ORBITAL FLUID SERVICING AND RESUPPLY OPERATIONS*

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ABSTRACT

The capability to reservice spacecraft and satellites with expendable fluids will provide significant increases in the usability, operational efficiency and cost-effectiveness of in-space systems. Initial resupply will be accomplished from the Orbiter cargo bay starting with monopropellant servicing which will eventually be extended to servicing of bipropellants and pressurants. Other fluids, such as freon, ammonia, methanol, superfluid helium and liquid/gaseous nitrogen may also need to be resupplied once a space station becomes a reality. These fluids/gases are required for subsystem working fluid replacement and payload/experiment fluid replenishment. A logistics module operating on a 90-day

turnaround is planned for space station servicing. Resupplying hundreds of thousands of pounds of cryogenic propellants and reactants (e.g., liquid hydrogen, liquid oxygen, liquid nitrogen trifluoride) for users such as the Orbital Transfer Vehicle (OTV) and DoD also represents future logistics challenges. Implementation of on-orbit fluid transfer requires solving many problems including fluid management in the low-g environment,

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system docking and interface mating, configuration of "user friendly" avionics to monitor and control the entire servicing operation, and minimized maintenance and enhanced reliability. Candidate fluid transfer methods and possible gas transfer methods are discussed, and preliminary storable monopropellant and bipropellant tanker designs are summarized.

I. INTRODUCTION

The life of many spacecraft can be significantly extended if they are resupplied on orbit with propellants and pressurant gases, and the life of many scientific payloads increased if their consumable working fluids are replenished. The capability to reservice spacecraft and satellites with expendable fluids will provide significant increases in the usability, operational efficiency and cost-effectiveness of in-space systems. Initial resupply will take place from the Shuttle Orbiter cargo bay starting with monopropellant servicing and proceeding to bipropellants and pressurant gases. A recent phase B study, Orbital Spacecraft Consumables Resupply Study (OSCRS), was completed addressing preliminary designs for storable tankers for these propellants and gases (Ref. 1 and 2). This first generation of servicing will utilize astronaut control from the Aft Flight Deck (AFD) and EVA for umbilical mate/demate.

Future propellant transfer will involve cryogenic propellants, and superfluid helium for scientific payloads. The trend will be to automatic, remotely operated servicer systems which can be used in conjunction with the OMV and space station to extend satellite life in orbit beyond the current range of the Orbiter. Resupplying superfluid helium to space observatories such as the Space Infrared Telescope Facility (SIRTF) offers significant cost savings by extending the orbital life without the need to return to the ground to replenish the liquid helium. The use of the OMV operating out of the space station to retrieve the SIRTR and bring it to the station for resupplying the helium is currently being investigated as a means of economically achieving a ten-year on-orbit operational life goal (Ref. 3). The technology for superfluid helium on-orbit fluid management is not as mature as for the storable propellant and is currently the focus of studies being carried on at both NASA-Ames and NASA-GSFC (Ref. 4 and 5).

The resupply of cryogenic fluids such as liquid hydrogen, liquid oxygen and liquid nitrogen have applications to space-based Orbital Transfer Vehicles (OTV), space station life support and laboratory facilities, scientific and applications satellites and space-based military systems. The technology base for orbital fluid management of these fluids, including resupply approaches and techniques is not as mature as for the storables or superfluid helium (Ref. 6). A cryogenic fluid management test facility has been in the planning stages for the past 10 years. It is a shuttle-based test bed configured to obtain the desired technology data base to permit the design of efficient cryogenic storage and resupply systems (Ref. 7). Orbital test data of the type to be obtained with this facility is required before phase B design studies can proceed.

Three elements are involved in orbital fluid resupply of any of the fluids mentioned above. These are the resupply tanker, a space depot and the user system to be resupplied. Shuttle-based tanker designs are strongly influenced by maximum diameter in the cargo bay and minimum length since these are parameters in the transportation costing algorithm. The high transportation costs likewise drive the tanker designs to derived requirements for redundancy and fail-safe/fail-operational features for all mechanisms. Logistics issues associated with the tanker include centralization of storage, maintenance, checkout and integration facilities to support ground operations and the degree of space-basing elements to provide quick-reaction capability for spacecraft servicing.

Logistics issues associated with the depot include the relative degree of extra vehicular activity (EVA) versus automated or intravehicular activity (IVA), which is a major driver in design complexities as well as timelines for mating and demating between the depot and user being serviced. Logistics considerations involving ancilliary facilities at the depot such as thermal enclosures become particularly important when considering the cryogenic fluids. Timelines for servicing cryogenics are sensitive to the thermal environment in a servicing bay; low emissivity interior surfaces are required to minimize childown losses and boil-off associated with the resupply sequence.

The diversity of the on-orbit consumables resupply task outlined above in terms of types of fluids, current status of technology, degree of autonomy, and ground vs space-basing of elements manifests itself in a wide range of logistics options which strongly influence the degree of cost advantage available from on-orbit fluid servicing. The remainder of this paper will thus try to outline for the decision makers and designers more definitive data regarding requirements and technology readiness, operation concepts and options and a summary of how these translate into specific preliminary designs for storable monopropellant and bipropellant tankers.

II. REQUIREMENTS AND TECHNOLOGY READINESS

Current and future space programs will require resupply of depleted fluids for a number of different subsystem applications, including propellants, power reactants, coolants, life support, and experiment or process consumables. Many of these applications will make use of fluid storage systems in space and will require orbital transfer for resupply of spent systems. Initial loading of these systems in space may also be required.

User Requirements

The potential for on-orbit resupply is extensive and is summarized by representative categories in Table II-1. The most likely early applications will be the resupply of satellites from the Orbiter cargo bay. Satellites in higher orbits can be reached by using an automatic refueling/fluid resupply system attached to an OMV, or spacecraft on-board propulsion can be used to lower the spacecraft

Table II-1 Candidate Spacecraft for Fluid Resupply

PROGRAM	FLUID RESUPPLY QUANTITY	RESUPPLY INTERVAL	PRESSURANT REQUIREMENT
Gamma Ray Observatory	2500 lb N_2H_4 (1136 kg)	2 YR	
Space Station Spartan Platform	800 lb N_2H_4 (364 kg)	1-3 MO	
Multi-Mission Modular S/C	2000 lb N_2H_4 (909 kg)	1-2 YR	
Mark II Propulsion	5000 lb N_2H_4 (2273 kg)	2-4 YR	40 lb GN_2 (18 kg)
Geopotential Research Mission	3000 lb N_2H_4 (1364 kg)	6 MO	
Cosmic Ray Experiment	550 lb N_2H_4 (250 kg)	2 YR	
Eureca	1700 lb N_2H_4 (773 kg)	9 MO	312 lb GN_2 (142 kg)

X-Ray Timing Explorer	Approx. 500 lb N_2H_4 (227 kg)	3 YR	
Mobile SAT-B	1100 lb N_2H_4 (500 kg)	Resupply at SS for GEO	Approx. 10 lb GN_2 (4.5 kg)
GEO Platform	2100 lb N_2H_4 (995 kg)	2 YR	
Mobile SAT-C	2200 lb N_2H_4 (1000 kg)	2 YR	

Table II-1 Candidate Spacecraft for Fluid Resupply (continued)

PROGRAM	FLUID RESUPPLY QUANTITY	RESUPPLY INTERVAL	PRESSURANT REQUIREMENT
DoD 1	7000 lb MMH & NTO (3182 kg)	2-3 YR	
DoD 2	6000 lb MMH & NTO (2727 kg)	3-5 YR	
EOS Platforms	5000 lb MMH & NTO (2273 kg)	2 YR	
Platform System Technology	2000 lb MMH & NTO (909 kg)	3 MO	
SIRTF	1100 lb LHe (500 kg)	2 YR	
AXAF	130 lb LHe (59 kg)	1.6 YR	
LDR	1900 lb LHe	2 YR	

	(8[illegible]4 kg)	
GP-B	440 lb LHe (200 kg)	2 YR
Dark Sky	550 LHe (250 kg)	3 YR
Material Technology Laboratory	500 lb (227 kg) LN_2 700 lb (318 kg) LO_2 180 lb (82 kg) H_2O 238 lb (108 kg) LAr 45 lb (20 kg) LH_2	
Orbital Transfer Vehicle	28000 lb (12727 kg) LH_2 168000 lb (76364 kg) LO_2	

to orbits accessible by the shuttle. The advent of space station and platforms in polar orbit will significantly improve resupply operations and provide substantial economic benefits by enhancing spacecraft maneuverability/ survivability, and improving mission performance capability. Additional specifics concerning storable consumable resupply requirements can be found in Ref. 2.

Interface Requirements

Three interface areas which drive the design of tanker subsystems include carrier, ground, and crew interface requirements. Basic tanker designs will initially be compatible with Orbiter interface provisions. An orderly transition to interface with other carriers is envisioned; however, this definition of requirements (for OMV, Space Station, OTV) has not been finalized and presently can be assessed in only generic terms. Possible tanker compatibility with expendable launch vehicles is an area of interest which will be addressed in the future. Most likely these interfaces will be very similar to the Orbiter's; typical interfaces are summarized in Table II-2 for different carrier applications for an Orbital Spacecraft Consumables Resupply System (OSCRS).

On-orbit operation of an OSCRS-type tanker to accomplish a spacecraft resupply mission includes interfaces with the crew for both EVA-operated mechanical and electrical umbilical connections and release, as well as tanker control and monitoring from a control station located on the Aft Flight Deck (AFD). The man machine/human factors requirements of the AFD control station were derived from preliminary operational scenario analysis which resulted in the following:

a) Provide a control station concept for the AFD which minimizes OSCRS impact on other payloads.

b) Optimize the man-machine interface for data display to the crew and OSCRS commanding.

c) Meet all redundancy/safety related requirements.

d) Provide manual safing and securing options for the OSCRS.

e) Include any optional interface with the Orbiter GPC.

Requirements for resupply tanker ground processing indicate the need for a completely flexible concept for ground checkout, servicing, launch support and mission turnaround, including refurbishment operations. The tanker requires a wide variety of ground support equipment (GSE) to accomplish these operations as well as transportation, handling, and processing GSE to provide the necessary capability to integrate the tanker into the Orbiter. The desire not to impact Orbiter processing by tanker's use of existing Orbiter facilities or Orbiter GSE is an important part of the development of the ground processing approach. General ground processing capabilities and facility requirements are listed in Table II-3.

Table II-3 Ground Processing Requirements

a) Receiving inspection and checkout area to perform off-line verifications and testing.

b) Bonded storage area for tanker equipment and spares.

c) Pressurant servicing of gaseous helium and gaseous nitrogen up to storage pressure of 5000 psig (34,475 kPa).

d) Servicing of N_2H_4, MMH, and N_2O_4, cryogens and other resupply fluids.

e) Tanker/Orbiter interface simulation and integrated interface testing.

f) Interfacility tanker handling.

g) Intrafacility tanker transportation and processing.

h) Standard Orbiter installation/removal.

Table II-3 Ground Processing Requirements (cont.)

i) Contingency fluid and pressurant deservicing during launch preparation and post-mission.

j) Contingency fluid decontamination during launch processing.

k) Areas for tanker associated EGSE to support ground processing, launch operations and mission turnaround activities.

l) Ordnance storage, handling and installation.

m) Other standard payload processing needs as identified in the Launch Site Accommodations Handbook for STS Payload (K-STSM-14.1), and agreed to in the Payload Integration Plan (PIP) and Annex 8, Launch Site Support Plan.

n) Emergency pressurant/propellant/fluid deservicing.

o) Turnaround area for off-line reconfiguration, component changeout, and post mission verification/testing.

p) Provisions for software reconfiguration and retest for the next mission.

System Requirements

The key system requirements that drive the design of on-orbit resupply servicers, and the rationale for their selection, are shown in Table II-4. Many impact the overall servicer configuration while others affect only specific subsystems. It is important to note, however, that they collectively reflect the complexities associated with different designs regardless of the fluid being resupplied. On-orbit resupply covers a broad range of servicing scenarios, first from within the Orbiter cargo bay and eventually from and around the Space Station, which involves the use of orbital maneuvering and orbital transfer vehicles. Propellants (N_2H_4, MMH, and N_2O_4) will be the first fluids to be resupplied, followed by pressurants (GN_2 and GHe) and other fluids (H_2O, etc.). Liquid helium (LHe) will most likely be the first cryogen to be resupplied followed by LN_2, LH_2, LO_2, LAr and LCH_4.

Table II-4 Requirements That Drive Resupply Tanker Design And Rationale

Requirements	Rationale
Monopropellant tanker sized for 3000 lb. Bipropellant OSCRS sized for 7000 lb (3182 kg) which is typical of larger bipropellant spacecraft. Other fluid capacity sizing is yet to be determined.	Optimize mass fraction
Permit interconnection of two separate tankers (or a tanker supplemental fluid module)	Convenience in servicing satellites that require more fluid than the nominal tanker capability
Standard orbiter interface provisions	Minimum cost and risk; operational flexibility
Design for useful life of 80 flights	Optimize life and minimize cost
Operational after one failure	Mission success probability
Safe after two failures	Acceptable safety

Manual connection initially with capability to evolve to automatic	Minimum cost and development risk
EVA friendly	Minimize EVA problems
Capable of relocation in the cargo bay during orbital operations	Maximum location flexibility for launch, on-orbit and landing operations
Capable of removal from the cargo bay without draining or venting	Flexibility in ground operations
Provide for emergency separation of satellite from Orbiter without EVA.	Safety
Modifiable for attachment to OMV, Space Station, or orbiting platforms	Maximize commonality, minimize overall costs
Provide thermal control independent of Orbiter attitude	Minimize operational constraints on Orbiter
Provide capability of venting fluids and/or gas from tanker and satellite	Flexibility in servicing different types of satellite propulsion systems

Table II-4 Requirements That Drive Resupply Tanker Design And Rationale (cont)

Requirements	Rationale
Modifiable to supply high-pressure gas	Flexibility in servicing different types of satellites
Permit resupply to satellite with various propellant orientation/acquisition systems	Capability to resupply all types of satellites storable fluid systems
Provide capability for short lead-time hardware/ software changes and minimize ground processing	Minimize ground turnaround time
Provide avionics growth capability to accommodate resupply systems for other fluids	Commonality; Minimize cost of overall resupply systems

A summary of the major technology issues associated with on-orbit fluid management and fluid resupply for the range of future systems application is presented in Table II-5. The applicability of the various types of servicer/tankers is indicated with the storable tanker having the greatest level of technology maturity at this time. Other major issues are also indicated such as long-term on-orbit operations, fluid conditioning and quantity gaging, which is just one specific example of a broader category called instrumentation/ diagnostics. Instrumentation diagnostics which are operable in zero gravity are key to the control and monitoring of orbital fluid systems. Special design considerations, such as control of fluid motion in the low-g environment, may be significant for systems requiring a stringent degree of pointing accuracy or minimized residual impulse imparted from the moving fluids.

Table II-6 Fluids Systems Technology Applicability

III. DESIGN/OPERATIONAL CONCEPTS AND FEATURES

The fluid transfer technique selected to resupply spacecraft tankage is highly dependent on the configuration of the tankage. Spacecraft propellant management for tankage generally can be classified into two different types - diaphragm and surface tension. Diaphragm-type tankage utilizes elastomeric membranes to separate the propellant from the pressurant (except for minimal migration/ permeation of both propellant and pressurant across the diaphragm). Such systems predominate in hydrazine tankage design. Tankage using surface tension propellant management devices (PMD), such as woven screens, perforated sheets and vanes, operates by preferentially positioning the propellant in the tank to meet specific user requirements. These systems are most common in bipropellant (and to a lesser extent in hydrazine) systems where tighter propellant management requirements prevail.

Current bipropellant incompatibilities with elastomeric materials (especially N_2O_4) also drive these systems to surface tension-type concepts which co-mingle pressurant and propellant within the tank. Surface tension forces are then used to effectively dominate the gravitational and flow forces, and position vapor-free liquid for delivery to the tank outlet. Expulsion efficiencies greater than 99% can be achieved by such systems.

Fluid Transfer Techniques

Four candidate transfer methods have been defined for accomplishing resupply. These techniques are most applicable to specific spacecraft user tankage configurations and include:

a) Adiabatic Ullage Compression - applicable exclusively to blowdown tankage systems utilizing either diaphragm or surface tension PMD's, and currently limited to use only on monopropellant systems.

b) Ullage Exchange - applicable to pressure-regulated surface tension tankage and currently limited to use only on bipropellant systems or non-diaphragm monopropellant tankage where a closed circulation loop can be established.

c) Vent/Fill/Repressurize - applicable to pressure-regulated surface tension tankage with in-tank liquid/vapor separation. No spacecraft are currently designed to use this technique. Also, any type of diaphragm tankage can use this technique.

d) Drain/Vent/Fill/Repressurize - applicable to surface tension tankage with simple or complex PMD's for either monopropellant or bipropellants.

Detailed discussions of each of these approaches can be found in Ref. 1.

A summary of fluid transfer system applicability is presented in Table III-1. Monopropellant and bipropellant systems are addressed, including both blowdown and pressure-regulated cases. Surface tension and diaphragm tankage options are included. The selection of the appropriate resupply method depends on the set of spacecraft design features. It is desirable for the servicer not to drive the design of the spacecraft to accomplish the resupply.

Selected fluid transfer approaches using the adiabatic ullage compression method for monopropellant and the drain/vent/fill/repressurize method for bipropellants are shown schematically in Figures III-1 and III-2, respectively. They represent optimized configurations for resupply of these propellants and are not constrained by the need to demonstrate open technology or unproven concepts.

Figure III-3 illustrates a simplified schematic of a cryogenic transfer/resupply system showing both the supply and user systems.

Modular vs Dedicated Design

Modular versus dedicated design approaches were examined for both monopropellant and bipropellant applications. In both cases, modular was found to be the most cost-effective approach considering the relatively significant cost for each pound to orbit. The study assessment for hydrazine illustrates the approaches used to select the preferred modular design.

Since the basic derived requirement for propellant load was approximately 3000 lb (1364 kg), the initial cost is minimized by minimizing the size (and number of tanks) that can meet the requirement; this results in the three tank configuration for monopropellant hydrazine. Minimum life cycle cost will be obtained by minimizing transportation cost which is achieved by using the system with the best mass fraction. Figure III-1 shows the mass fraction for various configurations considered in the trade study as a function of propellant load. The best mass fraction for the basic design load of 2910 lb (1323 kg) is achieved by using a three tank configuration. As shown, this configuration can be designed (and qualified) to a series of configurations from two tanks to five tanks, with a maximum delivered capacity of 4850 lb (2204 kg).

The total recurring cost for 80 flights of a representative propellant load distribution is shown in Figure III-2 for a 3000 lb (1364 kg) non-modular design, a 5000 lb (2250 kg) non-modular design, and a modular design. If a modular basic OSCRS is used over the propellant load range (i.e., 2, 3, 4 or 5 tanks are used for a given mission, as appropriate), the cost savings shown in Figure III-2 indicate that the modular approach is better than either three tank or five tank non-modular (fixed) OSCRS supplying the 80 mission propellant load distribution by $20 M and $49 M, respectively.

For scenarios requiring more propellant than the maximum capability of a single tanker/servicer, an approach to interconnect two servicers has been baselined and incorporated as a growth provision into the preliminary design.

High Pressure Gas Resupply Techniques

Pressurant resupply to a user system will evolve from low, to medium, to high pressure resupply for varying quantities of GHe and GN_2 gas supplied in conjunction with monopropellant and bipropellant applications. The following three transfer methods have been baselined and represent an evolution of technology needs as delivered pressure level requirements to a user increase:

a) Pressurant delivered at 50 - 500 psia (345 - 3450 kPa - Resupply in this pressure range will be accomplished by using variable set-point regulator control of pressurant stored in 1 to 3 storage bottles. Redundant control legs provide fail-operational capability.

b) Pressurant delivered at 500 - 3000 psia (3450 - 20,700 kPa - Resupply in this pressure range will be accomplished by using variable set-point regulator control of pressurant stored in 3 to 6 isolatable storage bottles using a cascaded resupply mode. One bottle at a time will be used in this approach. When spacecraft and bottle pressures equalize, the bottle will be closed and the next (higher pressure) bottle will be brought on line. The process continues until proper mass/pressure is delivered.

c) Pressurant delivered at 3000 - 5000 psia (20,700 - 34,500 kPa - This pressure range is accommodated by installing gas single stage compressors (with an outlet/inlet ratio of 3:1) into the regulated/cascaded system defined above. Each storage bottle (up to 7 plumbed in parallel) is depleted individually and when the 3:1 ratio of outlet-to-inlet pressure is reached the next bottle is brought on line.

For the above defined transfer methods the GN_2/GHe can be stored at pressure as high as 4500 psia (31,050 kPa) in 4.7 ft^3 (0.13 m^3) pressurant bottles. Each bottle holds 13 lb (6 kg) of GHe or 90 lb (41 kg) GN_2. Bottles can either be plumbed together without isolation or each bottle can be selected by a separate electrically operated valve. The pressurant requirements for each mission will be optimized so that the proper number of bottles will be included. Resupply of spacecraft pressurants will occur first, then residuals left in the bottles (which are significant when a cascaded mode is used) will be used to expel tanker propellants for user propellant reservice.

The most significant factor controlling the pressurant resupply process is the dissipation of the heat of compression in spacecraft tanks in the low-g vacuum environment. As the maximum temperature in these tanks is approached the amount of pressurant being introduced will have to be decreased, resulting in an increased resupply timeline. These tanks will have to be close-coupled with other spacecraft elements (propellant tanks) so that heat can be dissipated. Insulated pressurant tanks (even partially insulated) will be almost impossible to resupply using the methods previously defined.

IV. FLUID RESERVICING TECHNOLOGY

Two categories of technology (shown in Table

IV-1) have been identified for on orbit fluid resupply, technology enhancements and open technology issues. Technology enhancements can improve the performance and reduce risks, but are not prerequisites to accomplishing fluid transfer. The refueling of a hydrazine satellite with a diaphragm tank and a blowdown pressurization system does not require resolution of any open technology issues. However, the same is not true for fluid resupply of surface tension tankage where more complex fluid management issues come into play and include high pressure pressurant reservicing operations. Open technology issues must be addressed prior to design commitment of resupply systems having required fluid transfer flexibility.

Table IV-1 Fluid Reservicing Technology Issues

Technology Enhancement

Technology

o Hardware

a) Variable set-point regulators and relief valves

b) Monopropellant catalytic vent life with long burn times and high concentrations of non-condensible gases and pulsed operations

o Processes

a) Pressurant solubility effects during fill

b) Contamination control during venting

c) Adiabatic compression heating in surface tension tankage

Open Technology Issue

Technology

a) Automatic fluid coupling

b) Resupply mechanism to make and brake the fluid coupling

c) High pressure gas compressor is not state-of-the-art

d) Tank quantity gaging system

e) Oxidizer burner and fuel burner that can accept high concentrations of non-condensible gases, and pulsed operation. A burner that could handle both simultaneously or separately is desired

- Processes

a) Separation of gas/vapor from liquid during venting (required for ullage exchange and vent/fill/repressurize transfer methods to be effective)

b) Total filling of complex PMD's

c) No-vent fill

Recommendations

- o Hardware

  a) Design, build and test an electronics variable set-point regulator to minimize risk

  b) Test existing design over complete range of expected conditions

- o Processes

  a) Minimize the time the liquid is exposed to high pressure. Run tests to understand process for contingency operations

  b) Study required to better quantify requirements

  c) Refine computer programs using ORS data and extrapolate to PMD tanks

- o Hardware

  a) & b) Design, build and test these devices together to minimize risk

c) Design, build and test to assure reliable long life

d) Continue JSC contract work

e) Design, build and test over complete range of expected operating conditions

- Processes

  a) Studies followed by drop tower and Storable Fluid Management Demonstration (SFMD) testing

  b) & c) Conduct tests and analysis of storable fluid in ground tests and determine if zero-g tests are required

Total filling of complex Propellant Management Devices (PMDs) requires venting the tank after the liquid has been drained back to servicer catch tanks; this is followed by a no-vent fill. Evolution of dissolved gas and/or heating of vapor during the fill may prevent complete filling. Our present knowledge of adiabatic heating is adequate. However, we may be able to significantly shorten the fill time with a better understanding of the process. If dissolved gas comes out of solution during transfer it could slow down the transfer and interfere with complete filling. This can be minimized by reducing the time the tanks are pressurized. A better understanding of the process would maximize the efficiency of the filling operation. A more detailed discussion of fluid reservicing technology issues can be found in Ref. 1 and 2.

The resupply of cryogens on-orbit has many unresolved technology issues associated with thermal control and low-g fluid management. The Cryogenic Fluid Management Facility (CFMF) Program (Ref. 7) addresses these issues and provides an approach for investigating the behavior of LH_2 in a low-g environment with the object of performing on-orbit experiments to resolve open cryogenic storage and transfer issues. The uniqueness of liquid helium places this cryogen in a class by itself. LHe resupply is being addressed by the Astronomic/ Astrophysics science communities which require on-orbit instruments/sensors which operate at LHe temperatures (Ref. 4 and 5).

V. SYSTEM DESIGNS

Preliminary designs of both storable monopropellant and bipropellant resupply systems have recently been completed on the Orbital Spacecraft Consumables Resupply System (OSCRS) contract with NASA-JSC (Ref. 2). Provisions for resupplying relatively large quantities (on the order of 20 kg gaseous helium and 140 kg gaseous nitrogen) of high pressure (3000-5000 psig; 20,700-34,500 kPa) gas were also incorporated into the propellant tanker designs.

Monopropellant Design

The basic monopropellant design is shown in Figure V-1. It consists of three TDRS-type hydrazine storage tanks with diaphragms, a bolted aluminum structure, a triple redundant avionics subsystem for data handling and control, and a multilayer insulation blanket in combination with tank heaters for thermal control. The configuration shown has a capacity of 2910 lb (1323 kg), with an estimated mass fraction of 0.60. Each tank can be loaded 97 percent full, and operate at a maximum expected operating pressure (MEOP) of 500 psia (3,450 kPa). Two additional tanks can be added to this basic structure to provide a total capacity of 4850 lb (2205 kg), resulting in a mass fraction of 0.66.

In order to minimize tank changeout, two monopropellant OSCRS units are recommended; one containing three TDRS propellant tanks providing a maximum resupply capacity of 2910 lb (1323 kg) while the other is configured with two TDRS propellant tanks providing a maximum resupply capacity of 1940 lb (882 kg). An estimate of more than 75% of the resupply potential can be accommodated without reconfiguration of either of the units. A modular building block approach was adopted so that the servicer could be customized to meet user-specific needs for the remaining 25% of the reservicing missions.

Features of the basic fluid system design and its associated designed-in growth options are shown in Figure V-2. Provisions are included for two added propellant tanks in an add-on propellant module, added pressurant tanks for propellant expulsion and an add-on module for pressurant resupply. The propellant tank are plumbed so that they can be depleted individually or in combinations up to all tanks simultaneously. Flowmeters are provided in the transfer line to determine propellant transferred.

A major design driver influencing the level of redundancy shown was the requirement to be fail-operational, and to meet all the redundancy requirements for safety with the fail-operational system after one failure has occurred. Dual fluid disconnects for both propellants and pressurants, dual catalytic vents and quad valve packages are all part of the fail-operational and safe design features. Special operational features, such as the separate vent line at the gas disconnect, for venting of the gas side of spacecraft diaphragm tankage, if required, are provided. Fluid resupply lines to the spacecraft user incorporate emergency disconnect provisions. The design also includes provisions through appropriate fluid control orifices and variable driving pressure levels to minimize the potential for hydrazine decomposition and adiabatic detonation.

The detonation of hydrazine vapor at elevated temperatures depends on the local temperature and the quantity of vapor present. This detonation process is strongly affected by the catalytic action of materials in contact with the fuel. NASA-JSC, through STS Payload Safety Review panel interpretations, has established acceptable criteria and certification approaches for adiabatic compression detonation (Ref. 8). Typically, if the vapor never exceeds 160°F, then detonation can be avoided by controlling the material compatibility requirements. If the temperature never exceeds 200°F, then qualification of materials to 200°F is necessary to verify that detonation will not occur. If the temperature does not exceed 250°F, then qualification testing can be used to verify that detonation does not occur. Temperatures above 250°F are not allowed.

Bipropellant Design

A bipropellant OSCRS tanker for resupplying monomethyl hydrazine (MMH) and nitrogen tetroxide (NTO) is shown in Figure V-3, with the major subsystems and subsystem elements identified. The same simple pressure-fed approach adopted for the monopropellant tanker to expel propellants into user tankage was also selected for the baseline bipropellant design. Six L-SAT type propellant tanks with screen-type propellant management devices, and six pressurant bottles, make up the basic fluids capability. The oxidizer and fuel tanks are identical. Two of the tanks (one each oxidizer and fuel) are used as receiver "catch" tanks. They are used to dump the residual propellant remaining in the receiver tanks so they can be vented with a minimum of liquid in the vented gas. This configuration provides 7540 lb (3428 kg) of usable bipropellants. Propellant storage tanks can be loaded to 98 percent full and have a maximum expected operating pressure (MEOP) of 150 psia (1035 kPa). This basic propellant configuration achieves a mass fraction of 0.70.

The basic bipropellant OSCRS configuration can be reconfigured with only four L-SAT tanks to meet lower propellant requirements and increase the mass fraction. Also, the basic design may have all six tanks loaded with propellant if no catch tanks are required for resupply operations. The basic bipropellant structural configuration has been designed to allow for the increased propellant load, and all associated subsystem changes are incorporated to permit higher and lower propellant capacities. The full capacity six-loaded-tank option can provide a resupply quantity of 11,400 lb (5182 kg) with a mass fraction of 0.76. With tank changeout a bipropellant configuration with two loaded tanks achieves a mass fraction of 0.55.

Features of the basic bipropellant fluid subsystem design are shown schematically in Figure V-4. The bipropellant tanks are plumbed so that they can be depleted individually, in combinations up to all three at the same time or in a series arrangement. Dual fluid disconnects for all propellants and pressurants meet the fail-operational design requirement. Pressurant purge and overboard vent capability is provided for the propellant transfer line. All potential propellant-contaminated vent products exhaust through a bipropellant burner system (which is redundant) to reduce propellant to less hazardous and objectionable combustion products. Fluid resupply lines to the spacecraft user incorporate emergency disconnect provisions to allow quick jettison of the spacecraft should Orbiter operations require immediate cargo bay door closure and STS return. The disconnect provisions also provide a means of separating the spacecraft to permit cargo bay door closure should the servicing disconnect hang-up in the disconnect operation following servicing.

The bipropellant OSCRS can accommodate future growth, particularly with regard to the supply of high pressure pressurant gases. Gas compressors (not shown in Figure V-4) can be added to supply spacecraft users with up to 270 lb (123 kg) of gaseous nitrogen at up to

4500psia (31 mPa). Variable set-point regulators provide pressurant control in the 3000 psia (20.7 mPa) and below range. Pressure relief valves and variable set-point relief valves plumbed in parallel provide overpressure protection against regulator failure for both the OSCRS and a user spacecraft.

Avionics Design

The avionics subsystem is made up of equipment installed on the OSCRS structure and located in the cargo bay, and equipment located at the Aft Flight Deck. The OSCRS avionics design to perform these functions is shown in a schematic block diagram in Figure V-5. The equipment installed on the OSCRS structure includes sensors, microcomputers and valve drivers for monitoring and controlling the fluid transfer operation and other functions associated with berthing and separation. The equipment installed at the Aft Flight Deck provides the man-machine interface for crew monitoring and control of the fluid transfer operation. The Aft Flight Deck avionics also provides on-board data downlink, and an optional interface to the Orbiter General Purpose Computers (GPC) via the multiplexer-demultiplexer (MDM).

The avionics system is triply redundant and provides two-fault-tolerance for commanding valves and monitoring the propellant transfer operation. Valve commands are fed through a majority vote box that is designed to prevent valve actuation in the event of two failures. If two of the three OSCRS microcomputers fail, switches and a safety sequencer provide the capability to by-pass the microcomputers and shut down and safe the system. Also, even if two of the three OSCRS microcomputers fail, the third microcomputer continues to provide the capability to monitor the system.

VI. SUMMARY

The design of efficient and cost effective resupply tankers is strongly driven by the degree of flexibility and modularity incorporated into the configuration to accommodate the requirements and design preferences of the user community. Although it is a reasonable design goal to produce a tanker which will resupply every user no matter what his fluid quantities, tanker types, pressure levels, and thermal conditioning requirements, a severe design penalty may result when one set of requirements drives the design but that space system only represents one percent of the total mission model. In this case, from a total system standpoint considering both the tankers and the overall logistics scenario, it is more cost effective to either bring the system to the ground and resupply, or configure and launch a dedicated tanker.

For spacecraft designers, by judicially configuring the spacecraft to accommodate resupply rather than optimizing the propulsion of fluid systems independent of this interaction, significant overall cost savings for the logistics operations and the total program may result. For example, limiting gaseous system pressures to 3000 psia (20.7 mPa) will permit resupply of the gas in a cascade approach rather than requiring a compressor which is not state-of-the-art, have increased power requirements and lengthens transfer times. Selecting one concept of propellant management device over another is also a strong influence on the overall transfer operations and resultant cost. Appropriate tanker designs, however, need to incorporate as many provisions as possible to service the diversity of spacecraft configurations without adversely penalizing the design with features (and resultant configuration cost) not needed by the majority of users.

VII. REFERENCES

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TABLE II-2 OSCRS/CARRIER INTERFACE REQUIREMENTS

OSCRS CARRIER / INTERFACE	ORBITER	OMV	OTV	SPACE STATION	PLATFORM OR FREE FLYER	ANOTHER OSCRS	REMARKS
POWER	OSCRS will use carrier power.					N/A	
COMMAND & CONTROL (HARDWIRE)	Via SMCH cables to the OSCRS AFD Control Station.	Cable connection to OMV uplink only.	Cable connection to OTV uplink only.	Cable connection to the OSCRS Control Station aboard SS.	Cable connection to carrier uplink only.	Cable connection for command processing only.	
COMMAND & CONTROL (UPLINK)	If used, would be received from the GPC. Normal control from AFD Control Station.	Ground commands would be re- ceived from the OMV uplink.	Ground commands would be re- ceived from the OTV uplink.	If used, would be received from the SS. Normal control from SS OSCRS Control Station.	Ground commands would be re- ceived from carrier uplink.	N/A	No uplink receiving capability provided directly from OSCRS.
DATA HANDLING & MONITORING (HARDWARE)	Via SMCH cables to the OSCRS Control Station monitor.	Cable connection to downlink only.	Cable connection to downlink only.	Cable connection to the OSCRS Control Station aboard SS.	Cable connection to downlink only.	Cable connection for data handling between OSCRS only.	
DATA HANDLING & MONITORING (DOWNLINK)	Use Orbiter PDI for OSCRS data downlink.	Use OMV RF for all OSCRS data downlink to an OSCRS PSS.	Use OTV RF for all OSCRS down- link to an OSCRS PSS.	Use SS RF for all OSCRS down- link to an OSCRS PSS.	Use Platform or Free Flyer RF for all OSCRS downlink to an OSCRS PSS.	N/A	No downlink capability provided directly from OSCRS.
SAFING FUNCTIONS (HARDWIRE)	Provided from AFD OSCRS Control Station	N/A	N/A	Provided from the OSCRS Control Station aboard SS and a Safing Panel duplicating Orbiter SSP functions.	N/A	N/A	
SAFING FUNCTIONS (UPLINK)	If used, would be received from the GPC.	Received from the ground via OMV RF and transferred to OSCRS via hardwire.	Received from the ground via OTV RF and transferred to OSCRS via hardwire.	Received from the ground via SS RF and transferred to OSCRS via hardwire.	Received from the ground via OTV RF and transferred to OSCRS via hardwire.	N/A	
DATA RECORDING	Locate dedicated recorder on AFD or use Orbiter payload recorders.	N/A	N/A	N/A	N/A	N/A	Data recording to be accomplished by an onboard OSCRS recorder with data dump capability on-orbit.
MECHANICAL ATTACHMENT	Trunnion sill and keel fittings.	Attached to OMV with a standard berthing and docking latch.	Attached to OTV with a standard berthing and docking latch.	Use SS Standard attach provisions.	Use SS standard attach provisions.	Use a standard berthing and docking latch to attach an OSCRS	

TABLE II-2 OSCRS/CARRIER INTERFACE REQUIREMENTS (Cont)

INTERFACE / OSCRS CARRIER	ORBITER	OMV	OTV	SPACE STATION	PLATFORM OR FREE FLYER	ANOTHER OSCRS	REMARKS
THERMAL MANAGEMENT	Passive insulation interface only.	Interface heaters may be required on propellant lines if used as an OMV kit.	If OSCRS returns with the OTV from GEO, aerobraking heating could affect OSCRS thermal management.	Passive insulation interface only.	Passive insulation only.	Interface heaters at the OSCRS/OSCRS propellant interface are required.	
PROPELLANT SERVICE	N/A	MMH and NTO provided by OSCRS to OMV if used as an OMV kit.	N/A	N/A	N/A	Propellant tank lines between the OSCRS would be connected.	Capability to provide propellant to both a carrier and a user is required.
PRESSURANT SERVICE	N/A	GN2 and GHe provided to OMV if OSCRS is used as an OMV kit.	N/A	N/A	N/A	Pressurant tank lines between the OSCRS would be connected.	Capability to provide pressurant to both a carrier and a user is required.
OVERBOARD VENTING & CONTAMINATION	For all listed cases, OSCRS must dispose of either catalyzed vent or combusted propellant products overboard depending on the mode of operation. Requirements, limits, and other specifics for each case will have to be individually assessed.						Combusted bipropellants may not be compiatible with various users. Raw propellant venting may be required.
VIDEO (DOWNLINK)	If video links are provided by the listed carriers, OSCRS could provide a capability for monitoring various docking and resupply operations.				If video downlink is available, it could be used for monitoring resupply operations.	N/A	No video downlink capability provided directly by OSCRS.

Bill, we don't have an original for this table to go in paper, only a slide and this hardcopy of christine's machine. Will need original for manuscript

Add this at end of chapter II. Requirements.

Table II-5

Fluids Systems Technology Applicability

Technology	*Systems*					
	Space Station (Depots)	Payloads Freeflyers Platforms (Depots)	OMV	OTV	Tethers (Depots)	Space Plane
Large Tankage for Fluid Storage and Resupply	●	●			●	
Cryogenic Transfer and Resupply (e.g., $LH_2/LO_2/LN_2$)	●	●		●	●	●
Super Fluid Helium Transfer and Resupply		●	●		●	
Storable Fluid Servicer/Tanker	●	●		●		
Long-Term Onorbit Ops (e.g., Degradation)	●	●				
Propellant Scavenging	●	●	●	●	●	
Fluid Conditioning (e.g., Subcooling, Reliquefaction)				●		●
Quantity Gaging	●	●	●	●	●	●
Fluid Motion/Slosh Control	●	●			●	

Table III-1 Fluid Transfer Method Applicability

Transfer Methods	Monopropellant				Bipropellant		
	Blowdown		Reg.		Reg.		Blowdown
	Diap.	S.T.	Diap.	S.T.	S.T.	Bellows	S.T.
Adiabatic Ullage Compression	●	●					●
Ullage Exchange				●*	●*		
Vent/Fill/Repressurize	●		●	●*	●*	●	
Drain/Vent/Fill/Repressurize		●		●	●		●

Diap. - Diaphragm Tank
S.T. - Surface Tension Tank
*Not applicable to complex surface tension device

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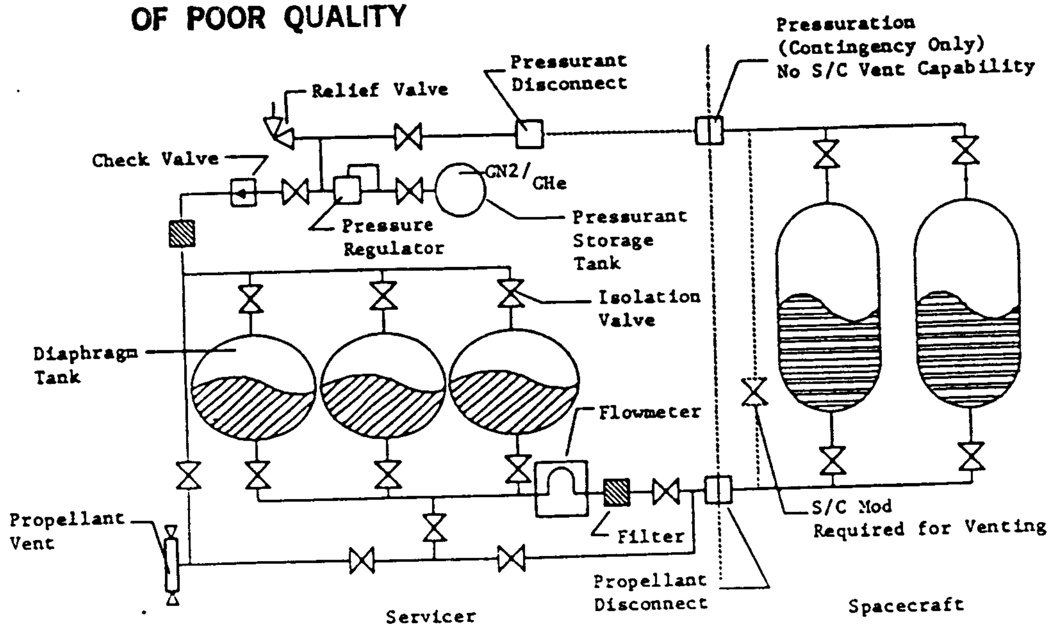

Figure 1 Servicer/Spacecraft Simplified Schematic for Adiabatic Ullage Compression Transfer

III-1

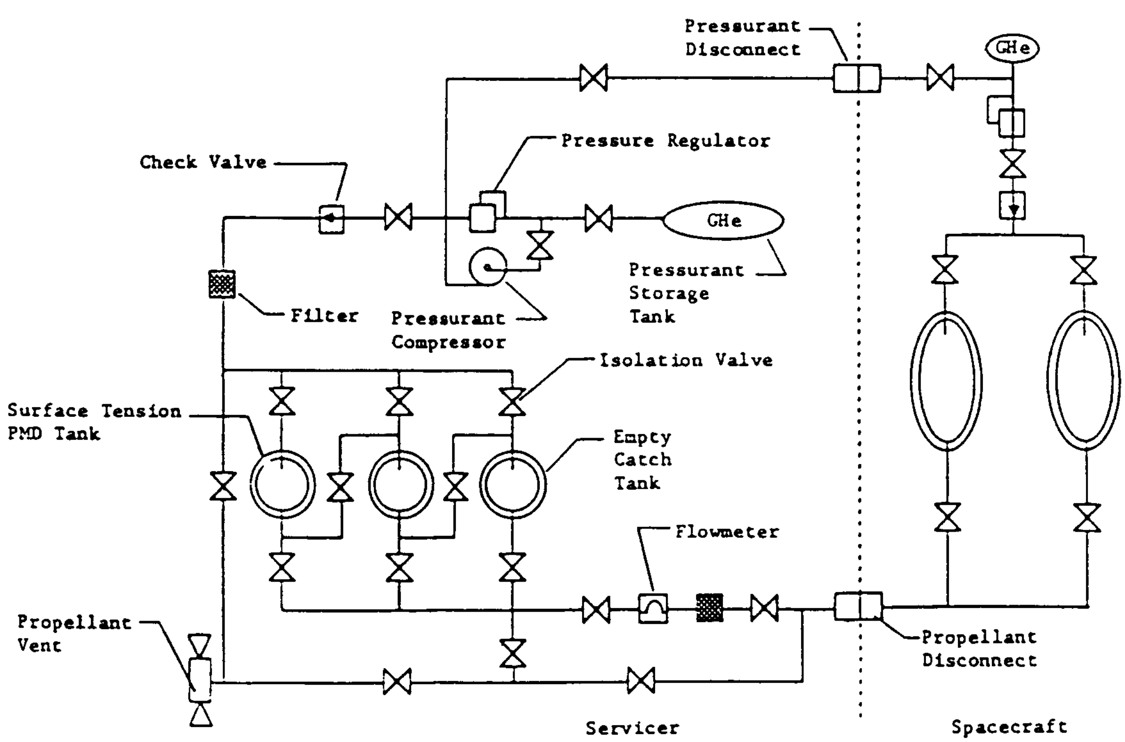

Figure 2 III-2
Servicer Interfacing with User Surface Tension Tanks for Drain/Vent/No-Vent Fill/Repressurize Transfer

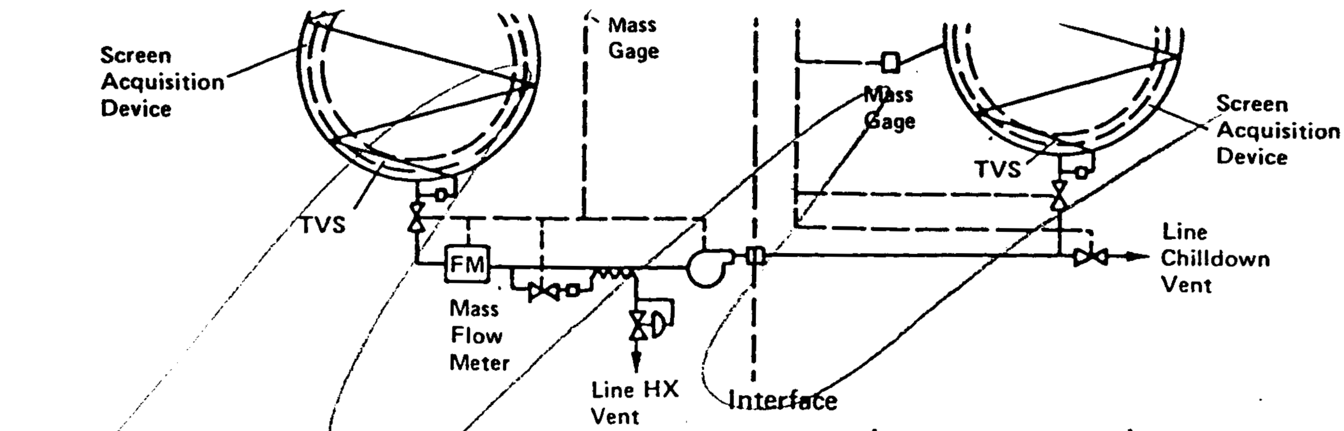

Figure 2 Fluid Transfer/Resupply—Tanker to Depot

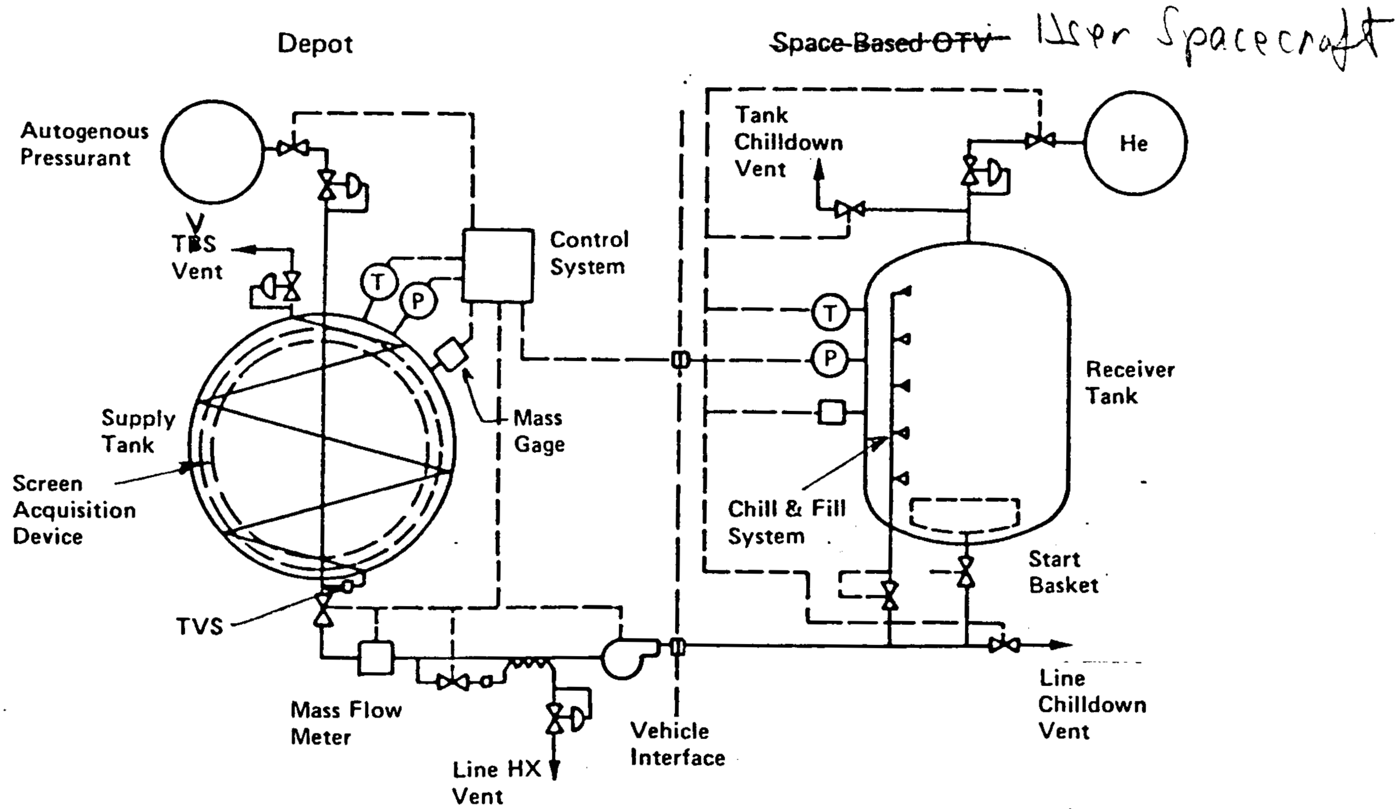

Figure 3 Fluid Transfer/Resupply~~—Depot to Space-Based OTV~~ Approach

III-3 Cryogenic

system would again consist of mass gages and mass metering devices to allow us to control the operation and status when we had filled the system. The space-based OTV would likely have some kind of chill and fill system that would allow chilldown of the initially dry and empty tank prior to the filling of the tank. The filling of the tank would likely be accomplished by what's called a no-vent fill operation.

~~IV~~ IV-1 Assemble as shown

Table ~~4~~ Fluid Reservicing Technology Issues

Technology Enhancement

Technology	Recommendations
o Hardware	o Hardware
a) Variable set-point regulators and relief valves	a) Design, build and test an electronics variable set-point regulator to minimize risk
b) Monopropellant catalytic vent life with long burn times and high concentrations of non-condensible gases and pulsed operations	b) Test existing design over complete range of expected conditions
o Processes	o Processes
a) Pressurant solubility effects during fill	a) Minimize the time the liquid is exposed to high pressure. Run tests to understand process for contingency operations
b) Contamination control during venting	b) Study required to better quantify requirements
c) Adiabatic compression heating in surface tension tankage	c) Refine computer programs using ORS data and extrapolate to PMD tanks

Open Technology Issue

Technology	Recommendations
o Hardware	o Hardware
a) Automatic fluid coupling b) Resupply mechanism to make and brake the fluid coupling	a) & b) Design, build and test these devices together to minimize risk
c) High pressure gas compressor is not state-of-the-art	c) Design, build and test to assure reliable long life
d) Tank quantity gaging system	d) Continue JSC contract work
e) Oxidizer burner and fuel burner that can accept high concentrations of non-condensible gases, and pulsed operation. A burner that could handle both simultaneously or separately is desired	e) Design, build and test over complete range of expected operating conditions
o Processes	o Processes
a) Separation of gas/vapor from liquid during venting (required for ullage exchange and vent/fill/repressurize transfer methods to be effective)	a) Studies followed by drop tower and Storable Fluid Management Demonstration (SFMD) testing
b) Total filling of complex PMD's c) No-vent fill	b) & c) Conduct tests and analysis of storable fluid in ground tests and determine if zero-g tests are required

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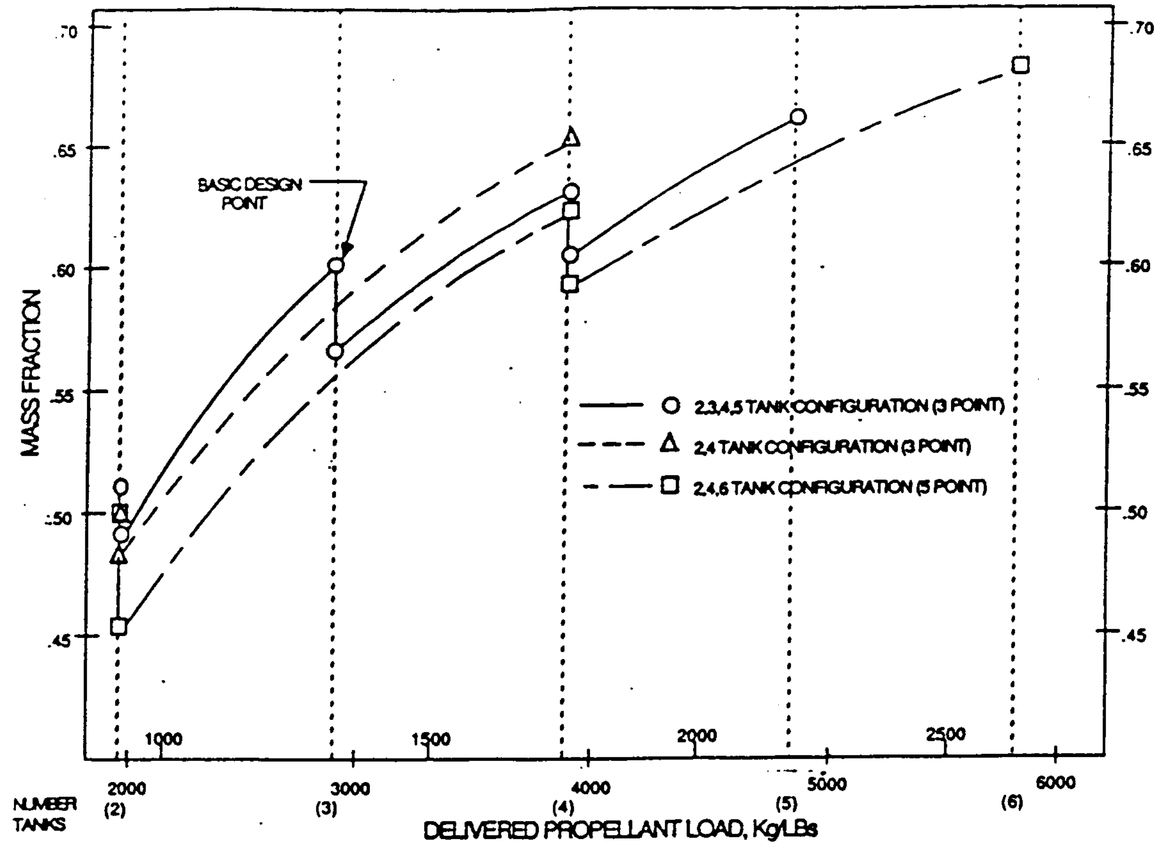

Figure III-1 4 Monopropellant Design Comparison Mass Fraction vs Propellant Load

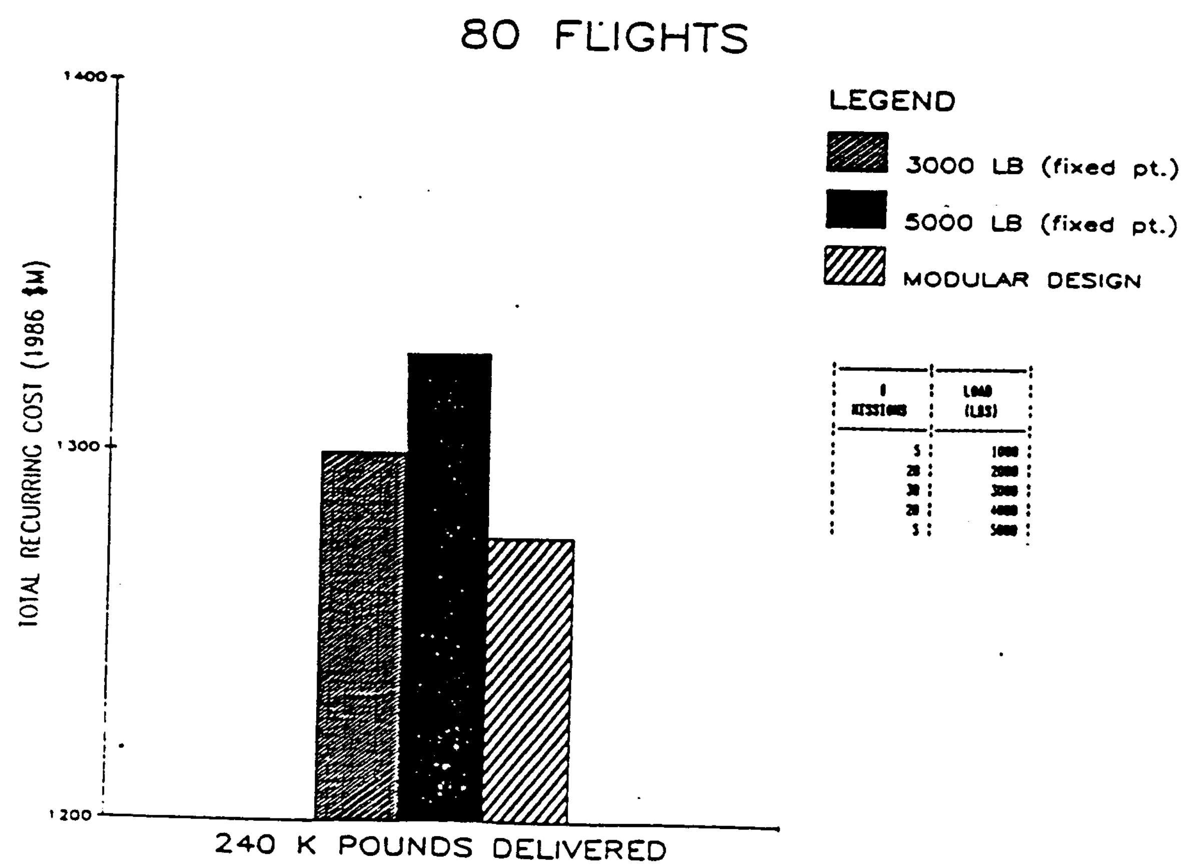

Figure III-2 5 OSCRS Recurring Cost Comparison

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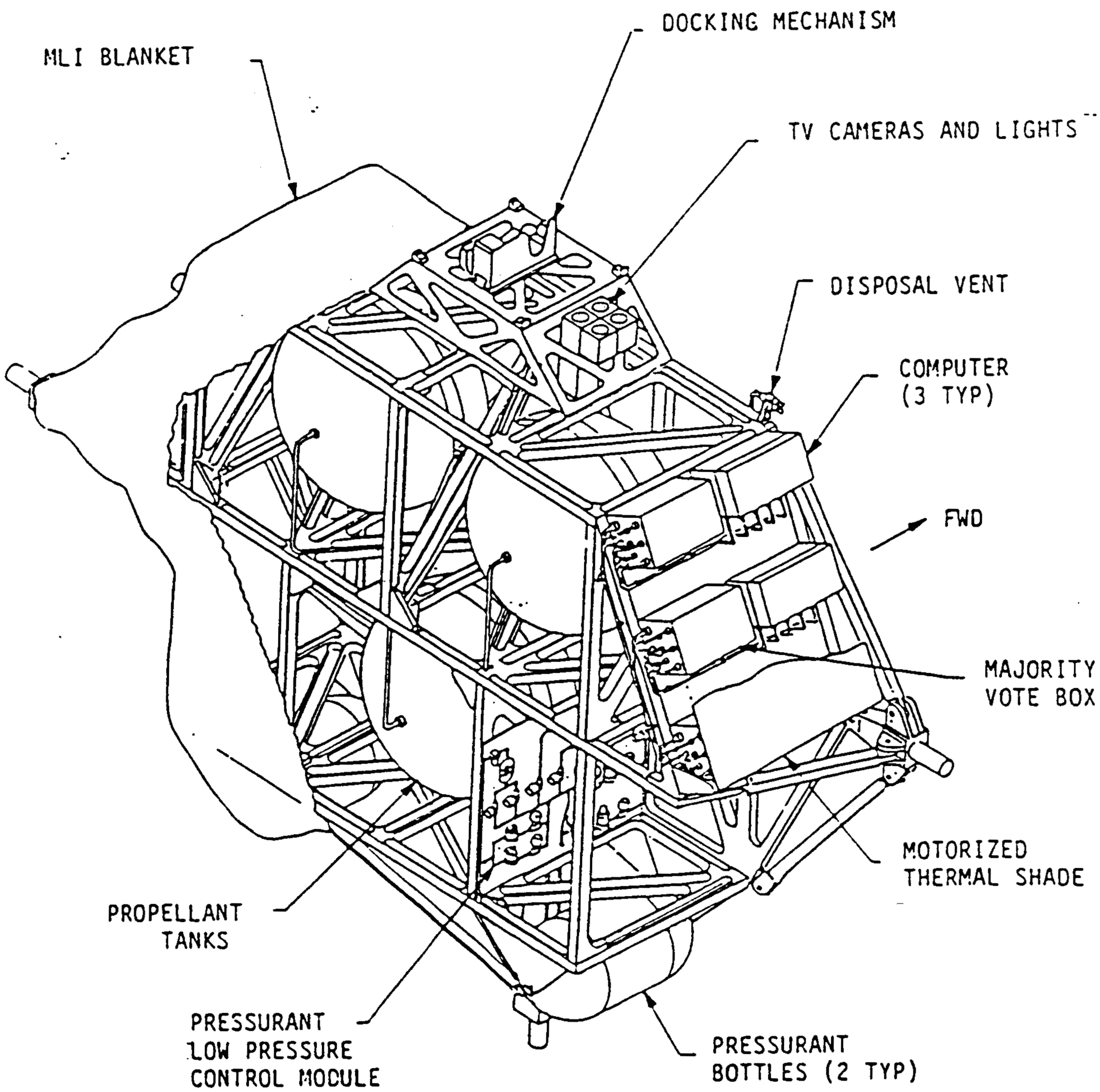

Figure A OSCRS Basic Monopropellant Configuration

V-1

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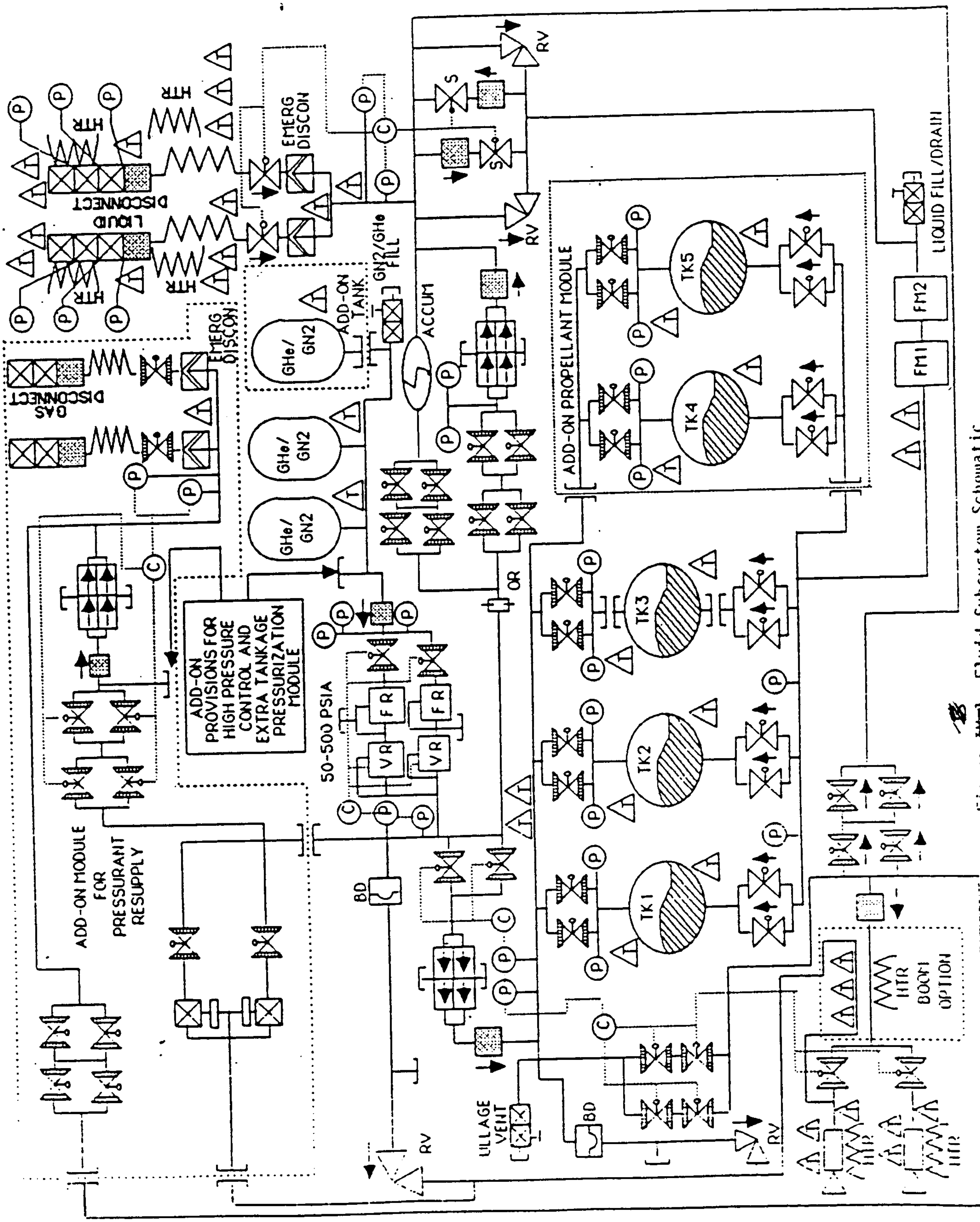
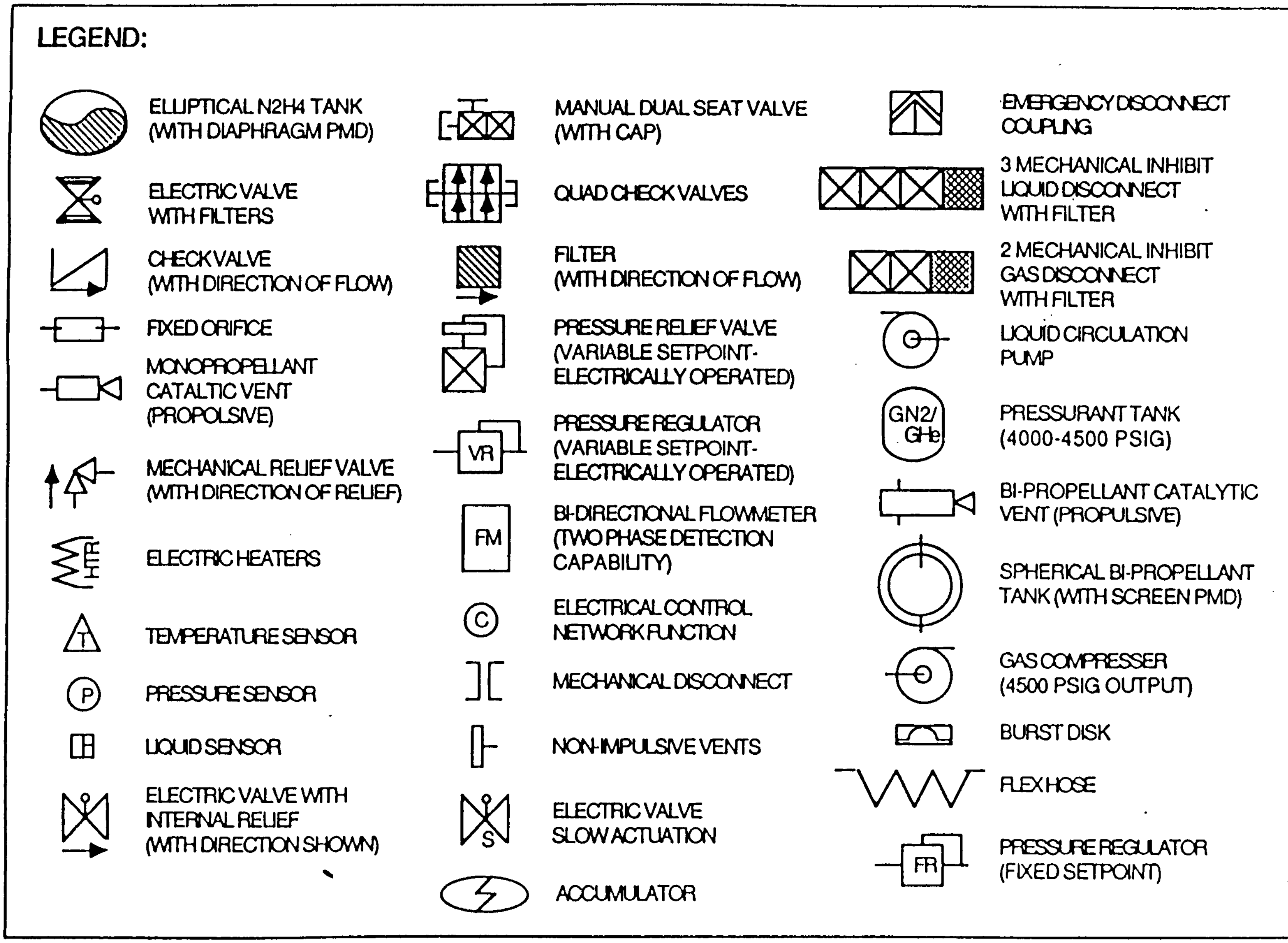


Figure V-2 Fluid Subsystem Schematic



FLUID LEGEND

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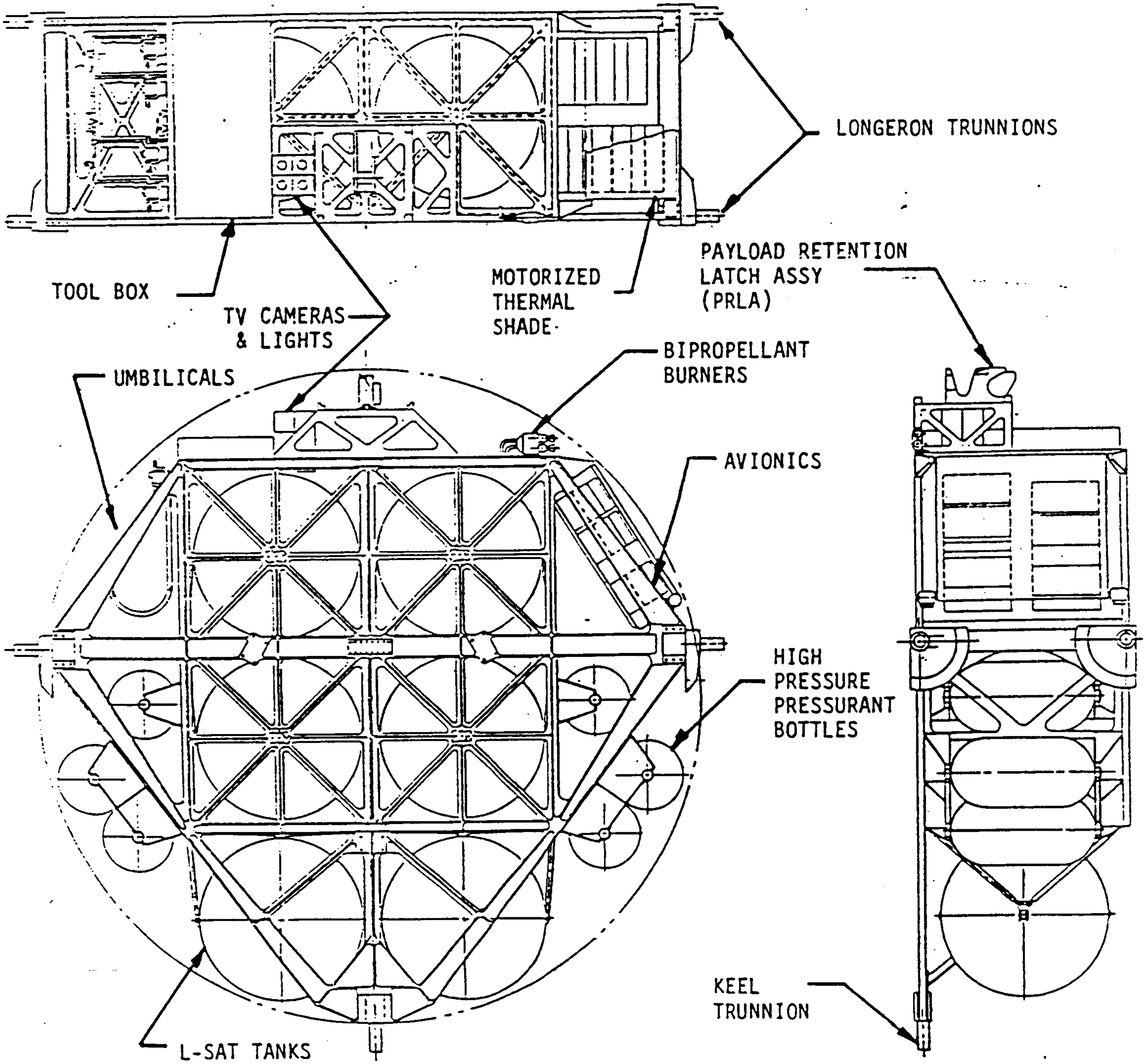


Figure V-3 Basic Bipropellant OSCRS

BIPROPELLANT

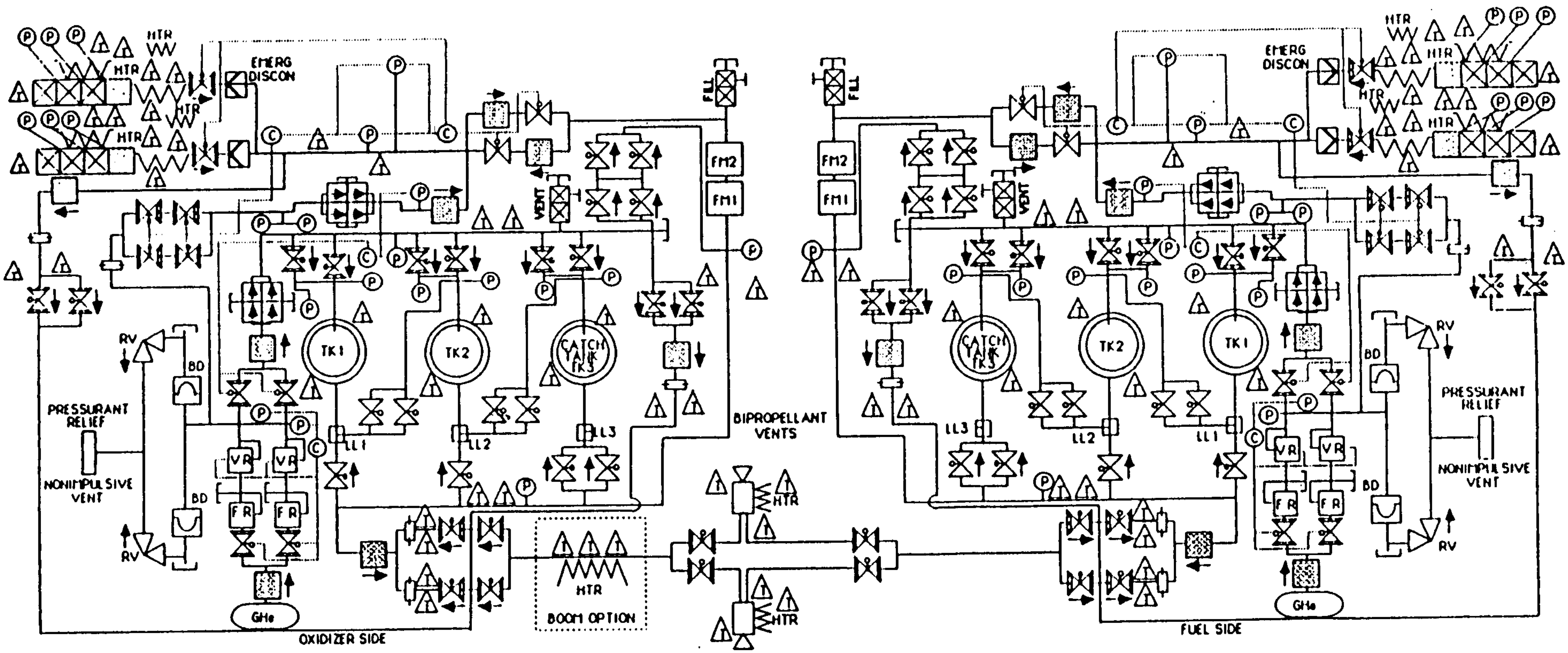
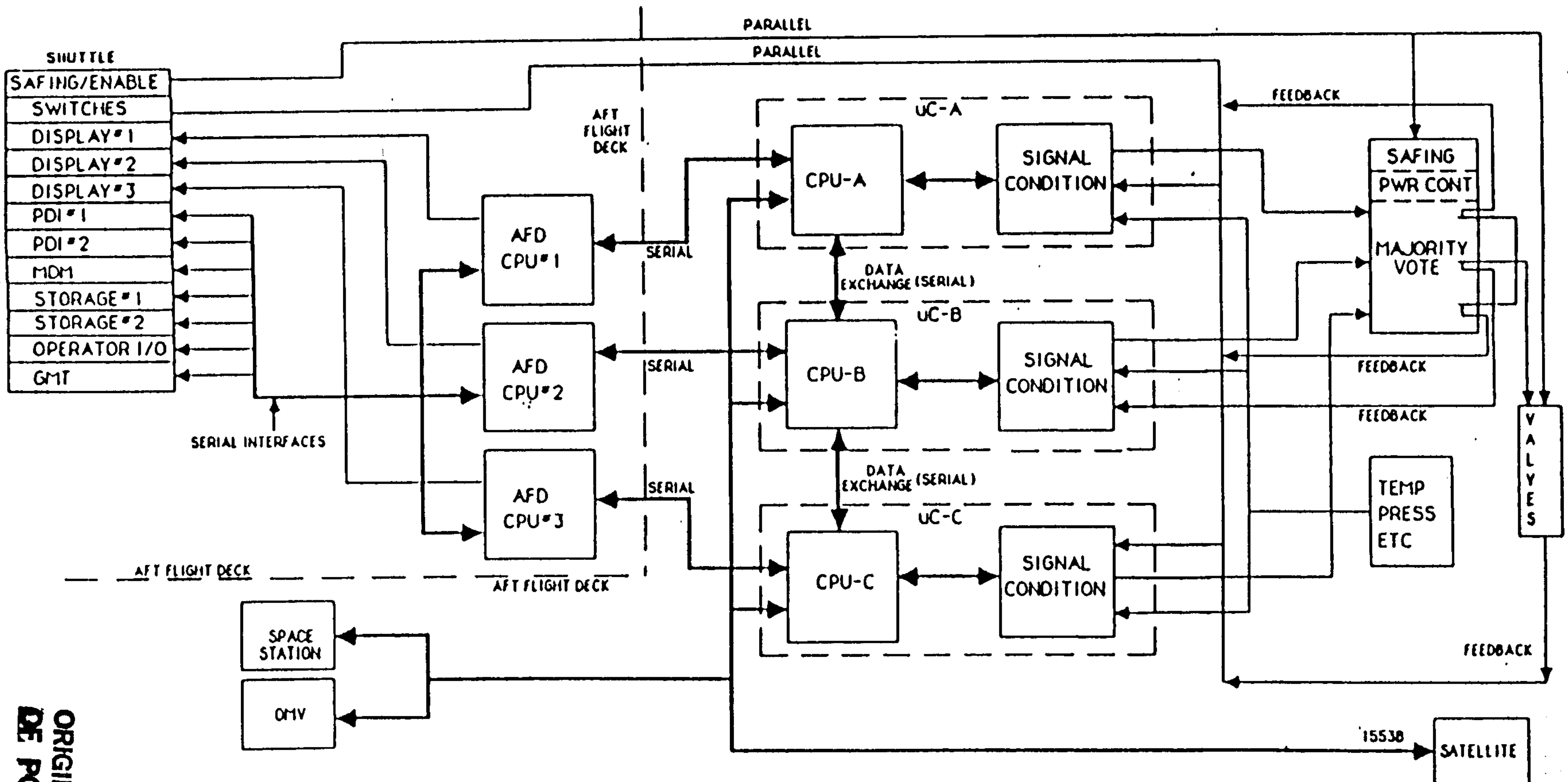


Figure ~~V-2~~ D Fluid Subsystem Schematic

~~IV-4~~ V-4



IV-5

Figure ~~IV-3~~ OSCRS Avionics Block Diagram

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