2
m/x

AEROSPACE REPORT NO.
ATR-71(7233)-3, VOL. II

Final Report
Orbiting Propellant Depot Safety

Volume II: Technical Discussion

Prepared by ADVANCED VEHICLE SYSTEMS DIRECTORATE
Systems Planning Division

20 SEPTEMBER 1971

Prepared for OFFICE OF MANNED SPACE FLIGHT
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Washington, D. C.

Contract No. NASW-2129

Systems Engineering Operations
THE AEROSPACE CORPORATION

90 P8

Aerospace Report No.
ATR-71(7233)-3 Vol. II

FINAL REPORT

ORBITING PROPELLANT DEPOT SAFETY

Volume II: Technical Discussion

Prepared by

Advanced Vehicle Systems Directorate
Systems Planning Division

20 September 1971

Systems Engineering Operations
THE AEROSPACE CORPORATION
El Segundo, California

Prepared for

Office of Manned Space Flight
National Aeronautics and Space Administration
Washington, D. C.

Contract No. NASW-2129

C

Aerospace Report No.
ATR-71(7233)-3 Vol. II

FINAL REPORT

ORBITING PROPELLANT DEPOT SAFETY

Volume II: Technical Discussion

Prepared by Advanced Vehicle Systems Directorate

Approved by

R. R. Wolfe, Study Manager
Director
Operations Office
Advanced Vehicle System Directorate
Systems Planning Division

S. M. Tennant
Assistant General Manager
Systems Planning Division
Systems Engineering Operations

The information herein is tentative and is subject to modification. Initial distribution of this document is confined to personnel and organizations immediately concerned with the subject matter.

PREFACE

This study was initiated as Subtask 3, Orbiting Propellant Depot Safety Study of NASA Study C-II, Advanced Missions Safety Studies. Other studies in this series are: (i) Subtask 1, TNT Equivalency Study, Aerospace Report No. ATR-71(7233)-4; and (ii) Subtask 2, Safety Analysis of Parallel versus Series Propellant Loading of the Space Shuttle, Aerospace Report No. ATR-71(7233)-1.

The study was supported by NASA Headquarters and managed by the Advanced Missions Office of the Office of Manned Space Flight. Mr. Herbert Schaefer, the Study Monitor, provided guidance and counsel that signifantly aided this effort.

Study results are presented in three volumes; these volumes are summarized as follows:

> Volume I: Management Summary Report presents a brief, concise review of the study content and summarizes the principal conclusions and recommendations.
>
> Volume II: Technical Discussion provides a discussion of the available test data and the data analysis. Details of an analysis of possible vehicle static failure modes and an assessment of their explosive potentials are included. Design and procedural criteria are suggested to minimize the occurrence of an explosive failure.
>
> Volume III: Appendices contains supporting analyses and backup material.

ACKNOWLEDGEMENT

The principal participants in this study of The Aerospace Corporation are:

M. Donabedian	Semimodular/Modular Concept Development and Analysis
R. P. Toutant	Docking/Transfer Interface Concept Development and Analysis
R. R. Wolfe	Study Manager and Director Operations Office Advanced Vehicle Systems Directorate
H. H. Yoshikawa	Integral Concept Development and Analysis

CONTENTS

CONTENTS (Continued)

CONTENTS (Continued)

FIGURES

TABLES

TABLES (Continued)

1. INTRODUCTION

1.1 GENERAL

Under consideration are orbital missions that require the use of orbiting vehicles, e.g., a cislunar shuttle, that is either chemically or nuclear propelled, functioning as orbit-to-orbit shuttles combined with space tugs for servicing earth-orbiting payloads. The flight frequency of these space-based vehicles may require that large quantities of propellants will have to be delivered to orbit for their use.

Orbiting propellant depots (OPD), in both geocentric and selenocentric orbits, are being considered as candidate methods of making the required propellants readily available.

This report presents the results of a top level study assessing the gross requirements and concomitant safety hazards associated with the operation of several configurations of the OPD. A qualitative cause-and-effect approach was employed throughout the study, and no consideration was given to the probability of a particular failure's occurring. The reader is reminded that the identification of safety hazards and their rectification are an iterative process and that a further safety evaluation should be performed after the OPD will have been better defined.

1.2 STUDY OBJECTIVES

The objective of this study was to establish design, operation, and emergency procedure guidelines, criteria, and requirements for the OPD and its operation.

1.3 STUDY SCOPE

The objective of this study was to analyze the potential safety hazards of an OPD in geocentric or selenocentric orbit and the hazardous interactions between the OPD Propellants Depot and transient space vehicles such as Space Shuttles and Space Tugs.

1.4 GROUND RULES AND CONSTRAINTS

The ground rules and constraints utilized throughout this study included:

a. The OPD must be capable of unmanned operation but be safe for servicing manned vehicles.

b. The OPD is to be composed of components within the size and weight limitations of the Space Shuttle payload bay.

c. The conceptual designs will not require significant advancement in the state of the art.

d. The OPD will service one User OV at a time and will be the active vehicle during transfer operations, i.e., will supply power, guidance, acceleration, etc.

e. All docking points will be part of a universal docking mechanism which will be common to all using vehicles.

f. Propellants will be stored at the conditions (temperature and pressure) required by the vehicles to be serviced.

g. The quantity of propellants transferred will be measured by the OPD.

h. Only series transfer of propellants will be possible.

i. Resupply of the OPD will be accomplished via a Space Shuttle.

j. No propellants will be returned to earth.

1.5 STUDY PLAN

1.5.1 Approach

The principal steps in the study included:

a. Development of conceptual OPD configurations to the level required to serve as the baseline for a top-level hazards analysis.

b. Development of top-level functional flows for each configuration.

c. Performing a gross hazards analysis based on the top-level functional flows.

d. Assessment and comparison of the levels of safety inherent in the concepts.

e. Provide recommendations as to safety requirements for normal and emergency operation.

1.5.2 Resources/Data Base

Since the study was primarily a hazards analysis, NASA and contractor technical reports, documents, and briefings were utilized to the maximum extent possible in establishing the OPD configurations. The reports were also utilized in selecting subsystems and defining their modes of operation. References to the specific reports actually utilized or reviewed are given throughout this volume in the pertinent sections to which they apply.

D

2. CONCEPTUAL OPD CONFIGURATIONS

2.1 GENERAL

Before the hazards analysis could be performed, several conceptual configurations of the OPD had to be considered; existing data were used whenever possible. It was intended that the configurations be defined only to the extent necessary to support a top-level hazards evaluation.

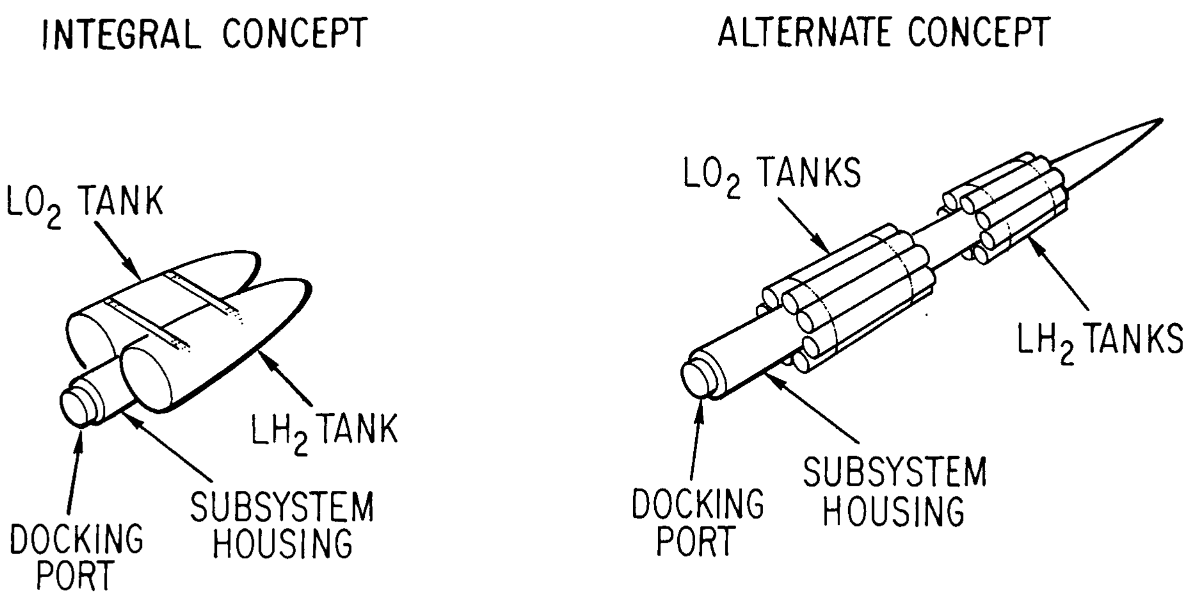
The following paragraphs describe, in gross terms, the major structural and operational aspects of the conceptual OPD configurations evaluated in this study.

2.2 INTEGRAL CONCEPT

2.2.1 Structural

An integral configuration of the OPD is illustrated in Figure 2-1. In this concept, the cryogenic propellant storage tanks, LO_2 and LH_2, are a permanent part of the OPD structure. Although large single tanks are shown for each propellant, an acceptable alternate would be a series of interconnected smaller tanks. Another tank configuration would incorporate a single large common bulkhead-type storage tank that would contain both propellants; this tank configuration was excluded from the study since a single failure in the common bulkhead would allow the propellants to mix.

The subsystems required to operate the OPD were assumed to be integrated with the tank structure; the subsystems that would be used to dispense propellants would be used during OPD resupply operations. The rationale for selection of specific subsystems and their operations is discussed in greater detail in Appendix A.



- CHARACTERISTICS
  - i PROPELLANT STORAGE TANKS PERMANENT PART OF OPD STRUCTURE
  - ii SUBSYSTEMS INTEGRATED WITH TANK STRUCTURE
  - iii TANKER OR MODULAR RESUPPLY

Figure 2-1. Integral Concept

2.2.2 Operational

2.2.2.1 Resupply

Three methods of resupply were considered in conjunction with this OPD configuration:

a. Probe and drogue

b. Modular resupply tank

c. Hard dock of resupply OV

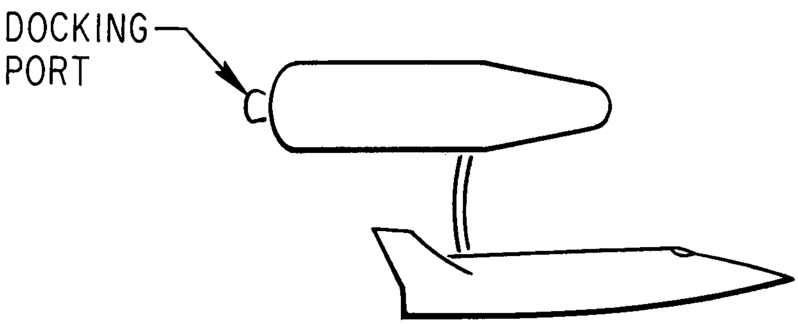
The probe and drogue method, Figure 2-2, is similar to that presently utilized for air-to-air refueling of aircraft. This method eliminates the requirement for a hard dock and minimizes the effects that instability of one vehicle would impose on the other. However, this system is the most complex of the three, both structurally and operationally. Also, the transfer boom is vulnerable to damage due to excessive motion of either the OPD or the resupply vehicle.

The modular method, Figure 2-3, of resupply appears to be the most desirable. In this method, a propellant tank module carried in the payload bay of the affected resupply OV would be docked to the propellant transfer part of the OPD. The resupply OV then would retreat to a safe distance from the OPD prior to the actual transfer of propellants. When the transfer was complete, the resupply OV would remove the empty module and return it to earth for refurbishment.

Hard docking and transferring propellants directly from the resupply OV to the OPD was excluded from the analysis. The main reasons for this were potential hazards involved in docking such large vehicles and their relatively slow reaction times in the event of emergenc(y)(ies) requiring vehicle separation.

2.2.2.2 User OV Servicing

Propellants would be flow-transferred to the user OV that has docked at the OPD resupply port. The docking mechanism is discussed in Appendix B.



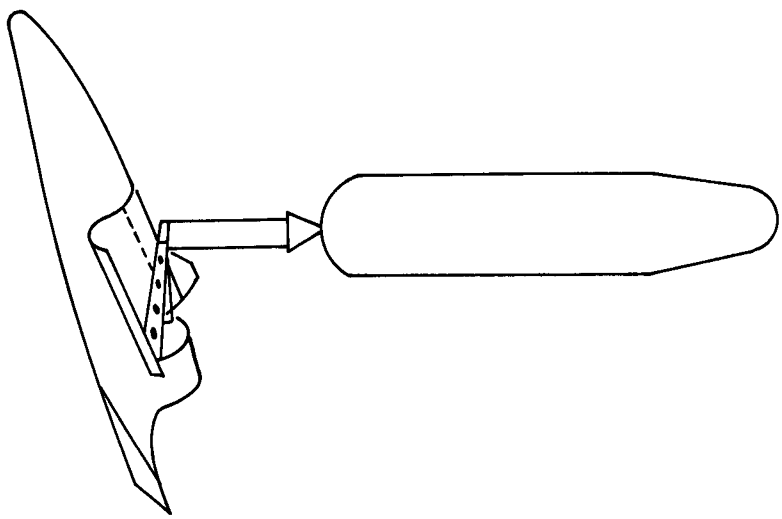
CHARACTERISTICS

i UTILIZATION OF PROPELLANT TRANSFER PROBES SIMILAR TO AIRCRAFT AIR-TO-AIR REFUELING

ii TRANSFER SUBSYSTEMS CONTAINED IN OPD

iii OV/OPD REQUIRED ACCELERATION DURING TRANSFER

Figure 2-2. Probe and Drogue Resupply, Integral Concept



CHARACTERISTICS

OV DELIVERS FULL TANK AND STANDS OFF DURING TRANSFER VIA OPD SUBSYSTEMS

Figure 2-3. Modular Resupply, Integral Concept

During the period of propellant transfer, all functions, acceleration, stabilization, power, flow control, etc., would be supplied by the OPD while the user OV is quiescent, except that it would monitor operations and provide backup capability for the more critical subsystems of the OPD.

The propellant transfer procedure utilized in this study is outlined in Table 2-1.

2.3 SEMIMODULAR CONCEPT

2.3.1 Structural

Figure 2-4 presents a conceptual semimodular configuration for the OPD. This configuration would consist of replaceable propellant storage modules and a central core that would contain the subsystems required for operation of the OPD. The subsystems contained within the core are identical to those required to operate the conceptual integral configuration of the OPD.

Spaced along the longitudinal axis of, and at 90 deg intervals around, the central core would be a series of manifolded docking ports for propellant storage modules. LO_2 and LH_2 are contained in separate modules and in discrete planes: LO_2 modules would be in one plane, and LH_2 modules in the other. Each docking port would incorporate the interface connectors necessary to link the propellant modules to the OPD's propellant transfer system. The docking port interface is discussed in Appendix B.

2.3.2 Operational

2.3.2.1 Resupply

The conceptual semimodular OPD would utilize a modular method of resupply. The technique employed in delivering a module to the depot would be the same as that described in paragraph 2.2.2.1 for the modular resupply of the integral OPD with one notable exception; propellants would not be pumped from the module to the OPD tanks.

In this configuration, the resupply OV modules would become the onorbit storage tanks for the depot. Propellants would be pumped directly from the

Table 2-1. Propellant Transfer Procedures

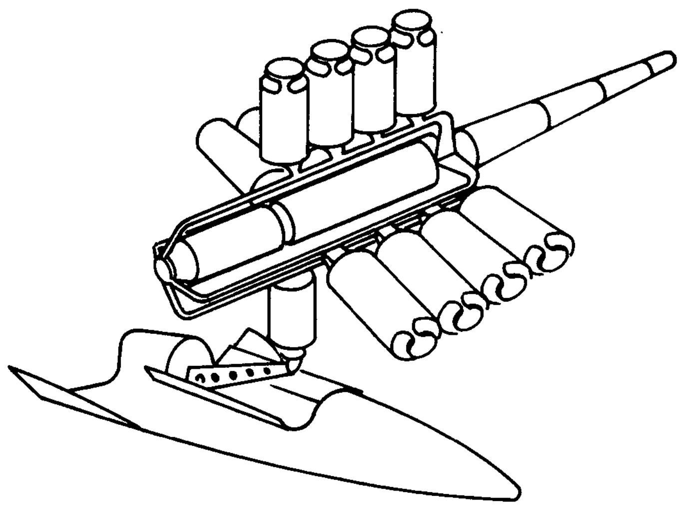
Sequence	Description
User OV	
Rendezvous	Use telemetry data from relay station and OPD to determine OPD state, orbit and position, and approximate quantities and qualities of propellants
	Make proximity rendezvous with OPD
OPD Assessment	Manned user OV would visually inspect remote checkout of OPD subsystems and condition
Mate with OPD	Activate guidance/rendezvous radar
	Extend docking cone on both OPD and user OV
	Secure mated vehicles
	Mate transfer interface connectors
Complete Checkout of all Systems	Valves
	Overboard dump
	Pressure/temperature gages
	Flowmeter
OPD	
System Conditioning	Cooldown of receiver tank if required
	Purge and cooldown of transfer lines
	Vent donor/user OV tanks, if required
Initiation of Transfer	Gas Generator (GG)
	Initiate transfer of gaseous propellant from OPD vent storage tanks
	Combust propellant in GG
	Direct (GG) products to secondary propulsion system (SPS) heat exchanger (HX)

Table 2-1. Propellant Transfer Procedures (Continued)

Sequence	Description
OPD	
Initiation of Transfer (Continued)	After attainment of acceleration and pressurization, obtain propellants from main tanks
	Pump and meter flow into GG
	Direct GG products to SPS, GG, and pressurization HX
	Secondary Propulsion System (SPS)
	Initiate transfer of propellants from start tanks
	Pump and meter flow into combustion chamber
	Propellant evaporated by GG products in HX
	Acceleration is attained
	After attainment of propellant pressurization, obtain propellants from main tanks
	Tank Pressurization
	Hydrogen tank
	Pump and meter LH_2 into HX
	Pass through HX to heat and vaporize and then back into vapor portion of tank
	Oxygen tank
	Pass gaseous high pressure helium into HX and then into vapor portion of tank
	Propellant Transfer
	After attainment of phase separation
	Initiate monitoring of liquid level using positive-g liquid level sensors
	Vent donor and receiver tanks, if necessary

Table 2-1. Propellant Transfer Procedures (Continued)

Sequence	Description
OPD	
Initiation of Transfer (Continued)	After attainment of pressurization, initiate propellant transfer
	Pump and meter propellant flow
	Monitor pressure and temperature of transferred propellants
	Vent receiver tank if necessary
	Transfer LO_2 propellant through thermodynamic liquid/vapor separator to gas storage in GG
	Transfer gaseous H_2 propellant to gas storage in GG
Termination of Propellant Transfer	Check pressure temperature, quantity in receiver tank
	Terminate propellant transfer
	Purge transfer lines
	Terminate SPS, GG, and pressurization
User OV	
Deactivate OPD	Zero all integrating flowmeters
	Vent all systems
	Disconnect all umbilicals
	Retract docking cone
	Disconnect all mating structural members
Undocking and Separation	Activate guidance system
	Maneuver away from OPD



CHARACTERISTICS

i MODULAR OPD WITH CENTRAL MANIFOLDING AND SUBSYSTEMS

ii MODULAR RESUPPLY WITH INTEGRAL TRANSFER TO USER OV

Figure 2-4. Semimodular Concept

modules to the user OVs. When empty, the modules would be returned to earth by a resupply OV and recycled.

The semimodular OPD can also function as a modular OPD. To operate in this manner, it would be necessary only to retract the interface connectors at the docking ports and utilize the propellant supply modules as will be described in paragraph 2.4.2.1.

2.3.2.2 User OV Servicing

Propellants would be transferred to user OVs in the same manner as that described for the integral OPD in paragraph 2.2.2.2. If the OPD were being operated in the modular mode, propellant transfer to the user OV would be as described in paragraph 2.4.2.2.

2.4 MODULAR CONCEPT

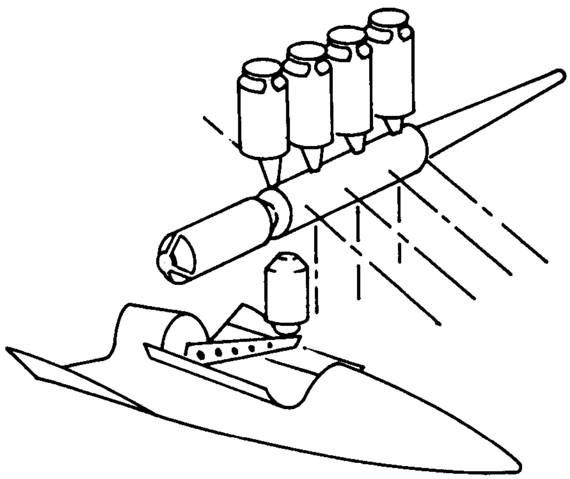
2.4.1 Structural

The conceptual modular configuration is shown in Figure 2-5. The central core would contain the propulsion and control subsystems and provide a simplified docking mechanism for storing the propellant modules. The external profile of this configuration is identical to the semimodular concepts, but there are several basic internal differences. There would be no requirement for the flow transfer of propellants either in or out of the OPD; therefore, there would be no propellant transfer subsystems, tank manifolding, or complex interfaces at the docking ports. The OPD, in essence, would be a storage rack for the propellant modules, each of which would contain both fuel and oxidizer.

2.4.2 Operational

2.4.2.1 Resupply

Propellant modules would be delivered and docked to the OPD via the Space Shuttle as shown in Figure 2-4. The docking sequence is discussed in Appendix C.



CHARACTERISTICS

i MODULAR RESUPPLY AND TRANSFER TO USER OV

ii COMPLETE MODULAR OPD WITH NO PROPELLANT TRANSFER OR PRESSURIZATION SYSTEMS

Figure 2-5. Modular Concept

2.4.2.2 User OV Servicing

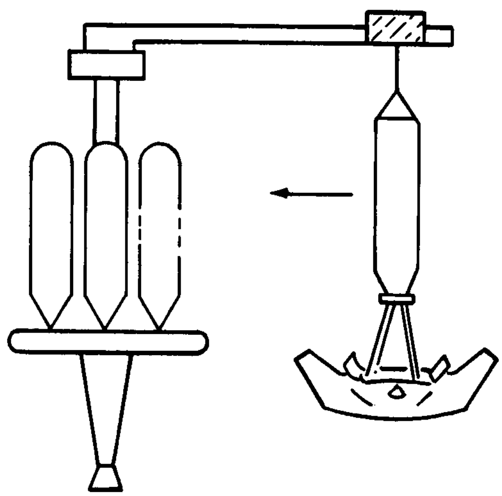
The user OV would obtain propellants from the OPD by direct tank exchange. The user OV would store its empty tanks at the OPD in a vacant docking port and then maneuver to acquire a full tank from the OPD. The empty tank modules would be recovered by a Space Shuttle for reuse when propellant deliveries are made.

2.4.3 Alternate Modular Concept

A variation of the modular concept which would minimize some of the disadvantages of the original concept for the former would be the addition of an OPD-mounted boom (Figure 2-6). The boom would perform the entire propellant tank exchange sequence both to and from the OPD. This concept would utilize a simple geometrical packaging of tanks in order to minimize the sequencing and control of the boom mechanism. The sequence would be pre-programed and controlled from the resupply OV or user OV with manual override capabilities and, in essence, would be analogous to a remote manipulator.

The basic advantage over the full modular concept would be that a single docking sequence would be involved and there would be a minimum payload penalty to the resupply OV since the provisions for tank exchange aboard that vehicle would be minimized.

This approach, however, also introduces some new problems. A fully complex boom or manipulator mechanism would be required. Any malfunction of this mechanism during the tank exchange sequence could cause severe damage to the OPD, the resupply OV, and/or the user OV, with potentially serious, if not catastrophic, safety hazards. From an operational viewpoint, servicing and maintenance of the boom would pose a very substantial problem area.



CHARACTERISTICS

i BOOM PERFORMS COMPLETE TANK EXCHANGE SEQUENCE FROM OV TO RACK-MOUNTED OPD TANKS

ii REMOTE CONTROL FROM OV

Figure 2-6. Alternate Configuration, Modular Concept

3. COMPARISON OF CONCEPTUAL CONFIGURATIONS

3.1 INTRODUCTION

Prior to performing the hazards analysis, an overall evaluation of the conceptual configurations was made to determine the advantages and disadvantages of each with respect to both safety hazards and operational features. The results of the evaluation are discussed briefly in the following paragraphs.

3.2 INTEGRAL CONCEPT

3.2.1 Advantages

The basic advantages of this concept is that it eliminates the complex manifolding and valving required for the semimodular concept. Also the OPD could be resupplied by a dedicated tanker which would improve the propellant payload capability of the resupply OV.

Several resupply options are available for this concept. Of these options, the probe and drogue and the modular concepts would tend to minimize any effects of instability or other differential movement between the vehicles. Of these two, the modular concept appears more desirable since the resupply OV would stand off at a safe distance throughout the refueling cycle.

3.2.2 Disadvantages

The major disadvantage of the integral concept is the requirement for propellant phase control, pressurization, and pumping during the propellant transfer process. This process could account for the largest number of potential malfunctions which might result in safety hazard(s).

Another undesirable feature of this approach is that a single tank rupture or failure could cause loss not only of the entire system but, possibly the OPD itself. The use of multiple tanks strapped together, with the necessary associated manifolding and valving, could reduce the probability of this occurrence; however, this approach would negate the basic advantage of the integral concept.

Although the probe and drogue resupply method would provide separation between the OPD and resupply OV, the complexity of the system and vulnerability to rupture of the connecting line seem at this point to outweigh the advantages.

3.3. SEMIMODULAR CONCEPT

3.3.1 Advantages

There are two primary advantages to the semimodular concept: (i) no propellant flow would be required to resupply the OPD; since propellants would not be required to flow during resupply operations, the need for phase control, pressurization, and pumping, that is considered a major disadvantage with the integral system, would be eliminated; (ii) the increased operational flexibility offered by this concept; the OPD could transfer propellants to the user OV via flow transfer from bulk storage tanks or tank exchange as would occur in the modular concept. For the latter method to be used, the specialized propellant tanks used with the modular OPD would have to replace the bulk storage tanks provided in that concept.

3.3.2 Disadvantages

The additional complexity of the multiple docking and manifold system could increase the possibility of failure which might affect system safety.

3.4 MODULAR CONCEPT

3.4.1 Advantages

A distinct advantage of this configuration would be that no flow transfer of propellants would be required and, therefore, the propellant flow transfer subsystems would be eliminated. As a result, the basic OPD is the least complex of the concepts studied.

3.4.2 Disadvantages

The propellant tank modules used with this configuration would contain both the fuel and the oxidizer. Most of the data reviewed indicated that a tank-within-a-tank configuration or a single tank with a common bulkhead configuration could be used for these dual propellant modules; single point failure of the bulkhead or inner tank wall would allow propellants to mix, resulting in potential fire or explosion, i.e., catastrophic failure.

Extensive maneuvering of the user OV would be required in the vicinity of the OPD. The user OV would be required to dock at the OPD, disengage the empty tank, maneuver to and dock with a full tank.

4. HAZARDS ANALYSIS

4.1 GENERAL

A qualitative approach was used throughout the analysis which was divided into three categories: system, components within systems, and interfaces between the systems. Although the safety hazards for three different OPD configurations were considered, many of the hazards identified are applicable to several of them. This results from the fact that some subsystems and operating procedures are common to two or more of the concepts, e.g.: (i) the flow transfer of propellants from the OPD to the user OV would employ the same subsystems and operational procedures in both the integral and semi-modular concepts; (ii) the docking mechanism and its operation are common to all concepts.

4.2 HAZARDS ANALYSIS FORMAT

Table 4-1 shows the form utilized for the hazard analysis. The following paragraphs contain a description of each column on the form.

4.2.1 Nomenclature

This column serves two functions: (i) to give the category of the analysis, i.e., system, component, or interface; (ii) to identify the specific item within the category and give a brief description of its function(s).

4.2.2 Failure Mode

The entries in this column describe briefly the manner in which the equipment malfunctions. The failure modes in this analysis only describe possible unsatisfactory performance without reference to probability of occurrence or confidence in the probability.

4.2.3 Effect of Failure

Since crew safety is a primary concern, the effects of failures indicated in this column are those representing safety hazards to the crews of either the resupply or user OVs. In the case of components, any effect(s) on crew safety may be indirect one(s).

Table 4-1. Hazards Analysis Form

Nomenclature	Failure Modes	Effect of Failure	Hazard Classification	Design and Operational Guidelines	
				Preventive	Remedial

4.2.4 Hazard Classification

This column classifies the effect(s) of the failure on OPD operation according to the standard NASA Hazard categories. The hazard categories are contained in Appendix C for the convenience of the reader.

4.2.5 Design and Procedural Guidelines

This column contains two subheadings; preventive and remedial. The data contained in the preventive category provide guidelines for inputs to engineered-in design and procedural requirements that will enhance system safety. Where applicable, the remedial column contains inputs for contingency operation(s) should failure(s) occur.

4.3 ANALYSIS OF SYSTEMS

4.3.1 Propellant Storage Tank System

4.3.1.1 Functional Discription

The propellant storage tank system consists of the propellant tank proper and all associated components, such as valving, fluid condition sensing meters, etc. (See Figure 4-1 for typical integral system tank schematic.) The primary function of the propellant tanks is to store (maintain) and condition the propellants Both hydrogen and oxygen use autogenous pressurization, and, conceptually, the tanks are identical except for their respective sizes. The propellant tanks store propellants in a zero-g condition.

4.3.1.2 Hazard Analysis

The major hazard associated with the propellant tanks is the mixing of the propellants which can result in a potentially explosive condition. This and other hazards are analyzed in Tables 4-2, 4-3, and 4-4.

4.3.2 Secondary Propulsion System (SPS)

4.3.2.1 Functional Description

The secondary propulsion system (SPS) provides the necessary OPD acceleration for phase control during propellant transfer. The required level of acceleration

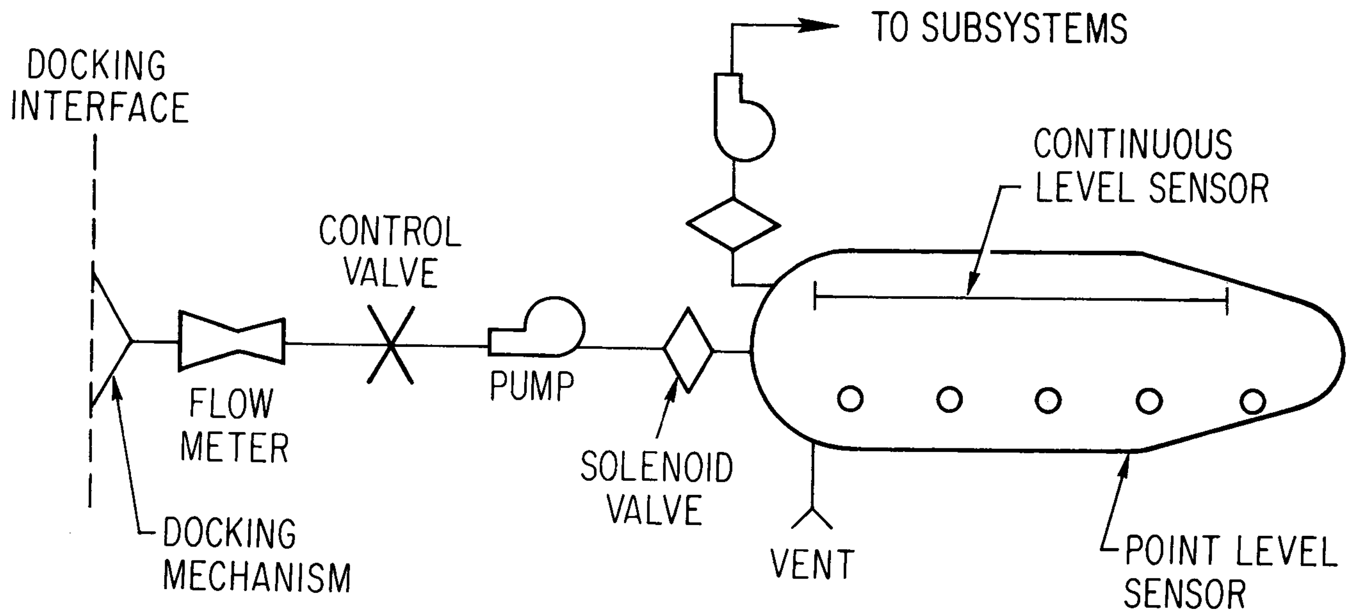


Figure 4-1. Propellant Transfer Schematic, Integral Concept

Table 4-2. OPD Propellant Tank Components, Integral and Semimodular Concepts

Measurement/ Conditioning	Transfer	Resupply	Interfaces
Positive-g liquid level sensors	Delivery pump	Docking cone/umbilical	Gas generator
Point sensors	Valves	Pressure/temperature sensors	Pressurization
Continuous sensors	Solenoid	Check valves	Vent
Integrating flowmeters	Flow control		Secondary Propulsion System
Temperature/pressure sensors	Throttling		
Destratification fan	Flowmeter		
Reconditioning vent system	Temperature/pressure sensors		
	Docking cone		

Table 4-3. Propellant Storage Tank Hazard Analysis, Integrated and Semimodular Concepts

Nomenclature	Failure Mode	Effect of Failure	Hazard Classification	Design and Procedural Guidelines	
				Preventive	Remedial
System Propellant storage tank Propellant storage	Transfer line leakage during active pumping	High overboard dump rate with possible propellant residing near OPD, potential combustible condition	Catastrophic	1. Monitor flow rate out of OPD and into user OV tanks 2. Automatic shutdown if flow-rates are different 3. Locate transfer lines in open area	Shutdown system, locate leak and fix by EVA
	Switching of LO_2 and LH_2 transfer lines	Mixing of the two propellants, potentially combustible mixture	Catastrophic	1. Color code all lines on connects 2. Use different fittings for oxygen and hydrogen lines	
	Overpressurization and line failure due to water hammer effect	Loss of propellant due to venting losses and non-transfer due to line failure	Critical	1. Adopt shutoff procedure with variable flow rate 2. Incorporate surge tank into system	
	Uncontrolled transfer line boiloff during transfer	1. Pressure surges 2. Loss of transfer control and propellant transfer monitoring	Critical	Incorporate both internal and external transfer line conditioning capability	Cease transfer, recondition line and reinitiate transfer operation
	Valve failure down-stream of transfer pump in closed position during active pumping	Transfer pump pumping against a closed line; over-pressurization and possible line rupture	Critical	Use pump with cutoff logic that terminates pumping at a pre-determined downstream pressure	
	Plumbing and transfer leakage	Propellant residing near OPD	Marginal	No enclosed areas on OPD (open-structured OPD)	Isolate detailed component and use EVA fix
	Loss of pumping capability	No propellant transfer user OV temporarily stranded	Negligible	Redundant transfer system	Isolate failed transfer system and use EVA fix

Table 4-4. Propellant Tank Hazards Analysis, Modular Concept

Nomenclature	Failure Modes	Effect of Failure	Hazard Classification	Design and Operational Guidelines: Preventive	Design and Operational Guidelines: Remedial
System Propellant Tank provides for delivery and storage of propellant flight weight tanks.	Tank ruptured during user OV docking	Propellants released, possible fire or explosion	Catastrophic	Shock mount tanks to resist docking impacts	Undock receiver and maneuver away from OPD until propellants have vented from damaged tank
	Vent valve failure	Overpressurization-damaged tank structure, potential fire or explosion	Catastrophic	Redundant pressure relief valves and/or rupture discs	Undock receiver and maneuver away from OPD until propellants have vented from damaged tank
	Common bulkhead failure	Propellants mixed, fire or explosion	Catastrophic	Redundant pressure relief systems	
	Interface fittings damaged Propellant transfer fittings	Loss of propellant, possible fire or explosion	Critical	Normally closed isolation valves between interface disconnects and tanks	Select alternate propellant tank; notify ground base of defective tank
		Inability to transfer tank to receiver	Marginal	Redundant transfer lines	Utilize redundant transfer line or select alternate tank
	Electrical fittings	Inability to transfer propellant	Marginal	Redundant electrical interface connectors	Utilize redundant connector or select alternate tank
	Propellant level sensing system inoperative	Unable to determine capacity of tank, receiver	Marginal	Redundant level sensor probe	Select alternate tank; notify ground base of defective tank

is on the order of 10^{-5} to 10^{-4} g's. A linear acceleration method was selected for this application (see Appendix A). The basic components within the SPS shown in Figure 4-2 and Table 4-5 are: (i) the start tanks which are capillary retention devices capable of propellant feed in a zero-g environment; and (ii) the engine thrusters. After acceleration is effected with feed from the start tanks, SPS propellants are obtained from the main tanks to sustain the required level of acceleration for the duration of the propellant transfer operation.

4.3.2.2 Hazard Analysis

The primary failure modes of the SPS are its inability to control acceleration and its inability to effect acceleration; in either case, the result would be the nontransfer of propellants. In addition, the former could result in not being able to uncouple the affected OV from the OPD. These hazards are discussed further in Table 4-6.

4.3.3 Pressurization System

4.3.3.1 Functional Description

The pressurization system provides the necessary net positive suction head (NPSH) of propellant settling to effect pump transfer. The system is an autogeneous warm, gas-pressurization system and is also a bootstrap system where propellant is taken downstream from the transfer pump and passed through a vaporizer. The primary components in the pressurization system are the heat exchangers and the pressure- and flow-regulating valves, Figure 4-3 and Table 4-7.

4.3.3.2 Hazard Analysis

A hazard associated with the pressurization system (see Table 4-8) is uncontrolled overpressurization of the donor tank which cannot be relieved by the tank pressure relief system. The result of such a failure would be a propellant tank explosion with possible failure of the entire OPD.

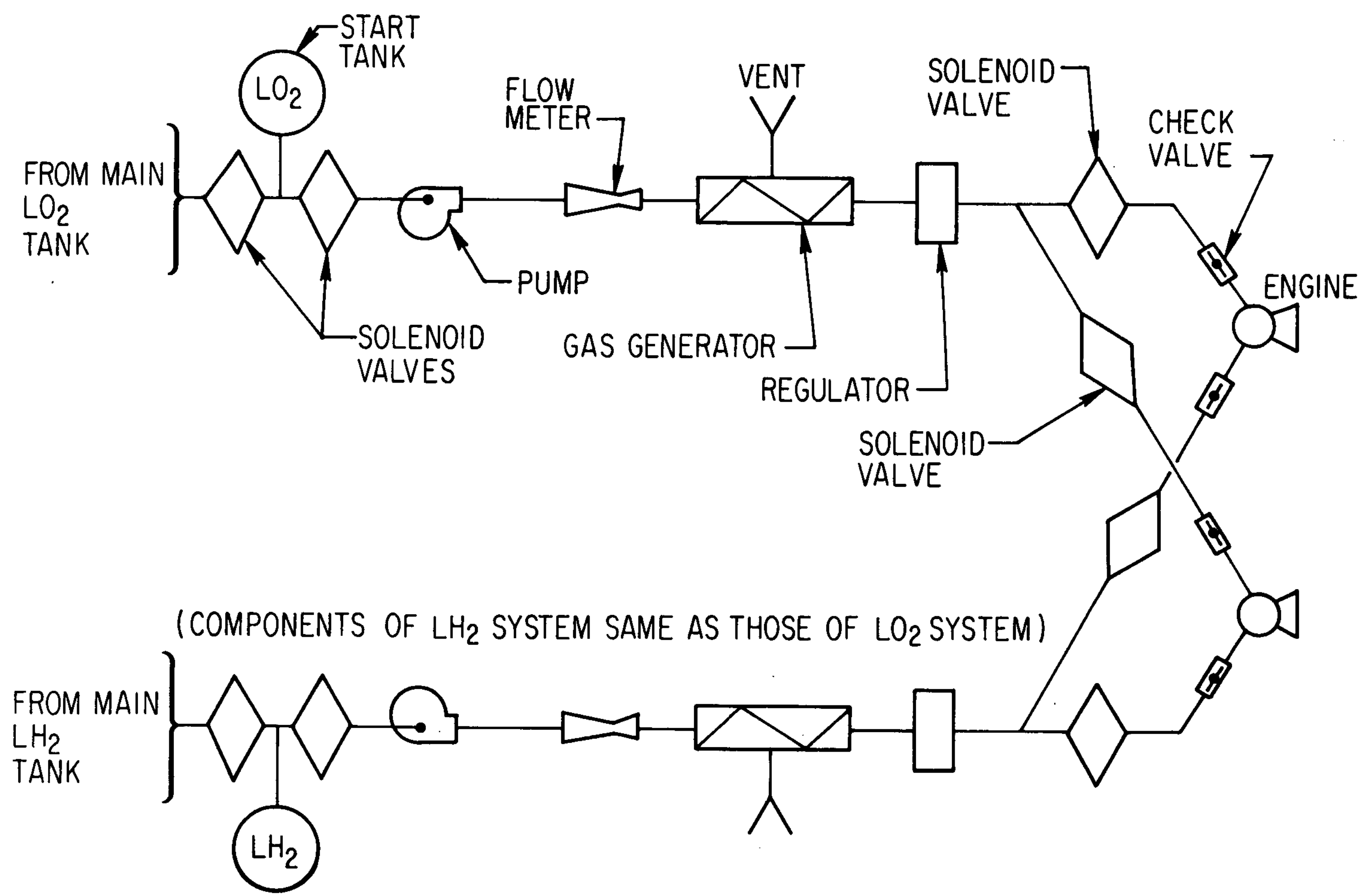


Figure 4-2. Secondary Propulsion System Schematic

Table 4-5. Secondary Propulsion System Start Tanks

1. Provides OPD Linear Acceleration to Settle Liquid
2. Start Tanks
    a. Capable of zero-g operation
    b. Fed from propellant tank
3. Components
    a. Pumps
    b. Flowmeters
    c. Valves
    d. Heat exchangers
        1) Heat propellants
        2) Liquid/vapor interface
    e. Combustion chambers
4. Interfaces
    a. Propellant tanks
    b. Gas generator

Table 4-6. Secondary Propulsion System Hazard Analysis

Nomenclature	Failure Mode	Effect of Failure	Hazard Classification	Design and Procedural Guidelines	
				Preventive	Remedial
Secondary propulsion system OPD acceleration for phase control	Erratic firing of the thrusters	Uncontrolled motion of the OPD results in nondocking/ nonseparation of the resupply or user OV from OPD	Critical	Completely separate SPS and attitude control system with capability of one to override the other	1. Manually override SPS with the altitude control system 2. Manual shutdown capability of the SPS
	Nonrefill of the start tanks	Inability to start SPS -- no OPD acceleration	Critical	Redundant start tanks capability of attitude control system to provide initial acceleration	1. Use attitude control system for initial acceleration 2. Repair start tanks (locate start tanks in an accessible area)

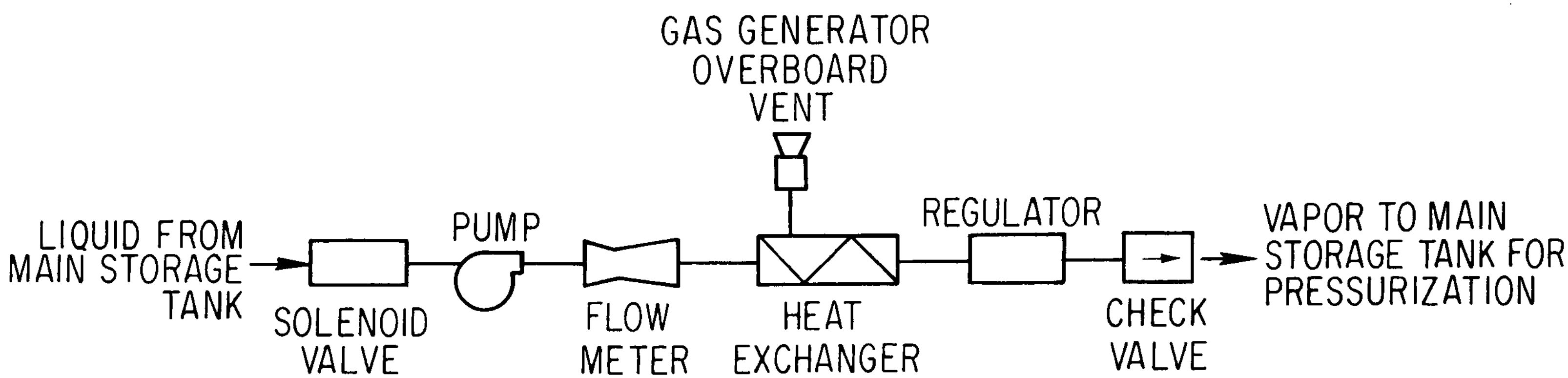


Figure 4-3. Pressurization System Schematic

Table 4-7. OPD Pressurization System

1. Provides NPSH to Propellants

2. Oxygen

    a. Helium Pressurization

        1) Stored high pressure helium

        2) He heater to ~500 R

    b. Components

    1 1) High pressure helium tank

        2) Valves

        3) Heat exchangers

        4) Pressure/temperature sensors

    c. Interfaces

        1) Oxygen tank

        2) Gas generator

3. Hydrogen

    d. Hydrogen Pressurization

        1) bled from main tank

        2) H_2 heated to ~500 R

    e. Components

        1) Valves

        2) Pump

        3) Flowmeter

        4) Heat exchanger

        5) Pressure/temperature sensor

    f. Interfaces

        1) Hydrogen tank

        2) Gas generator

Table 4-8. OPD Pressurization System Hazard Analysis

Nomenclature	Failure Mode	Effect of Failure	Hazard Classification	Design and Procedural Guidelines	
				Preventive	Remedial
Pressurization system Provide NPSH to transfer pumps	Loss of liquid delivery in the pressurization feed to the gas generator HX	Excessive norm gas feed into the propellant tank and consequent over-pressurization --possible failure of OPD tanks	Catastrophic	1. Control liquid feed into gas generator and gas feed into propellant tank 2. Provide flow restrictions in pressurization feed lines 3. Provide sufficiently large tank pressure relief system to prevent tank explosion	
	Water hammer effect during pressurization process	Pressure surges into propellant tanks with consequent over-pressurization of active system	Critical	1. Incorporate surge tanks into system 2. Incorporate transfer pumps operating on both a specific ΔP across pump and a specific absolute downstream pressure	

4.3.4 Gas Generator System (GGS)

4.3.4.1 Functional Description

The gas generator provides thermal energy to the pressurization system and to the secondary propulsion system. It is basically a combustion canister using oxygen and hydrogen as reactants to generate thermal energy. The hot gas products are passed through heat exchangers where pressurant gas and SPS propellants are heated. The primary components within the gas generator system are the combustion canister and the heat exchangers; a schematic of the system is presented in Figure 4-4 and a listing of the components is in Table 4-9.

4.3.4.2 Hazard Analysis

The major hazards associated with this system are the loss of oxidizer/fuel mixture control and the leakage of combustion gas products into the pressurization system. These hazards are listed in Table 4-10.

4.3.5 Vent System

4.3.5.1 Functional Description

The propellant tank vent system has a three-fold function: (i) relieve excessive propellant tank pressure caused by heat leaks into the tank; (ii) dump purge gas during a purging operation; and (iii) regulate tank pressure during a propellant transfer operation. The principle of thermodynamic conversion is utilized in the vent system to ensure that only vapors are vented. A schematic depicting the major components in the system is shown in Figure 4-5 and a listing of the components is in Table 4-11.

Initial venting of the storage tanks releases both vapor and a quantity of liquid propellant. The liquid and vapor are separated after passing through the relief valve. The vapor goes directly to the vent branch of the system. The liquid is converted to a vapor by diverting it through a throttling valve and heat exchanger for use in cooling the main tanks; the resulting vapor goes to the vent

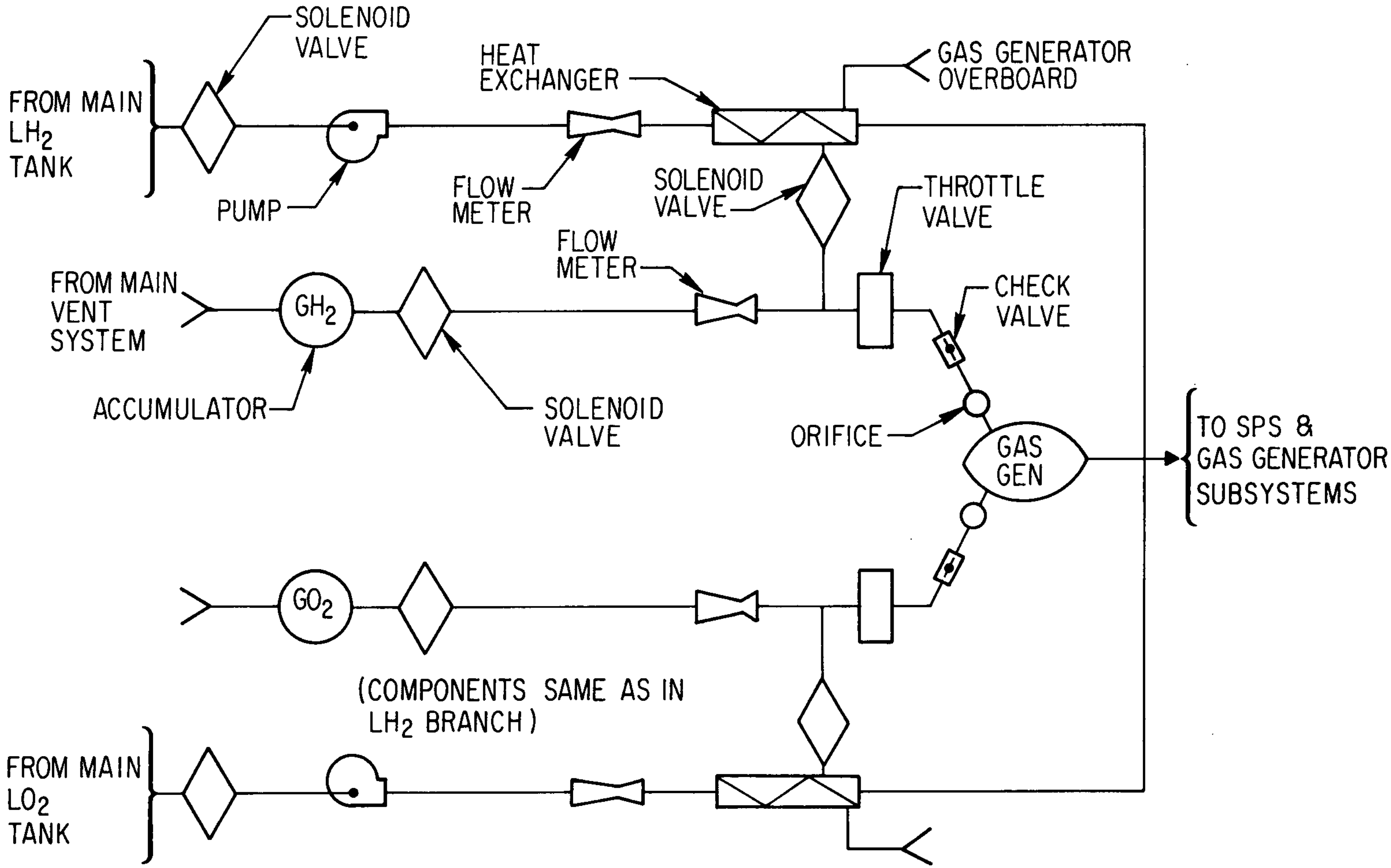


Figure 4-4. Gas Generator Schematic

Table 4-9. Gas Generator System

1. Provides Thermal Energy to Gas Generator System (GGS), Secondary Propulsion System(SPS), and Pressurization System
2. Initial Reactants from Vent System
3. After Start of SPS, Propellant Bled from Main Tanks
4. Components
    a. Valves
    b. Pumps
    c. Flowmeters
    d. Heat exchangers
    e. High pressure vent storage tanks
    f. Combustion canister
5. Interfaces
    a. Propellant tanks
    b. Vent system
    c. Pressurization system
    d. SPS

Table 4-10. Gas Generator System Hazard Analysis

Nomenclature	Failure Mode	Effect of Failure	Hazard Classification	Design and Procedural Guidelines	
				Preventive	Remedial
Gas generator system	Control sensor for oxidizer/fuel mixture	Excessive combustion temperature and burnout of the gas generator	Catastrophic	1. Incorporate redundant oxidizer/fuel control 2. Monitor combustion temperature 3. Provide automatic shut-down if combustion temperature exceeds predetermined value	
	Gas leakage across GG/SPS heat exchanger	Contamination of propellant tanks with combustion products (H_2 and H_2O), potentially explosive condition in oxygen tank	Catastrophic	Use intermediate heat exchanger	
	GG gas product dump valve pluggage due to water condensation	Inoperable GG	Marginal	1. Redundant dump lines 2. Add heaters to dump valve area	Turn heaters on to melt water and exercise valves by EVA

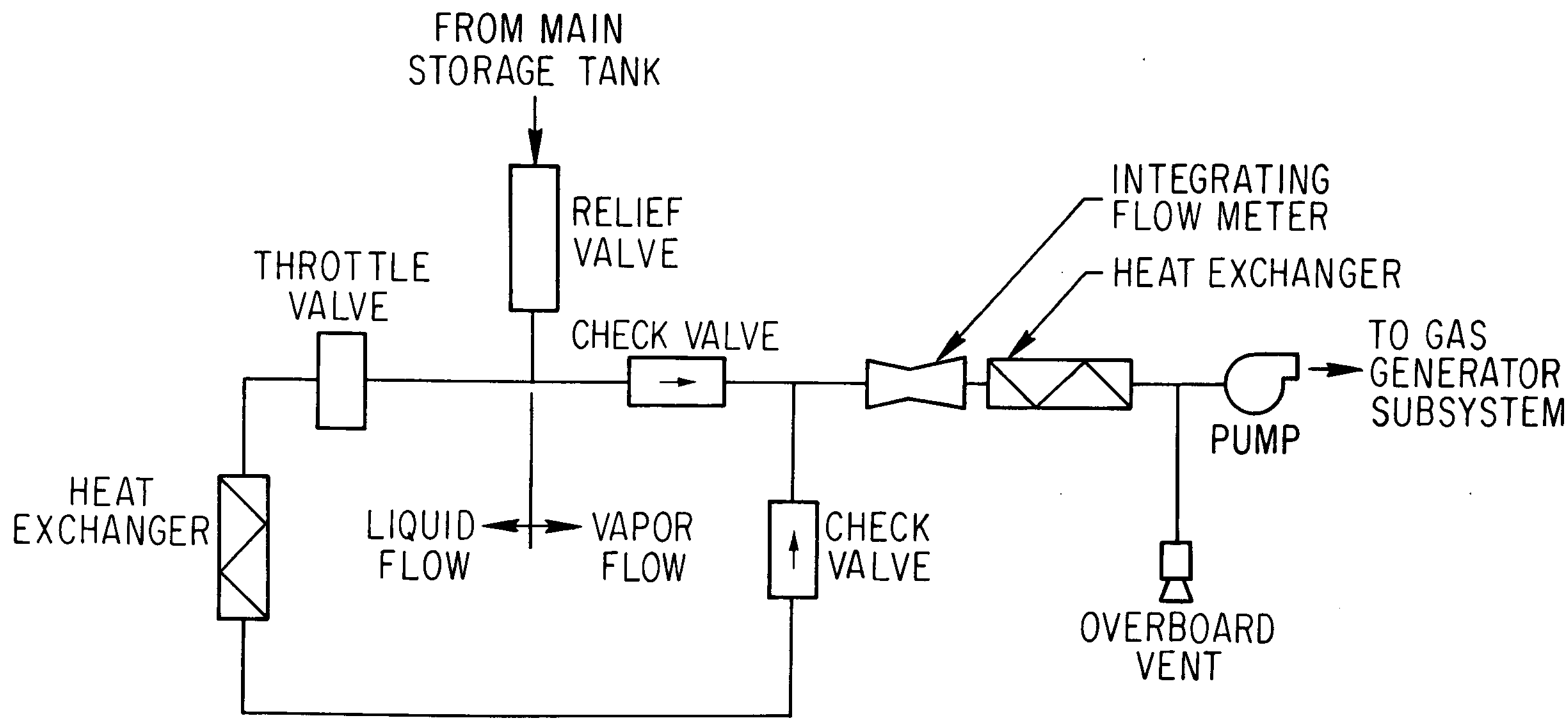


Figure 4-5. Vent System Schematic (Thermodynamic Liquid and Vapor Separator)

Table 4-11. OPD Vent System

1. Provides Propellant Tank Pressure Relief
2. Zero-g Vapor Venting
3. Thermodynamic Liquid/Vapor Separator
4. Vented Vapor Stored in GG Accumulators
5. Components
    a. Valves
    b. Heat exchangers
    c. Overboard dump
    d. Pump
    e. Integrating flowmeter
6. Interfaces
    a. Propellant tank
    b. Gas generator

branch of the system. In the vent branch, the vapors flow through an integrating flow meter which records the propellant loss due to venting. The vapors are subsequently pumped to storage accumulators and used for the initial start of the gas generator; the excess is vented overboard.

4.3.5.2 Hazard Analysis

Table 4-12 contains the hazard analysis for this system. The major hazard associated with the vent system is its failure in either the open or closed position. The vent system should provide both redundancy and backup in the event of a failure. Manual override capability should also be incorporated so that portions of the systems can be isolated.

4.3.6 Docking/Interface Mating System

4.3.6.1 Functional Description

The purpose of this system is to secure the resupply or user OVs to the OPD during propellant transfer operations. The system also provides the capability for mating the propellant transfer interfaces.

The primary components of the system are a universal docking adapter, locking latches, and transfer system interface connectors. The docking adapter is compatible with all vehicles servicing or being serviced by the OPD. The mechanism provides vehicle alignment in both axial and angular directions to facilitate docking. A series of hydraulic latches is mounted on the adapter to lock the vehicles together at completion of the docking operation. The transfer interface is comprised of the fluid and electrical connectors necessary to the propellant transfer operations.

Since the details of the mating/transfer operations vary slightly for the different concepts and modes of operation, only a brief generalized description will be given here; a more detailed discussion occurs in Appendix B.

Table 4-12. OPD Vent System Hazard Analysis

Nomenclature	Failure Mode	Effect of Failure	Hazard Classification	Design and Procedural Guidelines	
				Preventive	Remedial
OPD vent system	Vent system failure in the closed position	Tank overpressurization with consequent tank failure	Catastrophic	Redundant relief system burst diaphragm to prevent catastrophic explosion of the vehicle	
	Structural failure of accumulators	Explosion and consequent damage to other equipment	Catastrophic	Isolate accumulators from critical OPD systems	Replace damaged accumulators

Figure 4-6 shows the basic steps in the docking/interface mating procedure. When the docking adapter is not in use, it is stored in the retracted position. As a vehicle approaches the OPD, the adapter is extended for the docking phase. When the vehicles are docked and the locking latches secured, the adapter is retracted. This properly positions the vehicle with respect to the OPD and enables the transfer interface connectors to be mated. When the propellant transfer is complete, the docking/mating procedures are reversed.

4.3.6.2 Hazard Analysis

The following hazards analysis is divided into two sections. Tables 4-13 through 4-19 apply to both the integral and semimodular concepts. Table 4-20 applies to the modular concept.

4.4 COMPONENTS

Although the various systems have individual system-peculiar components, many of the components are common to all of the systems. Consequently, the components were considered collectively and not as part of a system. On a component level basis, failure modes include electrical shortage, mechanical component failures, valve failure in the open/closed positions, etc. An analysis of the more critical components is presented in Table 4-20. Although none of the component failures per se will result in a catastrophic failure (except perhaps for the mixing of the propellant within the GG heat exchangers), the domino theory is very applicable to the propagation of failures from a component. Therefore, although a failure of a single component may appear to be relatively inconsequential in terms of a hazard classification, all due precautions must be used to prevent or remedy the possibility of a component failure from propagating to a total system failure.

4.5 INTERFACES

Table 4-21 presents a matrix identifying the interfaces among the various systems; all but the power system interface were considered. The docking mechanism interface was discussed in paragraph 4.3.6.

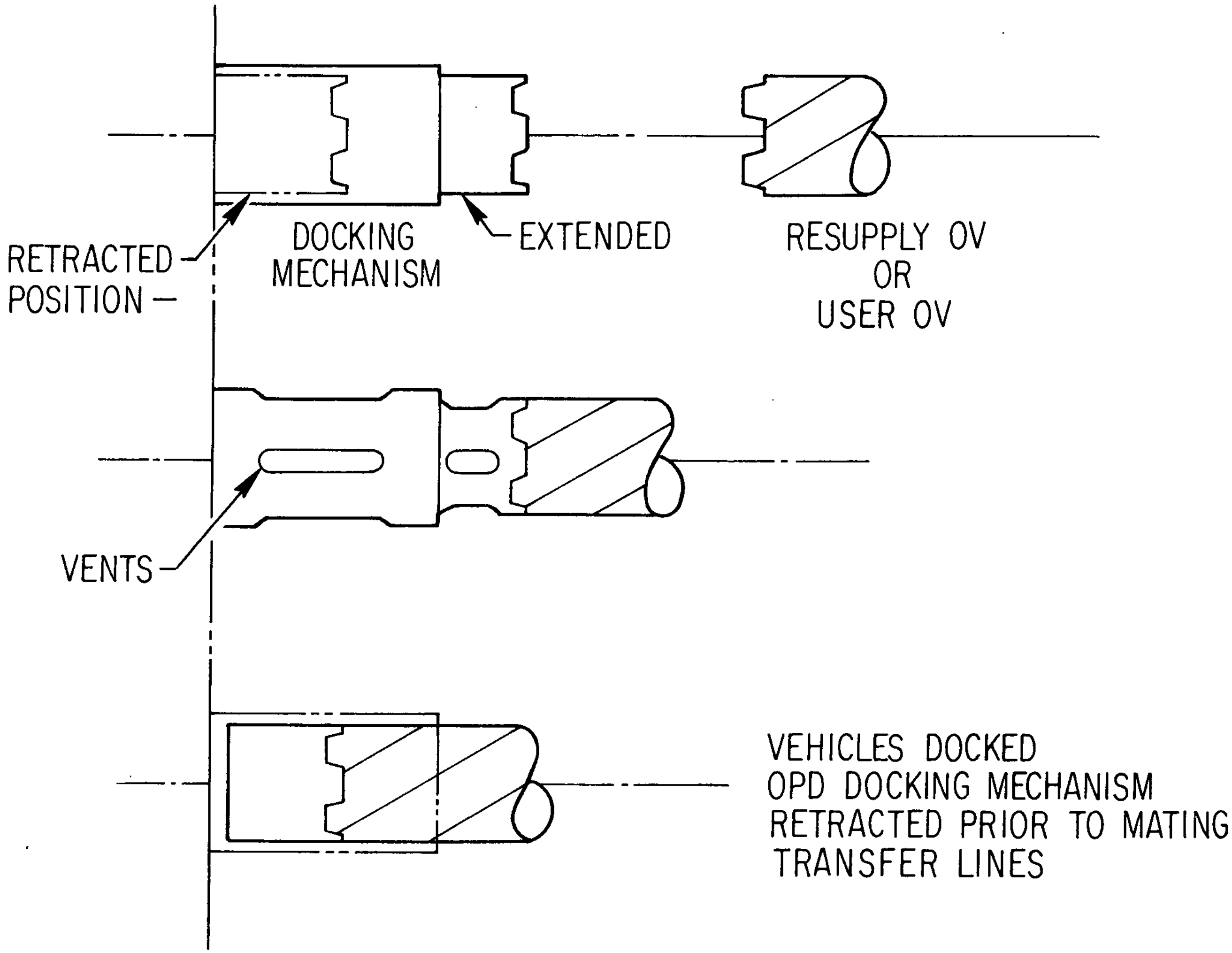


Figure 4-6. Docking Configuration, Integral and Semimodular Concepts

Table 4-13. OPD Resupply/Servicing Hazard Analysis, Integral and Semimodular Concepts

Nomenclature	Failure Mode	Effect of Failure	Hazard Classification	Design and Procedural Guidelines	
				Preventive	Remedial
Docking system Locks OPD to resupply OV during propellant transfer	Fails to extend for docking operation	Cannot resupply OV; no resupply capability User OV cannot dock; no propellant transfer capability	Marginal	1. Redundant actuating systems 2. Redundant docking ports	1. Recheck procedure 2. Utilize redundant capabilities 3. Attempt dock in retracted position 4. Dump resupply propellant and return to earth
	Fails to retract after docking	Cannot mate propellant transfer interface; no propellant transferred	Marginal	1. Redundant actuating system 2. Redundant docking ports	Utilize redundant capabilities
	Locking latches fail to lock	Cannot install tank; no resupply capability User OV cannot maintain hard dock; no propellant transfer capability	Marginal	1. Redundant actuating system 2. Redundant docking ports	1. Recheck procedure 2. Utilize redundant capabilities 3. Dump resupply propellant and return to orbit
	Locking latches fail - inadvertent release of tank	Potential damage to OPD/OV due to free floating tank	Critical	Safety tether	Recapture with OV and redock
	Locking latches fail to release	Empty tank cannot be retrieved User OV cannot depart OPD	Marginal Critical	Redundant actuating system	EVA for manual release EVA for manual release

Table 4-14. Modular Propellant Resupply Hazards Analysis, Integral and Semimodular Concepts

Nomenclature	Failure Mode	Effect of Failure	Hazard Classification	Design and Procedural Guidelines	
				Preventive	Remedial
Modular propellant resupply tank system (a) Contains propellant for delivery to OPD (b) Provides propellant storage Semi-modular System	Interface disconnects leak in OV payload bay	Liquid/gaseous propellant released in OV payload bay, potential fire or explosion	Critical	1. Provide disconnect shroud 2. Vent overboard	Open OV payload bay doors and vent to space
	Disconnects damaged during mating 1. On OPD 2. On resupply OV tank	Transfer lines cannot be mated; no propellant transfer to OPD Resupply tank vented to space; propellant lost	Marginal Marginal	Shock mount lines to absorb mating shocks Redundant docking port	1. Remove tank and install in redundant docking port 2. Dump propellant and return empty supply tank to earth 3. Stand off with OV and allow resupply tank to vent; return empty tank to earth for repair
	Disconnects fail to mate	Propellants cannot be transferred to OPD	Marginal	Redundant disconnects/ docking ports	1. Disengage tank and redock 2. Disengage tank and move to redundant docking port
	Disconnects leak after mating	Propellants released; potential fire or explosive hazard	Critical	1. Install isolation valves both sides of disconnect interface 2. Provide redundant disconnect	1. Close isolation valves on leaking interface and shift to redundant disconnect 2. Disengage tank and install in redundant docking port 3. Allow supply tank to vent off; return empty tank to earth for repair
	Resupply OV tank ruptured **1. Damaged during mate/demate sequence** **2. Overpressurized**	1. Propellants released; potential fire or explosive hazard 2. Potential damage to OPD/OV from debris in vicinity of OPD	Catastrophic	Shock mounts to absorb mating shocks	1. Remove OV from vicinity and allow damaged tank to vent off 2. Utilize OPD propulsive and control systems to maneuver OPD clear of debris
	Empty tank cannot be removed from OPD	Degradation of OPD resupply capability	Negligible	Provide redundant docking port	Request on-orbit maintenance

Table 4-15. OPD Resupply Fluid Interface Hazard Analysis, Integral and Modular Concepts

Nomenclature	Failure Mode	Effect of Failure	Hazard Classification	Design and Procedural Guidelines	
				Preventive	Remedial
Fluid interface system Links resupply tank fluid transfer lines to OPD resupply line	Disconnects or lines damaged in docking/ mating operation	Unable to transfer propellant to OPD	Marginal	Shock mount lines and disconnects to resist mating loads	1. If resupply OV tank hardware is undamaged, move tank to redundant docking position 2. If resupply OV tank hardware is damaged, vent tank and return to earth for repair
	Unable to release disconnects	Unable to remove resupply tank from OPD	Critical	Provide shear type locking pins rated below load capability of transfer lines	Utilize OV propulsive capability to shear locking pins and release tank
	Leakage during transfer operation	Release of propellant; potential fire or explosion, possible damage to OPD and/or OV	Catastrophic	Automatic actuation of isolation valves to stop propellant flow	1. Manual override by OV to deactivate OPD transfer subsystems 2. Allow propellant to disperse and open isolation valves on redundant line from OV
	Line or disconnect rupture during transfer operations	Release of propellant; potential fire or explosion, possible damage to OPD and/or OV	Catastrophic	Automatic actuation of isolation valves to stop propellant flow	1. Manual override by OV to deactivate OPD transfer subsystems 2. Allow propellant to disperse and open isolation valves on redundant line from OV

Table 4-16. OPD Resupply Electrical Interface Hazards Analysis, Integral and Semimodular Concepts

Nomenclature	Failure Mode	Effect of Failure	Hazard Classification	Design and Procedural Guidelines	
				Preventive	Remedial
Electrical interface system Supply power and communications across interface	Connectors damaged in docking/mating operation	Loss of power and control across interface; unable to transfer propellant	Marginal	Shock mount connectors to resist docking/mating shocks	1. If tank hardware is undamaged, move tank to redundant docking position 2. If tank hardware is damaged, vent tank and return to earth for repair
	Unable to release connectors	Unable to remove resupply tank from OPD	Critical	Provide shear type locking pins rated below load capability of cables	Utilize OV propulsive capabilities to shear pins and release tank
	Loss of power circuit	Unable to transfer propellant	Marginal	Automatic switch to redundant circuit	1. If failure is on OPD side of interface move tank to redundant docking port 2. If failure is in resupply tank, vent tank and return to earth for repair
	Loss of monitor or control circuit	Unable to control propellant transfer	Critical	Automatic switch to redundant circuit Power RF backup link for control from OV	Utilize RF backup link
	Arcing at interface	Potential fire or explosion	Catastrophic	Circuit breakers Interlock to prevent application of power before connector mate	Shutdown OPD power unit, vent resupply tank and return to earth

Table 4-17. User OV Servicing Fluid Interface Hazard Analysis, Integral and Semimodular Concepts

Nomenclature	Failure Mode	Effect of Failure	Hazard Classification	Design and Procedural Guidelines	
				Preventive	Remedial
User OV servicing fluid interface system Links user OV fluid transfer lines to OPD transfer lines	Primary transfer line actuators inoperable	Unable to mate interface; unable to transfer propellants; user OV stranded	Marginal	Provide redundant transfer system	Actuate secondary system
	Disconnects fail to lock	Unable to seal interface; unable to transfer propellant; receiver vehicle stranded	Marginal	Provide redundant transfer system	1. Recycle mating sequence 2. Actuate secondary system
	Unable to release disconnects	User OV cannot depart OPD	Critical	Provide shear type locking pins rated below load capability of transfer lines	Actuate user OV propulsion system to rupture shear pins
	Leakage during pressure check	Unable to transfer propellant; user OV stranded	Marginal	Provide redundant transfer system	1. Recycle mating sequence and retest 2. Actuate secondary system
	Leakage during transfer operation	Propellants released; potential fire or explosion	Catastrophic	Automatic actuation of isolation valves to stop propellant flow	1. Manually override from user OV to deactivate OPD transfer subsystem 2. Undock, separate vehicles and allow spill propellant to disperse 3. Redock, mate and actuate secondary transfer system
	Line or disconnect rupture during transfer operation	Propellant released, potential fire or explosion	Catastrophic	1. Pressure and flow regulation to ensure line and disconnect capacities are not exceeded 2. Automatic actuation of isolation valves to stop propellant flow	1. Manually override from user OV to deactivate OPD transfer subsystem 2. Undock, separate vehicles and allow spill propellant to disperse 3. Redock, mate and actuate secondary transfer system

Table 4-18. User OV Servicing Electrical Interfaces Hazards Analysis, Integral and Semimodular Concepts

Nomenclature	Failure Modes	Effect of Failure	Hazard Classification	Design and Procedural Guidelines	
				Preventive	Remedial
User OV electrical interface system Supply power and communications across interface	Actuators for primary connectors inoperative	Unable to mate interface; unable to transfer propellant; user OV stranded	Marginal	1. Provide redundant transfer system 2. Provide RF backup link	1. Actuate secondary system 2. Utilize RF backup link
	Unable to mate connector	Unable to transfer propellant; user OV	Marginal	1. Provide redundant transfer system 2. Provide RF backup link	1. Actuate secondary system 2. Utilize RF backup link
	Unable to release connector	User OV cannot depart OPD	Marginal	1. Provide shear type locking pins rated below load capability of cables 2. Provide cable cutters on user side of interface	1. Actuate user OV propulsion to rupture shear pins 2. Actuate cable cutters
	Loss of power circuit	Unable to transfer propellant	Marginal	1. Automatic switch to redundant line 2. Provide redundant transfer system	Actuate secondary system
	Loss of control circuit	Unable to control transfer operation	Critical	1. Automatic switch to redundant line 2. Provide redundant transfer system	Actuate secondary system
	Loss of monitor circuit	Unable to determine status of transfer operation	Critical	1. Automatic switch to redundant line 2. Provide redundant transfer system	Actuate secondary system
	Arcing at interface	Potential fire or explosion	Catastrophic	Circuit breakers	Disconnect defective circuit and activate secondary system

Table 4-19. OPD Resupply Docking System Hazard Analysis, Modular Concept

Nomenclature	Failure Mode	Effect of Failure	Hazard Classification	Design and Procedural Guidelines	
				Preventive	Remedial
OPD resupply docking system Locks propellant tank modules to OPD for storage	Locking latches fail to lock	Cannot install tank, no resupply capability	Marginal	Redundant actuator systems Redundant docking port	1. Recheck procedure 2. Utilize redundant capabilities 3. Dump propellant and return to earth
	Locking latches fail to release	Empty tank cannot be retrieved User OV cannot acquire tank	Marginal Critical	Redundant actuating system Redundant actuator systems	1. EVA for manual release 2. Utilize redundant actuator 3. Redock user OV to alternate tank, notify ground base of defective position
	Locking latches fail - inadvertent release of tank	Potential damage to OPD, OV, or user OV due to free floating tank	Critical	Safety tether	Recapture with OV or tug and redock

Table 4-20. Components Hazard Analysis

Nomenclature	Failure Mode	Effect of Failure	Hazard Classification	Design and Procedural Guidelines	
				Preventive	Remedial
Component					
1. Overboard dump valves Dumps gas generator byproducts	Failure in the closed position due to mechanical failure or frozen water	Inability to use GG	Marginal	Manual override of valves and incorporate heaters around valves	Manually exercise valve and activate heaters
2. Vent valves Pressure relief	Close position	Non-venting of tanks and consequent pressure buildup	Critical	Redundant vent system with manual override	Manually exercise valve
3. Start tank Initiates secondary propulsion system	Gas entrapment	No propellant feed in zero-g and consequently no acceleration	Marginal	Contingency high pressure tanks	
4. Liquid level sensor Measure propellant level in storage tanks	Electric short	Loss of propellant measurement capability and consequent inability to determine amount of propellant available for transfer	Marginal		Perform transfer operations, utilize user OV systems to monitor amount transferred
5. Transfer pump Propellant transfer	Motor failure mechanical breakdown	Loss of transfer capability if failure occurs prior to transfer initiation	Marginal	Redundancy	
		Sudden flow stoppage during transfer may cause water hammer with consequent pressure damage	Critical	Incorporate high flow pressure relief valve	
6. Integrating flow meter Record propellant flow, inputs to propellant inventory	Electric, mechanical	No indication of amount of propellant passed through transfer line which may in conjunction with failure of liquid level sensors in the OPD and user OV result in overfill of user OV	Marginal	Monitor propellant levels in OPD, user OV and transfer line; these three should give the same amount transferred	Utilize user OV systems to monitor propellants received
7. Heat exchanger	Leak across pressurization system HX	GG gas ($H_20 + H_2$) in propellant tank with consequent combustible mixture in LO_2 tank	Catastrophic	Intermediate heat exchanger	
		Frozen H_20 in tank with transfer blockage	Critical	Intermediate heat exchanger	

Table 4-21. System Interface Matrix

System	Propellant Tank	Secondary Propulsion	Gas Generator	Vent	Pressurization	Docking	Power
Propellant tank		X	X	X	X		X
Secondary propulsion	X		X	X			X
Gas generator	X	X		X	X		X
Vent	X	X	X				X
Pressurization	X		X				X
Docking	X						X
Power	X	X	X	X	X	X	

Table 4-22 delineates the interfaces and the failure modes which can exist across the interfaces. Generally, the most common type of failure is the nonscheduled transfer of propellant, electrical energy, etc. across an interface.

Table 4-22. Interface Hazards Analyses

Nomenclature	Failure Mode	Effect of Failure	Hazard Classification	Design and Procedural Guidelines: Preventive	Design and Procedural Guidelines: Remedial
Interface 1. Propellant tank/SPS, transfers propellant from main tanks through start tank to SPS	Electrical short-circuit of transfer logic	Excessive propellant feed resulting in undesired level of acceleration	Marginal	Redundant electrical circuits with manual override	1. User OV commands system shutdown 2. User OV propulsion capabilities to achieve required acceleration
2. Propellant tank/pressurization systems, propellant transferred from the propellant tank to the GGS interface and back to the propellant tank ullage	Overpressurization due to uncontrolled heat input to tanks	Failure of propellant tanks	Catastrophic	Pressure relief in pressurization system and in tanks. Control pressurant temperature and flow	1. Shutdown GG and pressurization system 2. Recheck flow control valves
3. Propellant tank/vent systems, provide transfer of vent gas from tank to vent system/accumulator	Vaporizer HX	Liquid propellant dumped overboard with consequent high propellant-to-heat ratio	Marginal	Locate HX in liquid sump area	
4. Vent system/SPS, directs vented gas to accumulator for use in starting SPS	Vent system logic failure which prevents fill of high-pressure gas accumulators	No gaseous propellant available to start the SPS	Marginal	Carry emergency high pressure bottles in OPD	Start vehicle motion with high-pressure bottles
5. Gas generator/propellant tank, propellant is transferred from the propellant tank to the gas generator	Loss of flow capability due to valve failure Flow of gas into pump leading to gas generator	No propellant flow to gas generator Cavitation within the liquid flow pump with pressure surges	Marginal Critical	Redundant valves Locate withdrawal line so that liquid is always withdrawn if any remains in the tank	Cease transfer and reinstate conditioning procedure
6. Gas generator/SPS, provides thermal energy to the pressurization system through a heat exchanger	Leakage across heat exchangers	1. Degradation of heat exchanger performance 2. Erratic thrust with unanticipated motion motion	Marginal Critical	Intermediate HX Intermediate HX	Smooth out motion with ACS
7. Gas generator/vent systems, provide capability to store gaseous propellant vent in the gas generator system	Failure in vent logic which sends gas to overboard instead of to GG accumulators	No gaseous propellants to start GG system	Critical	Separate high-pressure bottle to be used in contingency mode	
8. Gas generator/pressurization systems, provides thermal energy to the pressurization system through a heat exchanger	Leakage across heat exchanger with consequent mixing of hydrogen in hot gas with oxygen in the LO_2 pressurization system	A potentially explosive mixture of hydrogen in oxygen; hydrogen gas may reach oxygen propellant tank	Catastrophic	Use intermediate heat transfer loop between the two systems	

5. SUMMARY AND CONCLUSIONS

Three basic concepts of an OPD were assumed and evaluated to determine their respective safety hazards. Emphasis was placed on propellant transfer operations to and from the OPD, since these are the only occasions where manned vehicles would be involved in OPD operations. The concepts studied are summarized in Table 5-1.

The study indicates that a modular mode of depot resupply is desirable regardless of the OPD configuration. This resupply mode requires no flow transfer to resupply either the semimodular or modular OPD. For the integral OPD, the modular method of resupply allows the resupply vehicle to move to a safe distance during the transfer operations. However, in the case of the modular OPD, the resupply module is considered to contain both LO_2 and LH_2, which necessitates the use of a common bulkhead type tank. The possibility of rupturing this bulkhead and the catastrophic nature of such a failure, either fire or explosion, weigh heavily against the modular depot as a candidate configuration.

When servicing a user OV, the integral or semimodular OPD utilizes a propellant flow system to transfer propellants. The primary subsystems required for the transfer are ullage control, pressurization, and fluid flow, which are provided by linear accleration, liquid/vapor conversion, and pump transfer, respectively. The level of hazard is the same for either of these two concepts during this phase of operation.

The modular OPD transfers propellants by direct tank exchange. Direct tank exchange requires the user OV to dock its empty propellant tanks at the OPD and then maneuver with an auxillary propulsion system to acquire a propellant tank from the OPD. The additional maneuvering required of the user OV in close proximity to the OPD, plus the use of common bulkhead type propellant tanks which are susceptible to damage resulting in catastrophic

Table 5-1. Summary of OPD Concepts

Concept				
OPD	OPD Resupply Technique	User OV Resupply	Advantages	Disadvantages
Integral	Modular	Propellant flow	OV separate during propellant operation	1. Requires both propellant flow and tank exchange 2. Single tank rupture could result in loss of OPD
	Fuel transfer probe	Propellant flow	Unstable OPD operation has minimal impact on OV	1. Propellant transfer line vulnerable to unstable OPD 2. Single tank rupture could result in loss of OPD
Semimodular	Modular	Propellant flow	No propellant flow during resupply	Complex manifolding system required
Full modular	Modular	Modular	1. No propellant flow required 2. No propellant phase control required	1. Tanks have common bulkhead; bulkhead rupture would result in catastrophic fire/explosion 2. Requires more critical maneuvers during tank exchange
	Modular with OPD-mounted boom	Modular	1. No propellant flow required 2. No propellant phase control required	1. Tanks have common bulkhead; bulkhead rupture would result in catastrophic fire/explosion 2. Requires more critical maneuvers during tank exchange 3. Improper boom operation can cause tank/OV damage 4. Can result in OPD instability during tank movement

failure, as described above, raises the hazard level of the modular OPD above that for either the integral or semimodular OPD.

A summary of typical catastrophic and critical safety hazards is presented in Tables 5-2 and 5-3, respectively.

Of the threee concepts, the semimodular appears to provide the best operational advantage and lowest safety risk. This concept does not require a flow transfer of propellants to resupply the OPD, as does the integral concept. Since propellant flow is not required, the risk to the resupply vehicle is minimized. Further, since single propellants, either LO_2 or LH_2, are stored in individual modules, the likelihood of a single tank failure's incapacitating the OPD is minimized. Rupturing a single module will not result in a catastrophic failure due to propellant mixing, as could occur with the tanks used in the modular concept. Additionally a ruptured module can be isolated from the system at the transfer manifold. This is in contrast with the single tank storage of each propellant in the integral concept wherein a single tank failure results in the loss of all OPD operations.

Table 5-2. Typical Catastrophic Hazards

Subsystem	Failure	Effect
Resupply Tank	Rupture 1. Damaged during docking 2. Overpressurized 3. Common bulkhead failure	All failures will result in potential fire/explosion hazards Explosive hazards will produce debris further hazarding OPD, user OV, or resupply OV
	Leakage in OV payload bay	
Fluid Transfer	Leakage during transfer 1. Lines or disconnects damaged during mating 2. Lines or disconnects ruptured during transfer	
Electrical interface Arcing		

Table 5-3. Typical Critical Hazards

Subsystem	Failure	Effect
Docking Mechanism	Locking latches fail, tank released	Potential damage to OPD/OV due to free floating tank
	(Modular OPD) Locking latches fail to release	User OV cannot acquire tank
Fluid Transfer Interface	Unable to release disconnects	Unable to demate resupply tank or user OV from OPD
Electrical Interface	1. Unable to release disconnects 2. Loss of monitor or control circuit	1. Unable to demate resupply OV tank of user OV from OPD 2. Unable to control propellant transfer

Distribution List

External

NASA Scientific and Technical (3)
Information Facility
P.O. Box 33
College Park, Maryland 20740

NASA Headquarters
Washington, D.C. 20546
Attn: New Technology Representative
Code: UT

NASA Headquarters
Washington, D.C. 20546
Attn: Code: MT (50)

SAMSO
Air Force Unit Post Office
Los Angeles, Calif. 90045
Attn: Lt Col R. S. Bearman (2)

Internal

Bello, M.

Donabedian, M.

Farran, R. A.

O'Brien, N. R.

Sitney, L. R.

Steinman, J.

Toutant, R. P.

Wilkins, D. E.

Willens, D.

Wolfe, R. R.

Yoshikawa, H. H.