipropellant OSCRS also provides programmatic flexibility. The total number of development efforts is reduced, and much of it can occur in parallel early in the program. The high degree of commonality between the monopropellant and bipropellant Trigon systems is shown in Figure 6.

FLUID SUBSYSTEM

The fluid subsystem has been baselined for compatibility with the GRO spacecraft while providing for the probable variants that may be expected in future spacecraft requiring on-orbit servicing. It has been designed to be lightweight and incorporates one failure tolerance for mission completion and two failure tolerance for safety.

The OSCRS Fluid System Schematic shown in Figure 7 illustrates the extended capability OSCRS with two propellant tanks. Secondary schematics, illustrating the High Pressure Pressurant Replacement Kit and the Ullage Replacement Kit, refer to growth configurations with accessory kits intended to resupply propellant tank ullage in a spacecraft or other devices requiring pressurant gas. The baseline bipropellant fluid system schematic illustrated in Figure 8 is nearly identical to the monopropellant version in duplicate. Fuel and oxidizer systems will be of the same design except for materials, which must be compatible with the different fluids.

Liquid propellant is stored in a compartmented surface tension propellant management tank. Propellant is expelled from the tank by regulated gas pressure. Fixed displacement pumps boost the propellant pressure to the value required to balance the pressure in the spacecraft receiving tank. Gases and liquids are filtered at several points to insure reliable operation of OSCRS components and delivery of clean propellant to the spacecraft. A flexible metal hose and a coupling connect OSCRS with the spacecraft reception coupling and distribution manifold. For the initial GRO refueling mission, the coupling is operated manually by the astronaut. Control of flow is maintained from the aft flight deck. The hose and coupling can be separated from OSCRS at the jettison interface by command. Two independent hose/coupling sets will be installed for the GRO hydrazine service to comply with the requirement to perform the mission after a single failure.

The Nucleonics (gamma ray attenuation) concept was chosen as the primary quantity gauging approach. In this device a Kr-85 radiation source which emits gamma rays is attached to one end of the fluid tank. When the rays reach the radiation detector on the opposite end of the tank, the detector unit produces a pulse train at a rate proportional to the amount of radiation received. The ray attenuation by the hydrazine in the tank is maximum at full tank and diminished as the tank is emptied.

A disposal system will be incorporated to decompose surplus liquid propellant and ullage gas with entrained propellant. This will be a mission variable device because of the large variation between individual missions; it is not required for GRO. A building block approach, where a variety of accessory interchangeable disposal units will be created appears most suitable to the nature of the problem.

STRUCTURE & MECHANISMS

After safety, compatibility with potential user spacecraft, the Orbiter, Space Station, OMV and launch sites was a major design driver for the OSCRS structure and mechanisms. The design adheres to standard Orbiter interfaces and clearance envelopes, and is compatible with GRO in the baseline spacecraft interface. The interface requirements for OMV and the Space Station are as yet undefined.

The same, 28-inch diameter cylindrical fluid tank is used in all the configurations, singly to transport up to 3000 lbm of hydrazine, or in tandem with intertank fittings to transport up to 6000 lbm of hydrazine. A bipropellant OSCRS configuration involves primarily the addition of a 28-inch diameter oxidizer tank, a fluid components module, and valve drivers in the avionics module. The modular expansion is illustrated in Figure 9, which also includes the weight summary, by subsystem, for each OSCRS configuration.

Two potential spacecraft interface mechanisms were explored for the OSCRS study. The baseline design is based on the FSS interface, with added deployment, rotation and jettison devices. An alternate configuration which is lighter but more limited is based on the RMS end effector. Both mechanisms are modular -- attachable as needed -- and provide docking and fluid transfer capabilities. They are adaptable to either type OSCRS. They provide gas interconnectors and electrical connectors for telemetry, command and power transmission. Mounting of the interface mechanism is via a structural support frame attached to the fluid tank end caps. The mechanisms are automated; EVA is not necessary for operation but incorporated as a backup mode. By providing the capability to deploy the docking platform beyond the cargo bay envelope, spacecraft can be serviced without interfering with adjacent cargo.

The jettison mechanism, common to both the FSS and RMS type systems, consists of three zero contamination redundant pyrotechnic separation nuts attached to the docking platform, three separation nuts attached to the rotating platform, and three interconnection studs holding the two separation surfaces together. The spacecraft side separation nuts fire first, followed milliseconds later by the separation nuts on the other side of the jettison plane. The interconnection bolts are captured. When the separation nuts are fired, a spring loaded ejection device provides the force to separate the electrical and fluid/gas couplings and to push the spacecraft away from the OSCRS.

AVIONICS SUBSYSTEM

The avionics subsystem is designed to minimize GPC dependency for operation but an optional GPC interface is available. The avionics is one fault tolerant for mission success and two fault tolerant for safety, utilizing existing technology and some already flight qualified equipment. All cargo bay components utilize radiation hardened devices to provide the necessary reliability for the expected 50 mission lifetime. Additionally, the architecture allows fault isolation and box or sub-module level replacement for servicing. The system provides a safety shutdown feature and full safety monitoring after two faults in compliance with NHB 1700.7A STS safety requirements.

The avionics subsystem provides telemetry talkback on every function, allowing the crew full system visibility via a graphic display of telemetry. Automatic limit checking allows the crew to reset limit functions in the dual command and telemetry system. Software is user friendly for ease of operation and crew training. An internal Built In Test (BIT) function is provided for self testing. Health checks are also performed on other OSCRS subsystems. A Caution and Warning interface alerts the crew in the event of an anomalous condition.

There is a high degree of commonality between the monopropellant OSCRS (MPO) and the bipropellant OSCRS (BPO) avionics subsystems as shown in Figure 10. The commonality results from the flexibility of the avionics subsystem design, which requires only minimal changes to meet additional or differing mission requirements.

A single side of the redundant system in Figure 10 consists of an AFD terminal, an Advanced Communications and Data Handling (AC&DH) Unit, a Remote Interface Unit (RIU), and an Expander Unit (EU). This string commands and interrogates the Valve/Motor Drivers (VMDs), a Mechanism Select Box (MSB), and a Signal Conditioning Unit (SCU). A Power Switching Unit (PSU), primarily under Aft Flight Deck (AFD) Standard Switch Panel (SSP) control, is used to distribute power to the avionics subsystem components and the refueling spacecraft.

THERMAL SUBSYSTEM

The temperature control of the avionics and fluid control modules is through the use of insulation, heaters and selected optical surface finishes. Multilayer insulation blankets around components minimize cold case heater power requirements and isolate equipment from fluctuations in the external environment. White paint is used to cover external radiator surfaces which reject internally generated heat. Black paint is applied to interior surfaces of the equipment and structures to enhance internal radiative heat transfer. Heaters and thermostats insure that minimum allowable temperatures are maintained during cold case conditions. In all applications, primary and backup redundant sets of heaters are implemented and controlled by redundant mechanical thermostats with predetermined set-points. All switching circuits have override capability. Thermistors provide the telemetry input needed for monitoring critical components.

The propellant tank is covered with insulation blankets which have beta cloth outer covers. All lines and valves are heat sunk to the tank. A strip heaters are wrapped around the tank, and patch heaters are located at the Orbiter attachment points. Since the tank is thermally isolated from the avionics and fluids modules, removal of fluid from the tank would not affect thermal control of the modules.

SUMMARY

The OSCRS study led to a number of clear conclusions about what is involved in the task of consumables resupply. Using life cycle costs analysis, Fairchild was able to incorporate a systems approach to evaluate alternative OSCRS configurations in terms of their relative costs. The analysis showed several dramatic results about the features that would make the system cost-effective, namely minimal weight and modularity.

The Trigon is an elegant solution. With cost as the design driver, the important innovations, the tank design and the elimination of structure, are weight reductions. All the other components are the same as in a more conventional approach. While the Trigon is significantly lighter than other configurations, it employs few development items. The majority of the technology for the early missions is available.

The modularity gives the program budgetary flexibility. By starting with a bare minimum system, a low initial procurement can be met. Capability can be expanded as the budget permits.

For growth to its full capacity, there are still items of technology that need development. For an automated spacecraft interface mechanism to be provided, mechanical, fluid, and electrical interfaces need to be defined and standardized. Jettison, rotation, and deployment/reboost capabilities must be incorporated. Growth configurations will require a liquid-vapor separator to perform the venting and ullage exchange scenarios.

Incorporating versatility into the system is essential to meeting yet-undefined future requirements such as OMV and Space Station operations. The definition of OSCRS interfaces is an important effort that will require marketing, education, and user awareness activities.

The requirements definition and development efforts yet to be performed argue in favor of an immediate start for the OSCRS program. Even though its use may be several years off, the design, fabrication, and test program is a multi-year effort. Some of the development may have to occur in serial time. The schedule to meet GRO refueling of itself will be challenging.

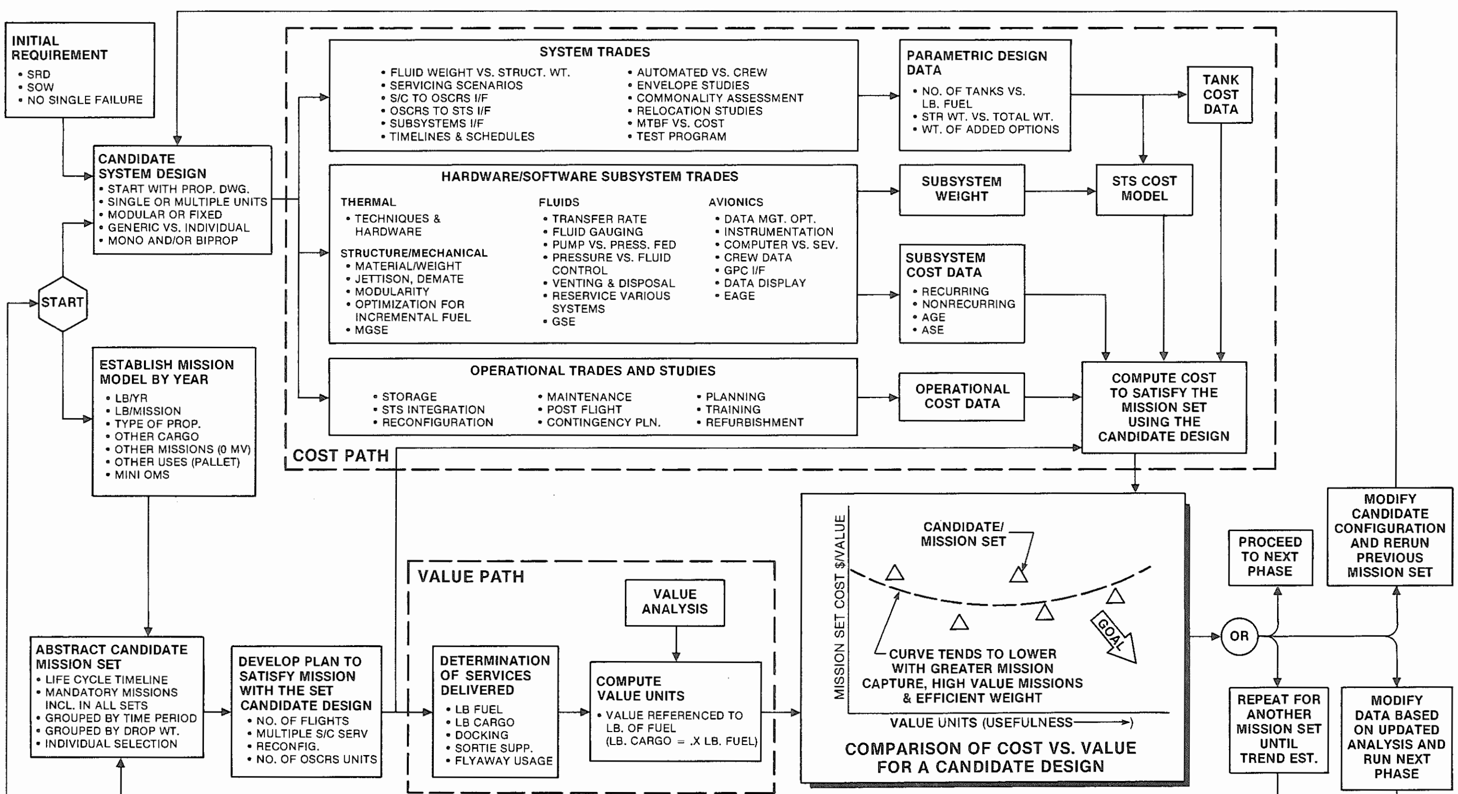


Figure 1. Design Selection Based on Program Life Cycle Cost Analysis

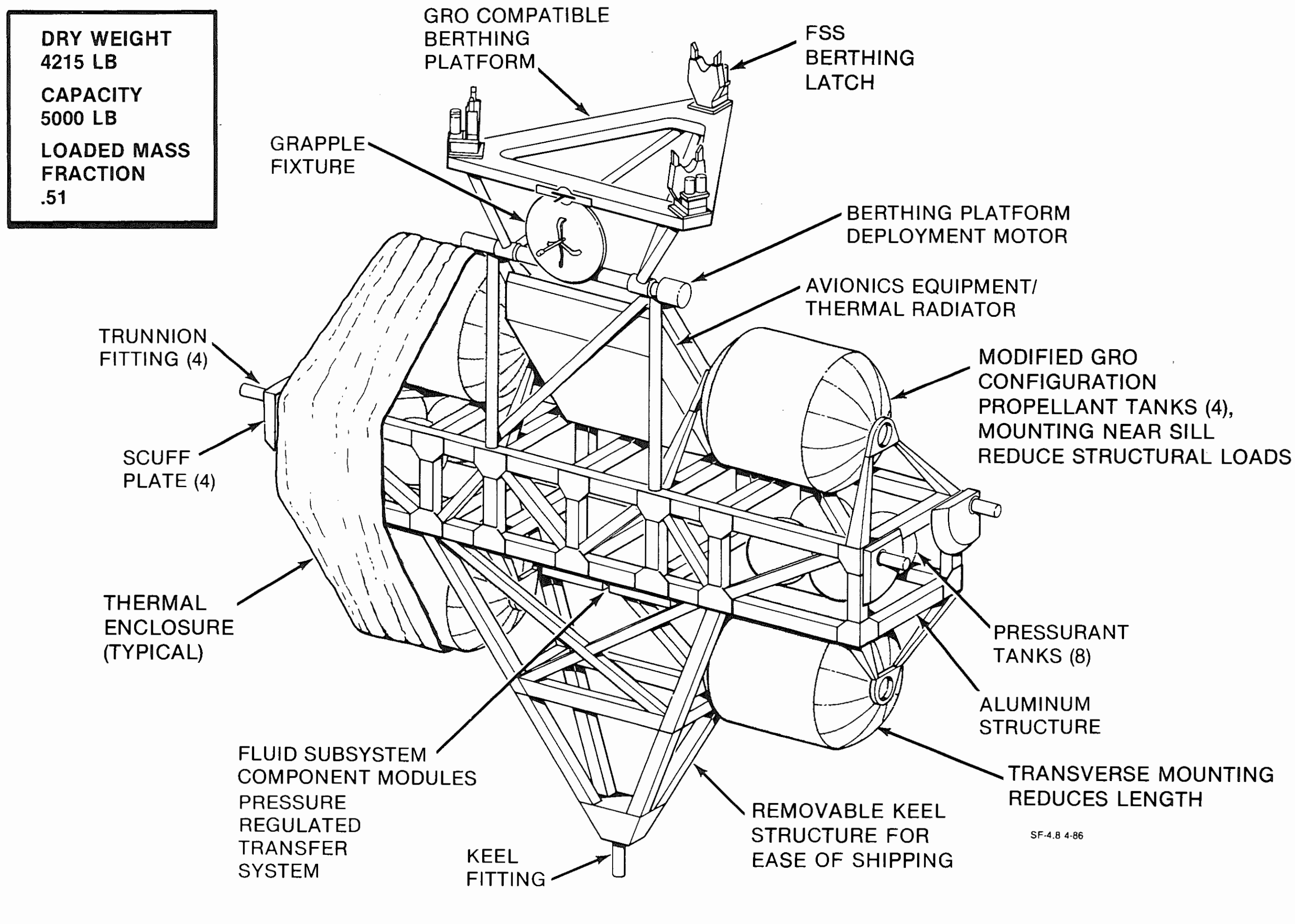
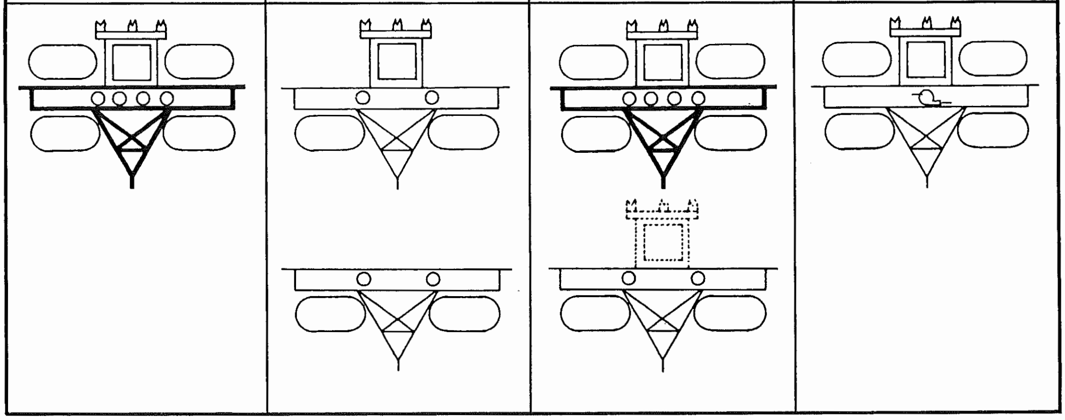


Figure 2. OSCRS Initial Reference Configuration

CANDIDATE SYSTEMS

1	2	3	4
- ONE UNIT • 5000 LB. CAP. - ALUM. STRUCT. - PRESSURE REG. - DRY WT 4215	- TWO UNITS • 2500 LB PRIME • 2500 LB AUXILIARY - ALUM. STRUCT. - PRESSURE REG. - DRY WT • 2886 PRIME • 2378 AUXILIARY	- TWO UNITS WITH TRANSFERABLE BERTH. MECH. & AVIONICS - ALUM. STRUCT. - PRESSURE REG. - DRY WT. - LARGE 4215 - SMALL 2856	- ONE UNIT • 5000 LB CAP GFRP STRUCT. PUMP SYSTEM DRY WT 3221 LB.



• "HIGH" MISSION ESTIMATE (153,796 LB TOTAL) • 48 MISSIONS • 31 JAN 86 DATA

CANDIDATE SYS DESIGN NUMBER OF UNITS STRUCT. MATL FLUID XFER METHOD	1 ONE ALUMINUM PRESSURIZED	2 PRIME & AUXILIARY ALUMINUM PRESSURIZED		3 LARGE SMALL ALUMINUM PRESSURIZED		4 ONE GFRP PUMP
FLUID SUBSYSTEMS	**6970**	**3550**	**3550**	**6970**	**3550**	**5880**
PRESSURANT	500.0	250.0	250.0	500.0	250.0	0.0
PRESSURANT TANKS	40.0	20.0	20.0	40.0	20.0	0.0
PROPELLANT	5000.0	2500.0	2500.0	5000.0	2500.0	5000.0
PROPELLANT TANKS	1200.0	600.0	600.0	1200.0	600.0	600.0
PLUMBING	150.0	100.0	100.0	150.0	100.0	200.0
MISCELLANEOUS	80.0	80.0	80.0	80.0	80.0	80.0
STRUCTURAL/MECHANCIAL SUBSYSTEMS	**2006**	**1472**	**1272**	**2006**	**1472**	**1697**
SCUFF PLATES	100.0	100.0	100.0	100.0	100.0	100.0
GRAPPLE FIXTURE	20.0	20.0	20.0	20.0	20.0	20.0
MECHANISMS	200.0	200.0	0.0	200.0	200.0	200.0
JOINT HARDWARE	132.0	90.0	90.0	132.0	90.0	116.0
SUPPORT STRUCTURE	1554.0	1062.0	1062.0	1554.0	1062.0	1261.0
AVIONICS	**339**	**339**	**80**	**339**	**339**	**339**
HARNESS	75.0	75.0	30.0	75.0	75.0	75.0
AVIONICS	200.0	200.0	0.0	200.0	200.0	200.0
THERMAL CONTROL	64.0	64.0	50.0	64.0	64.0	64.0
CONTINGENCY (9.5% OF DRY WT.)	**400**	**275**	**226**	**400**	**275**	**305**
TOTAL DESIGN WEIGHT (LB)	9715	5636	5128	9715	5636	8221
DRY WEIGHT (LB)	4215	2886	2378	4215	2886	3221
MASS FRACTION (FULL)	.51	.44	.49	.51	.44	.61
AVG. RELATIVE COST/ FLIGHT SAVING	0	$1076K		$2536K		$3352K

Figure 3. Preliminary Monopropellant Candidate System Comparison

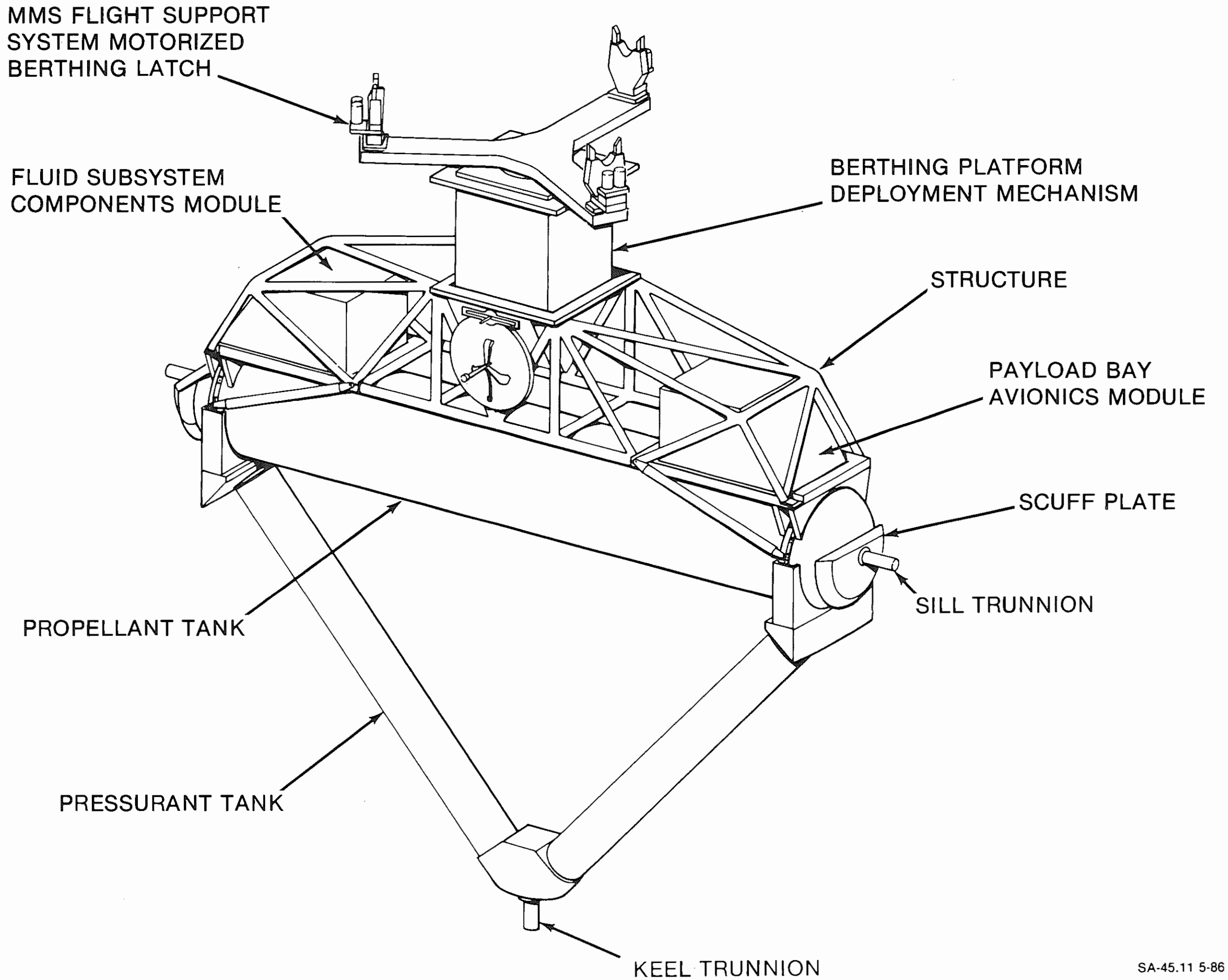


Figure 4. Monopropellant OSCRS Trigon Configuration

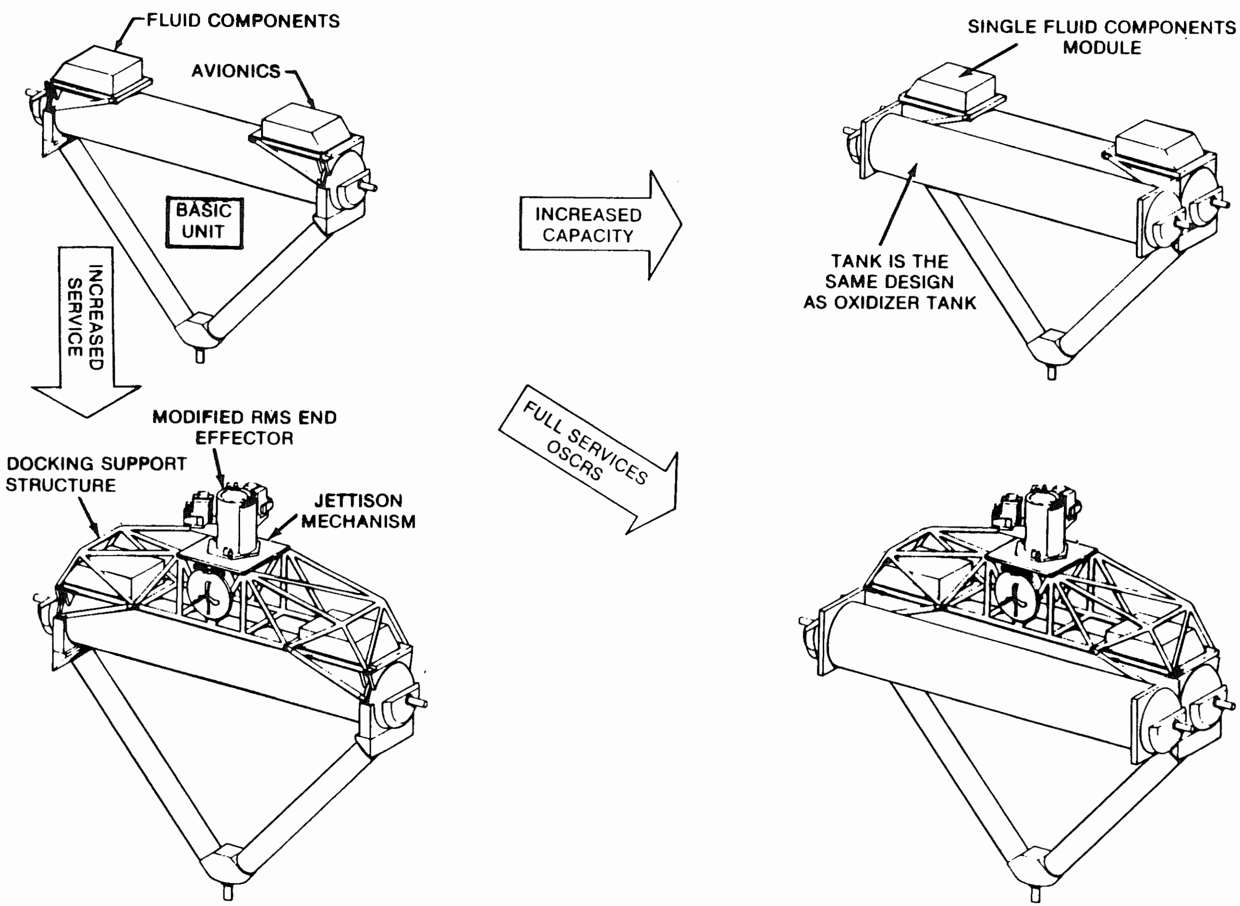


Figure 5. Tailoring OSCRS to the Spacecraft Needs is Cost Effective

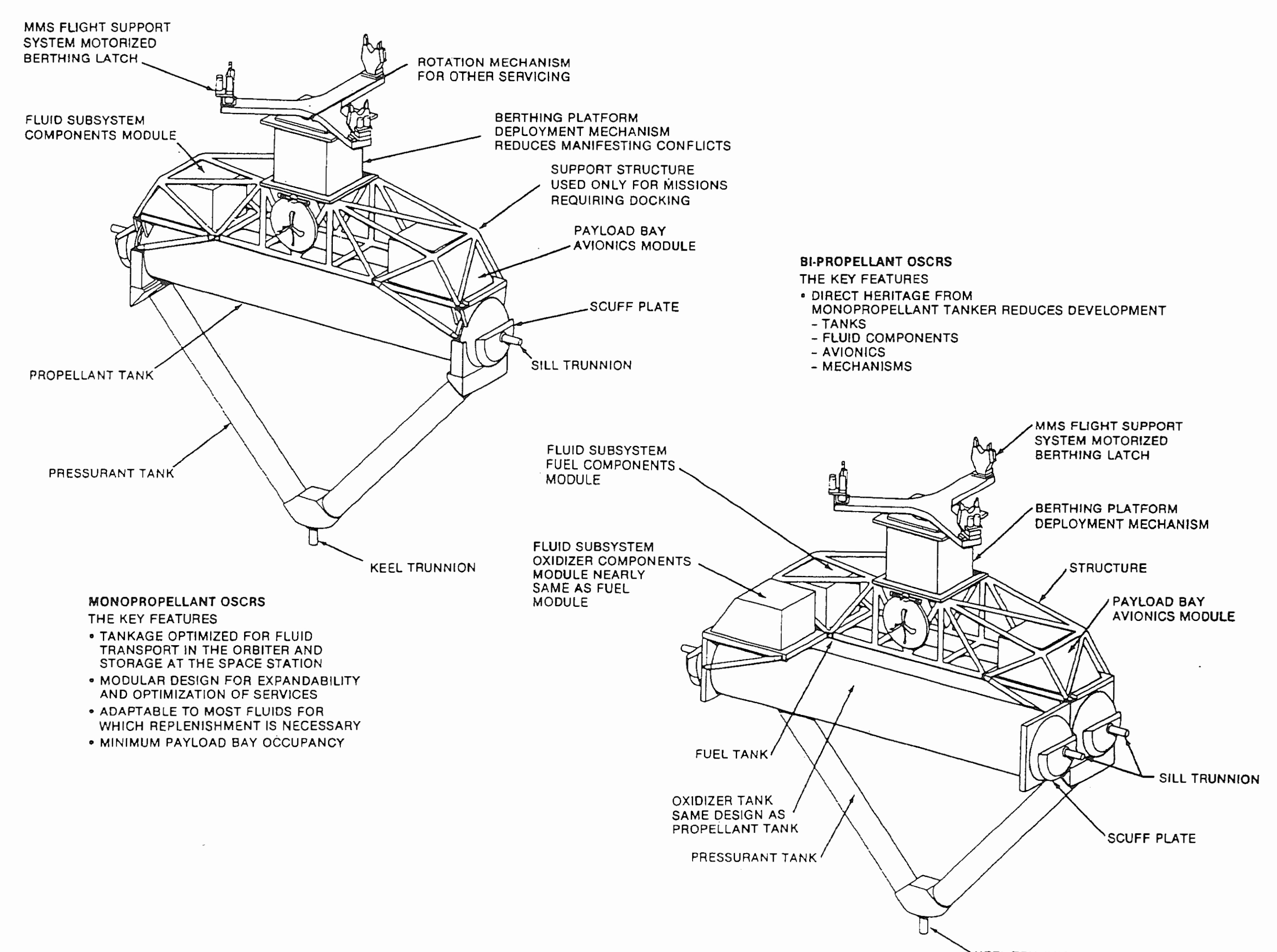


Figure 6. Extensive Commonality Exists Between Systems

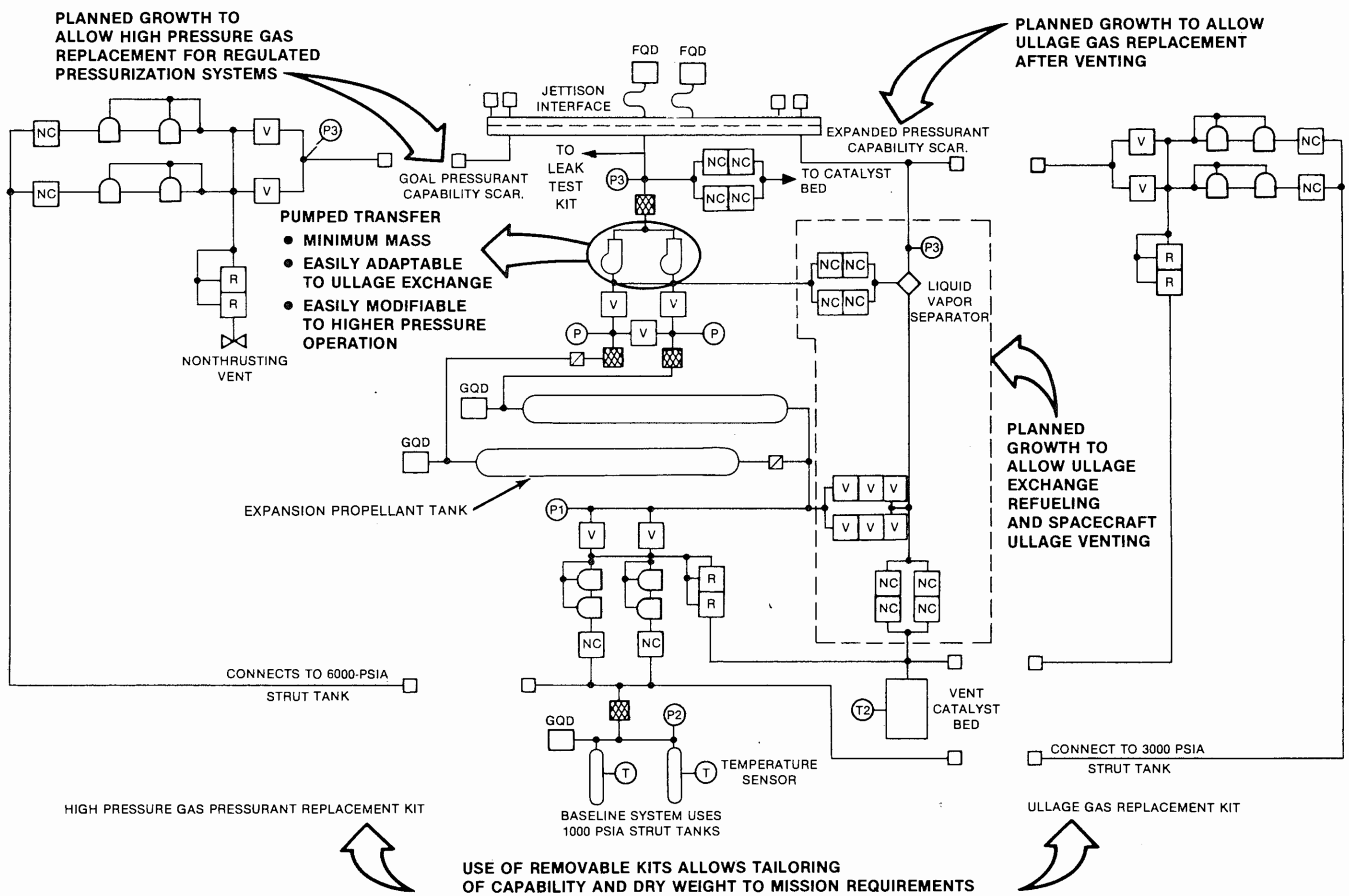


Figure 7. Monopropellant Fluid Subsystem Schematic

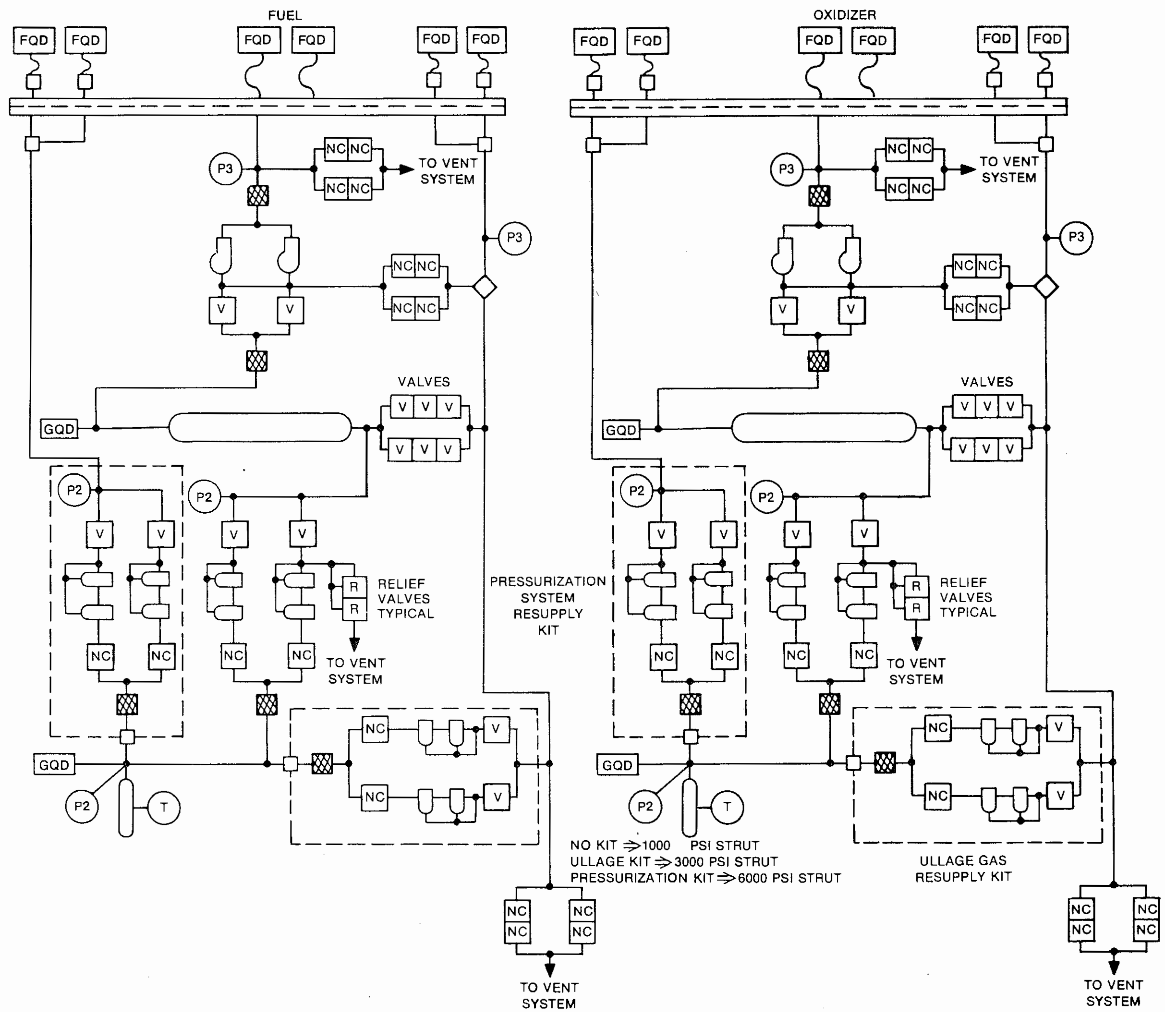
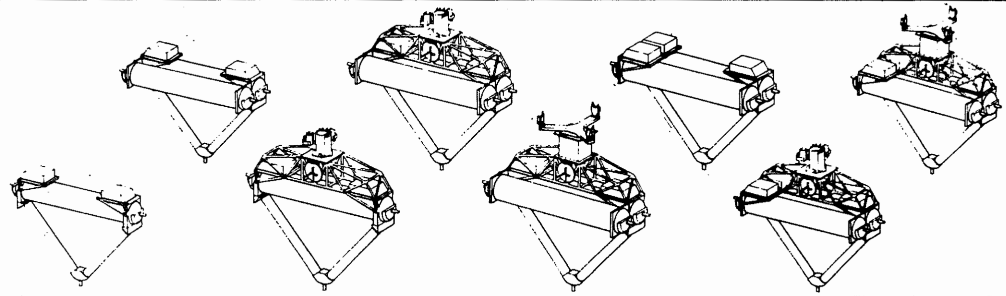


Figure 8. Bipropellant Fluid Subsystem Schematic



CONFIGURATION	M1	M2	M3	M4	M5	B1	B2	B3
FLUID SUBSYSTEMS	762.9	1177.0	762.9	1177.0	1177.0	1355.0	1355.0	1355.0
AVIONICS SUBSYSTEMS	254.7	254.7	254.7	254.7	254.7	272.7	272.7	272.7
THERMAL SUBSYSTEMS	70.0	103.0	70.0	103.0	103.0	103.0	103.0	103.0
STRUCTURAL SUBSYSTEMS	139.9	250.7	231.7	342.5	414.3	250.7	342.5	414.3
MECHANICAL SUBSYSTEMS	0.0	0.0	136.0	136.0	293.7	0.0	136.0	293.7
MISCELLANEOUS	50.0	75.0	50.0	75.0	75.0	75.0	75.0	75.0
DRY MASS	1277.5	1860.4	1505.3	2088.2	2317.7	2056.4	2284.2	2513.7
PRESSURANT	8.7	17.4	8.7	17.4	17.4	17.4	17.4	17.4
PROPELLANT	3000.0	6000.0	3000.0	6000.0	6000.0	7400.0	7400.0	7400.0
TOTAL MASS	4286.2	7877.8	4514.0	8105.6	8335.1	9473.8	9701.6	9931.1
MASS FRACTION	.700	.762	.665	.740	.712	.781	.762	.745

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Figure 9. OSCRS Configuration Weight Summary

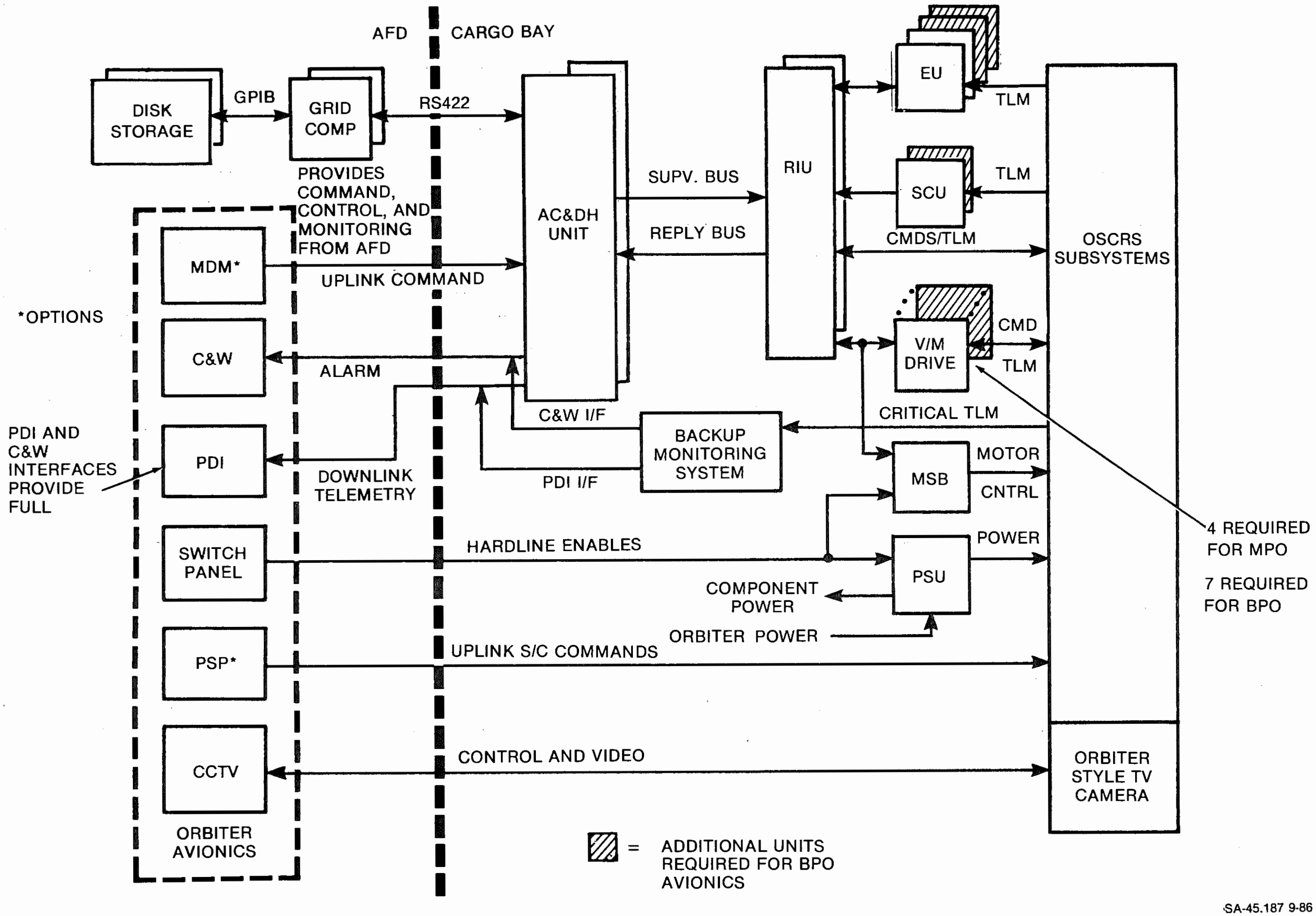

Figure 10. Avionics Subsystem