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Extravehicular Mobility Unit Subcritical Liquid Oxygen Storage and Supply System

CONCEPTUAL DESIGN STUDY REPORT

JANUARY 1992

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Refer to: CSC-92-0141

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Mark for Contract NAS9-18608

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Encl: (1) Eighteen (18) copies and one reproducible, MCR-92-1310, dated January 1992

1. Eighteen (18) copies and one reproducible are submitted in accordance with Reference (a) for your review and information.

2. Questions regarding this submittal may be referred to the undersigned at (303) 971-6548, Mail Stop S2421, or Mr. J. Anderson at (303) 971-9305, Mail Stop DC8082.

Very truly yours,

MARTIN MARIETTA CORPORATION

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MCR-92-1310
DRD MA-183-TH
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January 1992

Extended Mobility Unit Subcritical Liquid Oxygen Storage and Supply System (EMU SLOSSS)

Contract NAS9-18608

CONCEPTUAL DESIGN STUDY REPORT

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FOREWORD

This report documents work conducted by Martin Marietta Civil Space and Communications Systems under Contract NAS9-18608, EMU SLOSS Program, Task 1.0 - Conceptual Design Study. The contract is administered by the National Aeronautics and Space Administration Lyndon B. Johnson Space Center Houston, Texas. Mr. Chau Pham is the NASA program technical monitor. This report contains the data required under the Data Requirements List line item no. 3, DRD- MA-183-TH.

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ABSTRACT

The storage of life support oxygen in an Extravehicular Mobility Unit in the liquid state offers some advantages over the current method of storing the oxygen as a high pressure gas. In the first place, storage volume is reduced because of the increased density associated with liquid. The lower storage and operating pressures also reduce the potential for leakage or bursting of the storage tank. The potential for combustion resulting from adiabatic combustion of the gas within lines and components is substantially reduced. Design constraints on components are also relaxed due to the lower system pressures.

A design study was performed to determine the requirements for a liquid storage system and prepare a conceptual design. The study involved four separate tasks. The first was to identify system operating requirements that influence or direct the design of the system. The second task was to define candidate storage system concepts that could possibly satisfy the requirements. An evaluation and comparison of the candidate concepts was conducted in the third task. The fourth task was devoted to preparing a conceptual design of the recommended storage system and to evaluate concerns with integration of the concept into the EMU. The results of this study are presented in this report.

LIST OF ACRONYMS AND ABREVIATIONS

ACRONYM	MEANING
DAM	Double Aluminized Mylar
EMU	Extravehicular Mobility Unit
EVA	Extra-Vehicular Activity
GHe	Gaseous Helium
INSTEP	IN-Space Technology Experiments Program
IR&D	Internal Research and Development
JSC	Johnson Space Center
LAD	Liquid Acquisition Device
LCS	Liquid Cooled Shield
LO2	Liquid Oxygen
LOX	Liquid Oxygen
MLI	Multi-Layer Insulation
MMCAP	Martin Marietta Cryogenic Analysis Program
NASA	National Aeronautics and Space Administration
POS	Primary Oxygen System
QFD	Quality Functional Deployment
SLOSSS	Subcritical Liquid Oxygen Storage and Supply system
SOP	Secondary Oxygen Pack
TVS	Thermodynamic Vent System
VCS	Vapor Cooled Shield
VTRE	Vented Tank Resupply Experiment

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1.0 INTRODUCTION

Life support oxygen for use in the Space Shuttle Extravehicular Mobility Unit (EMU) is stored in high pressure gas containers and supplied to the oxygen ventilation system as required through regulators and control valves. Two separate supply system are provided in the EMU. A primary system provides oxygen for normal EVA operations, while a secondary system is available for an emergency purge operation in the event that a failure in the oxygen ventilation system or in the water cooling system should occur during the EVA. The initial storage pressure in the primary storage tank is nominally 6.2MPa (900 psia) while in the secondary system the initial pressure is 41.4 MPa (6000 psia). Even though the EMU performance has been excellent to the present time, there is a continuing concern regarding the safety associated with high pressure oxygen operations. Storage of oxygen in the liquid state (LOX) offers the possibility of lowering the system operating pressures which increases the handling safety by reducing the potential for leakage or bursting of storage tanks and lowering of the potential for combustion resulting from adiabatic compression of the gas. In addition, the design constraints on system regulators, valves and other system components are also reduced. The higher density of LOX can also result in a reduction of the storage system volume requirements. An example of the current use of LOX storage is in the medical profession in the treatment of patients requiring oxygen therapy. Small, portable oxygen tanks containing 1.4 kg (3.0 lbm) of liquid and capable of supplying up to 8 hours of oxygen gas are presently available that permit patients to perform daily activities. Oxygen vapor is withdrawn from the top of the tank. The vapor is then heated by ambient air in a coiled heat exchanger before it is delivered to the patient. Resupply of these tanks is provided by dewars containing 13.6 to 45.4 kg (30 to 100 lbm) of LOX that may be located in the patient's home. Although safety is still a prime concern, relatively simple procedures if applied with reasonable care can reduce hazardous conditions from occurring and make it practical to utilize oxygen in its liquid state on the ground. Storage of LOX in space applications can also be advantageous except there are two environmental factors that make the storage and supply process more difficult. The first of these is the absence of gravity to orient the liquid so that vapor only may be widthdrawn. For space operation; liquid, vapor, or a two phase mixture must be considered in supplying oxygen. Thermally conditioning of the oxygen to some minimum temperature also is a problem in space since ambient air is not available as a heat source. The Extravehicular Mobility Unit Subcritical Liquid Oxygen Storage and Supply System Program was initiated by NASA-JSC to evaluate these problems and investigate methods for utilizing liquid oxygen in the EMU.

This program consists of three phases, the first of which is a base contract to establish a liquid oxygen storage system conceptual design. Phases II and III are options to be exercised at NASA's discretion for continued development of the storage concept. Phase II will be devoted to development of a detailed design of the storage system concept developed in Phase I. Finally, Phase III will be devoted to fabricating a breadboard system and subsequent testing to verify system operation and performance. This report presents the results of conceptual design study conducted during the first phase which was conducted during a four month period. The first task performed during this time was to establish system requirements. Candidate storage concepts that might satisfy these requirements were then defined. An evaluation phase was then performed on the candidates leading to a recommended system for further analysis and design. The last effort during this study was to establish a conceptual design for a breadboard test system. The results of these tasks are presented in the following sections.

2.0 SYSTEM REQUIREMENTS

The first task to be performed during the study was to establish system design requirements. A review of the system interface and performance requirements as presented in the contract statement of work was initiated. Some changes or additions were included to the original requirements as a result of discussions at the program kick off meeting at the Johnson Space Center on October 21, 1991, and subsequent teleconferences with the Program Technical Monitor. The final requirements are presented in the following Tables 2-1 and 2-2. For system performance, these changes include the addition of emergency purge flow rate and delivery pressure and an increase in maximum oxygen delivery pressure from 15.56 C (60 F) to 23.33 C (74 F). For the system interface requirements, a range for the available cooling water flow rate for thermally conditioning the oxygen was given as 70.5 to 109.1 Kg/hr (155 to 240 lb/hr). The minimum cooling water temperature was also lowered from a value of 20.6 C (69 F) to 12.2 C (54 F). One other interface requirement that was not specified in the contract statement of work is the acceleration environment.

Table 2-1 EMU LOX Storage System Performance Requirements

PARAMETER	BREADBOARD MODULE VALUE		FLIGHT-LIKE SYSTEM VALUE	
O2 Delivery Flow Rate	Kg/Hr	Lbs/Hr	Kg/Hr	Lbs/Hr
Minimum	0.023	0.05	0.023	0.05
Normal	0.074	0.164	0.074	0.164
Maximum	0.227	0.5	0.227	0.5
Emergency Purge	2.682	5.9	2.682	5.9
O2 Delivery Pressure	KPa	Psia	KPa	Psia
Minimum	27.58	4.00	27.58	4.00
Normal	57.23	8.30	57.23	8.30
Maximum	517.11	75.00	517.11	75.00
Emergency Purge	48.26	7.00	48.26	7.00
O2 Delivery Temperature	C	F	C	F
Minimum	-162.22	-260.00	-162.22	-260.00
Maximum (Preferred)	15.56	60.00	15.56	60.00
Maximum (Allowable)	23.33	74.00	23.33	74.00
O2 Operating Time	Hours	Hours	Hours	Hours
Normal EVA(@ 8.3 psia)	8.00	8.00	8.00	8.00
Emergency Purge	0.50	0.5	0.50	0.5
Leakage to Ambient	Kg/Hr	Lbs/Hr	Kg/Hr	Lbs/Hr
	4.54E-05	<0.0001	4.54E-05	<0.0001
Boil-off to Ambient	Kg/Hr	Lbs/Hr	Kg/Hr	Lbs/Hr
	Minimum	Minimum	Minimum	Minimum

Environmental acceleration due to drag on the Space Shuttle is normally 10^{-5} to 10^{-8} g with values as high as 10^{-2} during thruster firings. An estimate of the maximum acceleration in the EMU due to astronaut movement during an EVA was 0.125 g.

Contact was made with four commercial suppliers of portable liquid oxygen systems used by medical patients requiring oxygen therapy. These contacts were to investigate requirements and design concerns that might be common to the EMU application. The approach to thermal storage is similar in that vacuum jackets employing multi-layer insulation (MLI) and getter material are included in the tank design. Since gravity is present to orient the liquid, only vapor is withdrawn from the tank. There is a need to condition the cold vapor to ambient temperature. This is accomplished by tubular heat exchangers exposed to ambient air. Gaging appears to be accomplished by differential pressure measurements or by weighing.

Table 2-2 EMU LOX Storage System Interface Requirements

PARAMETER	BREADBOARD MODULE VALUE		FLIGHT-LIKE SYSTEM	
External Ambient Pressure	KPa	Psia	KPa	Psia
Minimum	0	0	0	0
Maximum	102.73	14.9	102.73	14.9
External Ambient Temperature	C	F	C	F
Minimum	1.7	35	1.7	35
Maximum	29.4	85	29.4	85
Available Cooling Water				
Flow Rate	Kg/Hr	Lbm/Hr	Kg/Hr	Lbm/Hr
	70.5-109.1	155-240	70.5-109.1	155-240
Temperature	C	F	C	F
	12.2-23.3	54-74	12.2-23.3	54-74
Acceleration	G		G	
Environmental	0.0001-0.001		0.0001-0.001	
Astronaut Movement	0.125		0.125	

3.0 CANDIDATE CONCEPTS

After the system requirements were established, a review of possible candidate storage and supply systems was begun. From this review, a total of sixteen concepts were generated that appeared to be possible configurations for the EMU LOX storage and supply system. Fifteen of these are subcritical systems that trade between supplying vapor only, a mixture of liquid and vapor, or liquid only. The sixteenth concept is a cryogenic supercritical system that will supply a supercritical gas to the EMU and was included as a basis for comparison with the liquid storage concepts. Table 3-1 describes the concepts in detail and they are schematically represented in Figures 3-1 through 3-16.

Table 3-1 Configuration Concepts Reviewed

1) Conventional TVS system providing vapor flow only

2) Conventional TVS system providing constant vapor flow rate (fixed restriction to accommodate parasitic heat leak) with extra flow provided by liquid

3) Vane liquid acquisition system with direct venting providing vapor flow only

4) Vane liquid acquisition system providing constant vapor flow rate (matched to parasitic heat leak) with liquid flow providing added mass flow

5) Magnetic liquid orientation system providing direct vapor venting

6) Magnetic liquid orientation system providing constant vapor flow rate (matched to parasitic heat leak) with liquid flow providing added mass flow

7) Magnetic system providing liquid only flow into liquid cooled shield

8) Liquid outflow only provided by liquid acquisition system

9) Fluid system without liquid acquisition or orientation with electric heater control to maintain pressure (supplies liquid, vapor, or two phase flow)

10) Collapsing bladder system with external helium pressurization system

11) Expanding bladder system with external helium pressurization system

12) Diaphragm system with internal pressurization (blowdown system)

13) Diaphragm system with external pressurization system

14) Metal bellows system with internal pressurization

15) Metal bellows system with external pressurization

16) Supercritical storage and outflow with electric power to develop and maintain pressure

Configuration 1, the thermodynamic vent system (TVS) concept, employs throttling of a saturated liquid through a restrictor to reduce the pressure (and thereby the fluid temperature). The throttled fluid is then routed through a heat exchanger that is either attached to the wall or is in contact with the bulk liquid. The two-phase fluid flow is boiled in the heat exchanger resulting in vapor exiting the tank. This concept is required for vapor venting due to the random orientation of the liquid under low-gravity conditions. If the tank vent valve were opened there is a high likelihood that liquid will vent instead of vapor. The TVS therefore provides a means to ensure that vapor will exit the tank in a low-g environment. The primary disadvantage of this concept is that the fixed restrictor used to throttle the liquid will have only a small operating range of flow rates. Therefore an active, variable area restrictor must be used to provide for a greater range of flow rates. In addition, this type of system has a lower reliability and is difficult to develop. To get around this constraint, configuration 2 was conceived to allow for the nominal flow to be supplied by the vapor with the extra flow to be provided by liquid outflow as required. This concept has the disadvantage of requiring active flow control that will respond to system demand requirements.

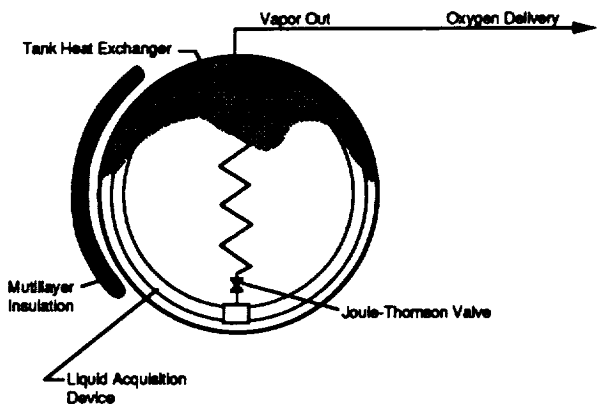

Figure 3-1 Configuration #1 Schematic

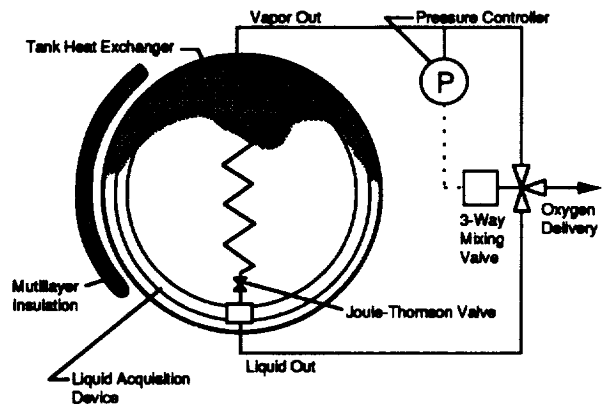

Figure 3-2 Configuration #2 Schematic

Another possibility for controlling liquid position in a low-g environment is to use a system of vanes, as in configurations 3 and 4, that will provide a large enough capillary force on the liquid to ensure that it can be positively located within the tank. The vane system can be designed to locate the liquid over the tank outlet allowing for liquid free venting to occur. This concept can accommodate a larger vent rate range and therefore may be more attractive than the TVS systems. If the vent rate for the system is too large though, the tank pressure will drop very fast. On the other hand, liquid outflow from the tank will not affect the tank pressure as quickly. That is because the liquid outflow will simply reduce the liquid volume, not the fluid energy. To accommodate this aspect the mixing concept presented for the TVS system is also proposed here as shown in configuration 4. The vane system does have a few disadvantages. The first is that vane technologies are still experimental and while capillary vanes have been flown in space to provide liquid acquisition for thrusters, they have not been used in vent systems. This technology area will be investigated in the Vented Tank Resupply Experiment (VTRE) program which is being funded through NASA's IN-Space Technology Experiments Program (INSTEP) organization. The vanes also have such a small capillary pumping force that they cannot be verified in a one-g test. The only methods presently available to evaluate a vane design are to perform drop tower testing, KC-135 flight tests, or an orbital experiment. Finally, the low level of capillary forces produced by the vanes means that any extraneous accelerations imparted onto the system by the astronaut or other sources could result in liquid slosh and loss of liquid position control in the tank. It would also be advantageous for the tank system to impose the minimum amount of operational constraints on the astronaut, so the use of vanes may not be optimal.

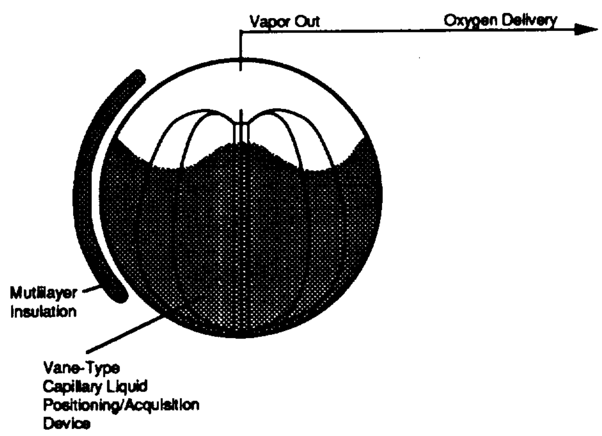

Figure 3-3 Configuration #3 Schematic

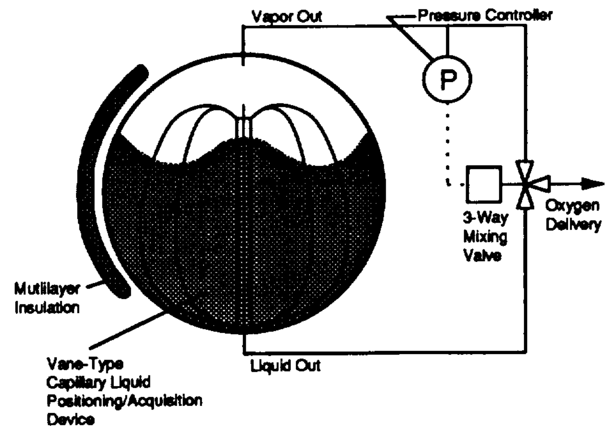

Figure 3-4 Configuration #4 Schematic

The magnetic liquid acquisition concepts (configurations 5 through 7) are similar to those proposed for the vanes except that liquid position control is established and maintained by a magnetic field. Configuration 7 also uses a magnetic field to position the liquid but provides liquid flow only to the liquid cooled shield. Liquid oxygen possesses magnetic characteristics that could possibly be used to provide orientation and control of the liquid by location of a magnet near the tank outlet. If the magnet can position the oxygen as the vanes would, then the same two concepts proposed for the vanes could be used. The magnetic forces required to position the liquid are unknown and therefore the size of the magnet required is unknown. This technology is currently being investigated by an in-house research project and is being monitored closely. The other acceleration aspects of the vane system will apply here also, except that there is a possibility of using the magnetic field to gauge the amount of the liquid in the tank. The idea would be to wrap the tank with coil and to measure the inductance of this coil. The inductance will be a function of the amount of liquid in the tank and other items. If the system can be adequately calibrated, then the inductance will give a measure of the tank liquid contents. This gauging aspect is also being investigated in the in-house research project.

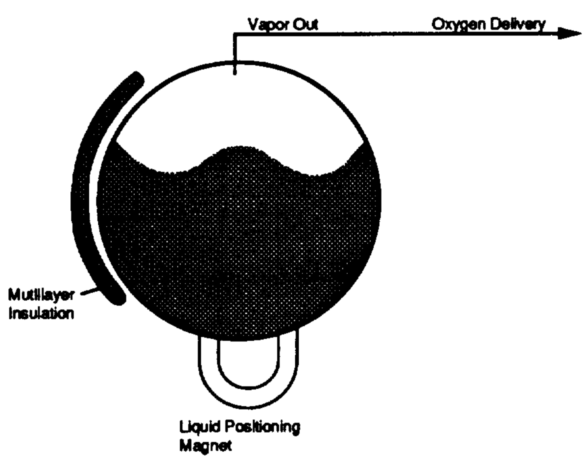

Figure 3-5 Configuration #5 Schematic

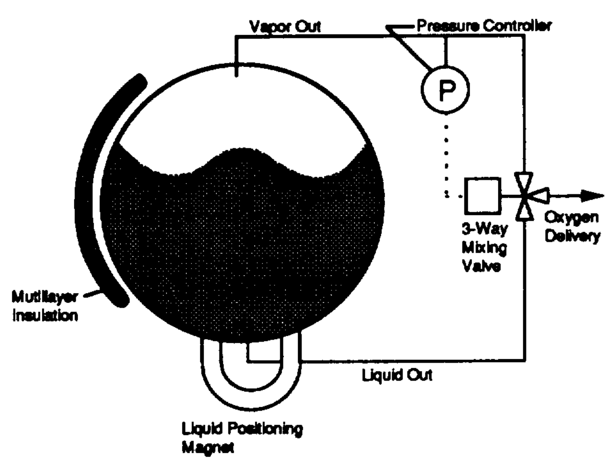

Figure 3-6 Configuration #6 Schematic

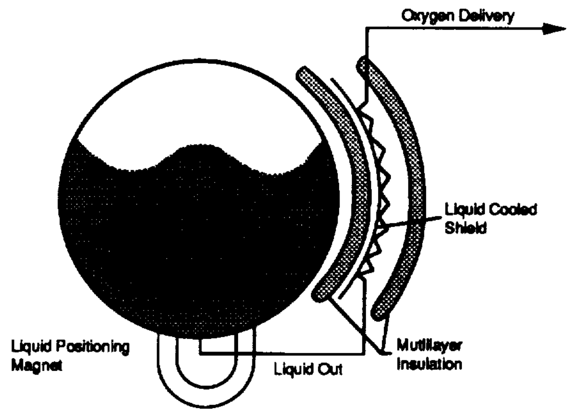

Figure 3-7 Configuration #7 Schematic

The rest of the concepts do not rely on low-g venting techniques since liquid free vapor outflow is not required. Concept 8 withdraws only liquid from the tank. The drawback to this is that the tank pressure will continue to rise during the outflow for the same reasons stated previously. If the tank pressure rises too high, then the relief system will open resulting in a loss of liquid from the tank. The tank pressure can be controlled if the heat leak into the tank is reduced significantly (to a point that the vapor volumetric boiloff rate is lower than the liquid volume reduction rate). The only way to reduce the heat leak into the tank is to boil the outflow on a liquid cooled shield (LCS). The LCS is similar to a vapor cooled shield (VCS) except that the inlet fluid is liquid. The heat leak into the tank is intercepted by the LCS and is used to boil off the outflow liquid. If the flow rate is high enough, the LCS will cool to liquid temperature and the resultant heat leak into the tank will reduce to nearly zero. This concept also has the advantage of being self regulating, in that the flow rate can be controlled downstream of the device and does not require an active flow control network (as would be required for the mixing valve concepts). The design aspects of the LCS make this a somewhat more complex system, but tanks have been constructed with this concept that have performed as the design required. This concept does require a system for acquisition of liquid to provide vapor free outflow to the LCS. A small capillary channel LAD could be easily designed and manufactured to provide for this capability. The capillary retention forces that are produced by a channel LAD are much greater than those produced by a vane system therefore alleviating the acceleration problems that the vane have. Channel type LADs may only be used for liquid acquisition though (not liquid position control) so they cannot be used in the same manner as the vanes are.

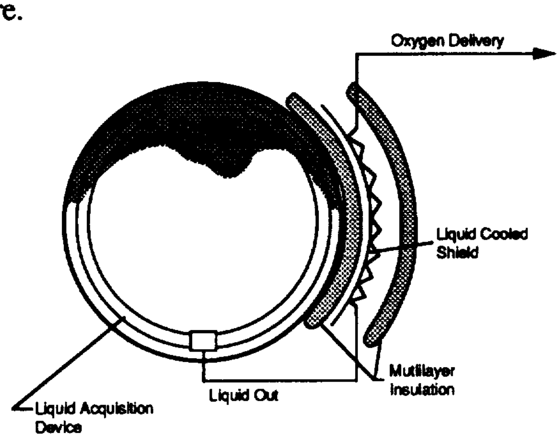

Figure 3-8 Configuration #8 Schematic

It is possible to design the system to allow for either liquid or vapor to exit the tank, as in configuration 9, thereby deleting the need for either a liquid positioning device or a liquid acquisition device. The system must also have a LCS to accommodate long term liquid outflow. If it is designed with an LCS, then the pressure will drop substantially if vapor were to exit the tank (since the heat leak into the tank will not be great enough to account for the loss in fluid energy). To accommodate the affect of vapor venting, a tank heater will have to be included into the system. The heater will be used to provide a constant tank pressure during outflow. The heater power level will be very low (or off) while liquid is venting, but it will have to quickly increase in power if vapor were to vent. This system would be simple to build and easy to validate, but there are certain control and safety issues associated with the heater. The extra power required for the heater is also one major disadvantage.

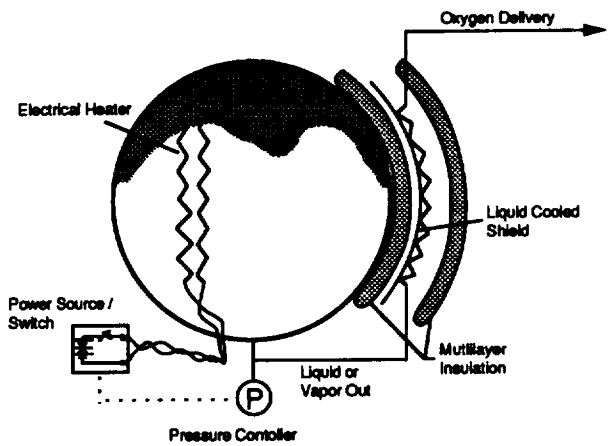

Figure 3-9 Configuration #9 Schematic

Configurations 10 and 11 are bladder systems employing polymeric material to separate liquid and gas and provide positive expulsion of the liquid from the tank. Two methods of applying the bladder concept are possible. The collapsing bladder system shown as Configuration 10, contains the liquid oxygen inside the bladder which is expanded to the tank walls. Injection of pressurant into the tank and outside of the bladder forces liquid through a standpipe into the outflow line. The bladder material is compressed around the standpipe. The second bladder configuration is called an expanding bladder system and is identified as Configuration 11. The bladder material is initially compressed about the standpipe with the liquid oxygen located in the tank outside of the bladder. Introduction of the pressurant into the bladder through the standpipe causes the bladder to expand, forcing the liquid from the tank into the outflow line. Both systems require an external pressurant gas source for actuation. The gas must be non-condensible therefore helium will be used.

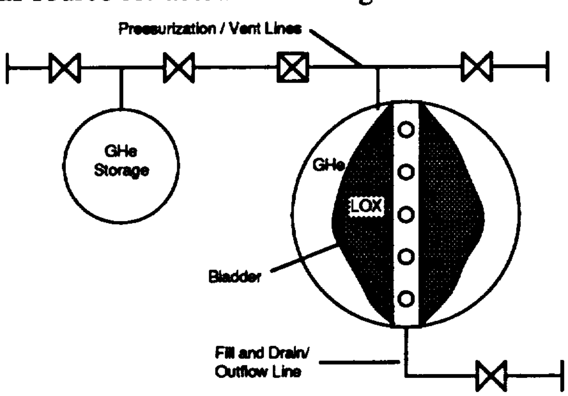

Figure 3-10 Configuration #10 Schematic

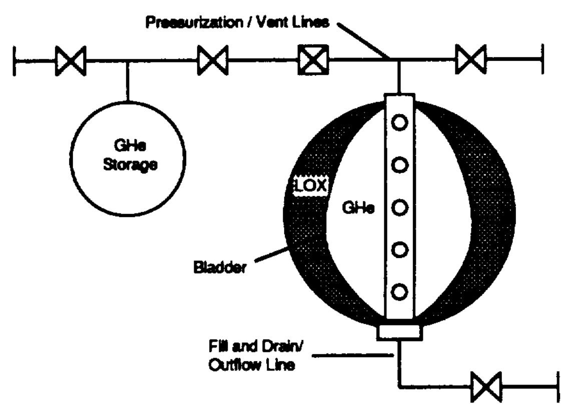

Figure 3-11 Configuration #11 Schematic

Configurations 12 and 13 also employ polymeric material for separation of liquid and ullage gas, and are called diaphragm systems. In Configuration 12, the required amount of liquid is loaded into the tank under the diaphragm. The volume above the diaphragm is then pressurized to some initial value and then locked up. Expulsion is provided by expansion of the pressurant and is referred to as a blowdown system. The second approach shown as Configuration 13 employs an external pressurant storage and regulation system for pressure control during expulsion. The entire storage tank will be filled with liquid except for a small ullage volume for initial pressurization.

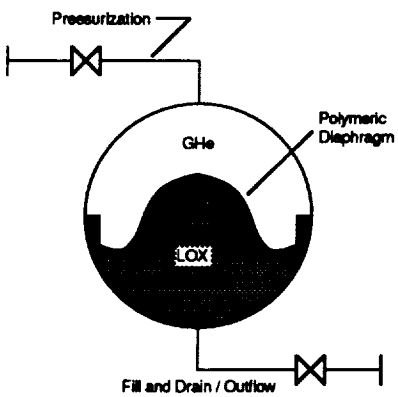

Figure 3-12 Configuration #12 Schematic

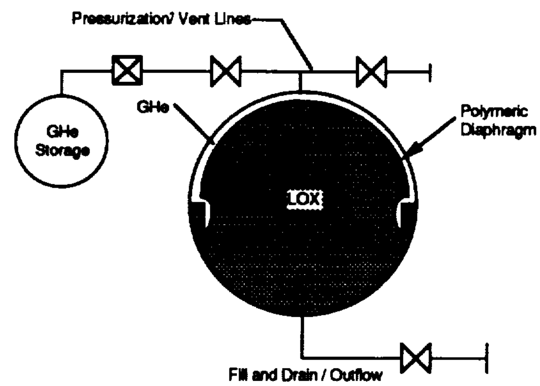

Figure 3-13 Configuration #13 Schematic

Configurations 14 and 15 employ metal bellows to provide expulsion. In both concepts the liquid oxygen is stored on the inside of the bellows and the pressurant is on the outside. The pressurant is used to compress the bellows thereby forcing liquid oxygen out of the tank. Configuration 14 depicts the pressurization system as being an integral part of the LOX tank (thereby reducing heat transfer to the liquid), while in configuration 15 the helium gas is stored in an external tank set.

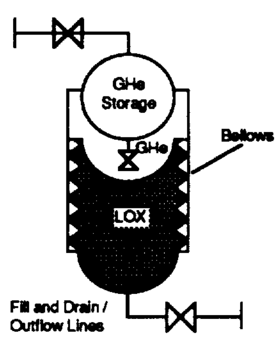

Figure 3-14 Configuration #14 Schematic

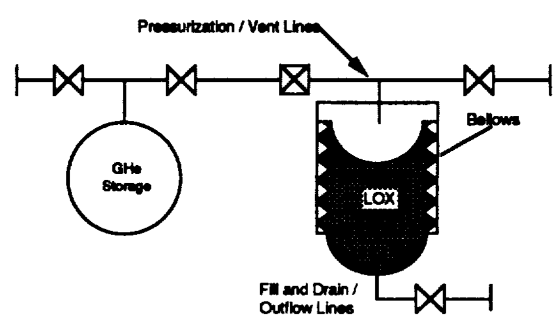

Figure 3-15 Configuration #15 Schematic

The last option, configuration 16, is to store the oxygen as a cold, high pressure gas. Since the oxygen is loaded in the liquid state and then allowed to warm to supercritical conditions, the tank system would be the smallest possible configuration due to the high density of the fluid. Due to the fact that a supercritical fluid is homogeneous the need for liquid acquisition or positioning control are deleted also. There are certain disadvantages to this system though. The first is that the tank pressure will have to be nearly as high as the present EMU gas tanks since the critical pressure of oxygen is 5.047 mPa (731.4 psia). The high pressure required will result in a tank system that weighs much more than the subcritical concepts, and the actual volume reduction will be minor. Finally, a supercritical system also requires a heater (and the associated issues that go along with one) to maintain a constant tank pressure during outflow.

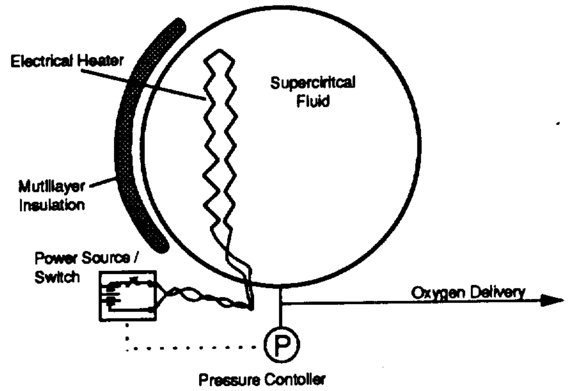

Figure 3-16 Configuration #16 Schematic

4.0 CONFIGURATION TRADE ANALYSIS

To determine the optimal configuration for the Extravehicular Mobility Unit (EMU) Subcritical Liquid Oxygen Storage and Supply System (SLOSSS) LOX tank system a trade analysis was conducted of the 16 configurations that were developed. This trade study was conducted in two phases. The first review was on a top level and simply screened the configurations in an attempt to determine which options were thermodynamically possible and which were not. After the initial screening a more detailed trade study of the remaining configurations was conducted. This trade study rated the final configurations in each of 11 different categories. The 11 categories were broken down into sub-categories to allow for an objective review of the designs and a final relative rating factor was then determined. The results of this trade defined the optimal storage system configuration from which the system design would be generated.

4.1 Initial Configuration Screening

An initial screening of the 16 configurations developed and presented in section 3.0 was conducted to determine which concepts were undesirable from a thermodynamic or a producibility point of view. The first analysis looked at the thermodynamics behind the liquid storage and outflow processes. This review determined that the vapor only concepts were not thermodynamically possible without the addition of extra heat into the cryogen. A further look at the producibility of the systems concluded that other options should be deleted from the final review list.

4.1.1 Thermodynamic Analyses -

The EMU LOX oxygen supply flow will be provided by outflow from a subcritical liquid oxygen tank. There are many concepts for providing the warm gaseous oxygen to the astronaut, which were documented in section 3.0 of this report, but they all consist of a system in which subcritical oxygen (either liquid or vapor) is drawn off of a tank, warmed to the required operating temperature in a forced convection heat exchanger, and supplied to the astronaut in the same manner as the present EMU gaseous oxygen flow is. The major difference between each concept is the manner by which the oxygen is withdrawn from the tank (i.e. using capillary positioning devices, an LAD, a bellows, etc.) Each of these concepts fall into one of three categories. The first is where cold vapor only is withdrawn from the tank. The concepts of TVS, capillary vane device, and magnetic liquid position control fall into this category. The concept is to control the liquid position so that the ullage can be located near the vent pipe of the tank. In this case, vapor can be withdrawn just as it is done in a one-g environment. In the second category, only liquid oxygen is removed from the tank and boiled on a liquid cooled shield. The concepts of a LAD, a bellows, or any other positive expulsion device fall into this category. The liquid cooled boiler shield will be required to reduce the heat leak into the cryogenic tank, thereby allowing for control of the tank pressure. The third category is to use the concepts outlined in category 1 to provide for a constant vapor outflow from the tank (to provide for tank pressure control) while the demand flow rate will be provided via liquid outflow. This combination of the two previous options allows for a wide range of operating flow rates while deleting the need for the liquid cooled shield to boil the liquid outflow. The drawback to this concept is the associated extra complexity and components required to provide for both gaseous and liquid outflow. From a thermodynamic point of view this option can be modeled the same way as the liquid only outflow case.

The first law of thermodynamics can be used to accurately model the pressure response of any subcritical cryogenic fluid system. The main limitation to this approach is the amount of modeling detail that must be undertaken to account for an thermal stratification that could develop in the fluid. Thermal stratification results when there is excess energy storage in one part of the liquid or gas (i.e. liquid near the tank walls or the liquid/vapor interface). To account for this the tank fluid must be modeled as a collection of numerous nodes, each at a different temperature. The solution of such a thermal network is very difficult since heat is transferred in a cryogen via fluid convection, requiring an accounting of mass transport between each node of the model. If the fluid is not stratified (i.e. all of the liquid and vapor in the tank is nearly isothermal) then the system can be modeled with one liquid and one gas node. The amount of mass and energy bookkeeping for this system is greatly reduced and the fluid can be treated as a two-phase solution of liquid and vapor. Since the pressure is only a function of temperature (and vice versa) for a two-phase mixture, then a simple energy balance of the two node system can be used to predict the pressure history of the tank.

The major drawback to this simplified analysis approach is the ease with which a cryogenic system will stratify. There are a few items inherent in the design of the EMU LOX tanks though that lead to the conclusion that thermal stratification will be very insignificant. The first is the size of the tanks. Thermal stratification is more of an issue the bigger the tank becomes. Since the EMU tanks will be much less than 3 liters (0.1 cubic feet) in volume the allowable thermal stratification will be greatly reduced. The fact that the tank walls will be relatively thick compared to the tank diameter leads one to believe that there will be more conduction of heat circumferentially around the tank wall. Therefore if one end of the liquid does become hotter than another portion, this excess heat will be easily transported throughout the tank wall, thereby reducing the amount of thermal stratification. Finally, the liquid could easily be agitated by the motion of the astronaut or by the simple act of outflowing the fluid. If the fluid becomes agitated the internal convection coefficients will increase, thereby mixing the tank and reducing the thermal stratification.

The first law of thermodynamics can be used to model a two-phase liquid/vapor mixture in a non-stratified cryogenic tank with external heat input. The first law states that energy is conserved, therefore any heat input into the fluid will either end up as energy storage in the fluid (with the associated temperature and pressure increase of the tank fluid) or must be removed from the tank via the outflow of either liquid or vapor. This is schematically presented in Figure 4.1-1 below, which shows the heat input to the tank, the two fluid nodes, and the exiting fluid flow. The Figure also shows the sign convection that positive heat flow will be into the tank. This sign convention will be used throughout all of the equations that are presented in this report.

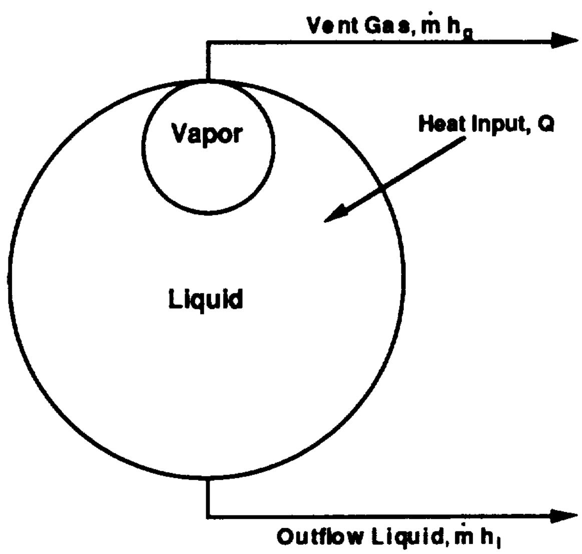

Figure 4.1-1 - Thermal System Schematic

As can be seen in the Figure, there are two fluid exit paths. This is to account for the difference between liquid exiting or vapor exiting. In reality only one of these fluid species will exit the tank at any time, with the difference being the enthalpy of the exiting fluid. There are two equations that define this system, the first being the conservation of mass relationship and the other being the conservation of energy. The mass conservation equation is shown below.

$$1) \qquad m_1 = m_2 \text{ or } m_{g1} + m_{l1} = m_{g2} + m_{l2} + m_{exit}$$

where : m is the fluid node mass,
the g and l subscripts refer to the gas and liquid phases respectively,
and the 1 and 2 subscripts refer to the initial and final states of the system.

The conservation of energy equations are detailed below.

$$2) \qquad m_2 u_2 = m_1 u_1 + m_{exit} h_{exit} + Q$$

$$\text{or } m_{l2} u_{l2} + m_{g2} u_{g2} = m_{l1} u_{l1} + m_{g1} u_{g1} + m_{exit} h_{exit} + Q$$

where : m is the fluid node mass,
u is the fluid internal energy,
h is the exit fluid enthalpy (gas enthalpy for venting, liquid enthalpy for outflow),
Q is the heat transferred into the tank,
the g and l subscripts refer to the gas and liquid phases respectively,
and the 1 and 2 subscripts refer to the initial and final states of the system.

By simultaneously solving these two relationships the system pressure response to liquid outflow can be modeled. This equation has many variables but only one unknown, the final pressure of the tank at time 2 for a given set of initial conditions, tank heat flux, and fluid outflow rate. By assuming a pressure, calculating the internal energy of the liquid and gas phases at that new pressure, and then solving the relationship for the new set of masses; the final pressure of the system can be determined in an iterative manner. The iterative solution is required due to the formulation of the equations. Using derivatives of the fluid properties, a fully explicit relationship can be generated. The solution of the set of iterative equations is very simple though and is therefore the preferred approach.

There are special equations that will result if limiting assumptions are made. The first case is if there is no fluid outflow from the tank, i.e. the tank is "locked up". During this time the tank will self pressurize at a rate dependent on the fluid masses and the heat rate into the tank. The relationship describing this process is simply the one presented below.

$$m_{l2} u_{l2} + m_{g2} u_{g2} = m_{l1} u_{l1} + m_{g1} u_{g1} + Q$$

where : m is the fluid node mass,
u is the fluid internal energy,
Q is the heat transferred into the tank,
the g and l subscripts refer to the gas and liquid phases respectively,
and the 1 and 2 subscripts refer to the initial and final states of the system.

This equation is solved the same way as the the previous ones with the exception that there is no input of an exit flow rate.

Another simplified cases is where the fluid exiting flow rate will be at a point that will just offset the heat influx to the fluid. In this case the system pressure will remain constant and the energy equation (#2) simplifies to the following relationship.

$$m_{l2} u_l + m_{g2} u_g = m_{l1} u_l + m_{g1} u_g + m_{exit} h_{exit} + Q$$

This new equation does not seem very simplified, but the fact that the pressure remains constant allows for the fluid properties to remain constant from time 1 to time 2. This fact coupled with the fact that for a small flow rate of vapor only the gas volume will only slightly change, allowing the gas mass change to be neglected. This relationship then simplifies to the one shown below which is only valid for vapor venting. For the case of liquid outflow from a tank the general form of the equations must be used since most of the pressure reduction is due to the ullage expansion and not the removal of energy.

$$m_{exit}(h_g - u) = Q$$

where : m is the fluid node mass,
u is the fluid internal energy,
h is the exit fluid enthalpy (equal to the vapor enthalpy),
Q is the heat transferred into the tank,
and the g and l subscripts refer to the gas and liquid phases respectively.

These three sets of equations (the general case, the zero outflow case, and the constant pressure case) can all be used to model the tank pressure response. A set of parametric runs was conducted to determine the impacts that the choice of outflow will have on the tank pressure response of the system. These analyses are detailed in the following paragraphs.

The first analysis looked at the pressure rise rate of the system during tank lockup. This situation will correspond to the time after the system has been filled with LOX but the oxygen flow is not required. The lockup relationships were used to parametrically determine the pressure rise rate for a heat input of 1 Watt. The value of 1 Watt was chosen to allow for easy scaling of the results to the actual heat leak of the EMU SLOSSS system. This approach allowed a design goal heat leak to be determined to meet the desired minimum hold period of 8 hours. It was assumed that the tank would be filled at 586 kPa (85 psia) to allow for use of the system immediately after filling with LOX and that it would begin to vent at 931 kPa (135 psia). Therefore the insulation system of the LOX tank must be designed so that the heat leak will be lower than the value that would result in a rise from the lower to the higher pressure in 8 hours. For example, if 5 watts of heat input will raise the tank pressure from 586 kPa to 931 kPa in 4 hours, this value of heat leak would be too great for the system and the design goal would be a heat leak of 2.5 Watts.

The tank pressure rise rate is determined only by the heat input and the amount of fluid mass in the tank. There were three proposed tank sizes to deal with. The first one was the size given in the proposal. The original concept was to size the tank to provide 8 hours of nominal oxygen flow and to provide for a 1/2 hour purge flow of 0.227 kg/hr (0.5 lbm/hr). These requirements resulted in a tank that was 0.94 liters in volume (0.033 ft^3) with a loaded tank mass of 4.29 kg (1.95 lbm). A further look at the requirements though determined that the purge flow would have to be increased to 2.68 kg/hr (5.9 lbm/hr). This resulted in a tank that was 2.4 liters in volume (0.085 ft^3) with a loaded tank mass of 2.39 kg (5.26 lbm). The second tank size has one drawback though. It is larger than the present Primary Oxygen System (POS) tanks. A third option was then generated. This tank would be designed to provide the 2.68 kg/hr purge flow rate but for only 15 minutes. Since the system will have two LOX tanks for redundancy, then the total 1/2 hour purge flow requirement could be met via the use of both tanks (as is presently done with the EMU purge system). The third option then was a tank 1.56 liters in volume (0.055 ft^3) with a loaded tank mass of 1.54 kg (3.40 lbm). This option allows for total redundancy in the nominal mode and will also accommodate the purge requirements. A look at the possible causes for a high flow purge rate concluded that there are no failures that could be caused by the LOX subsystem that would result in a need for the purge flow rate. Therefore it would take two failures to have the need for the high purge flow rate and the inability to achieve outflow from both tanks. If one tank were to go off line, the other could provide the required nominal oxygen flow rate (or greater) to get the astronaut back to a safe location. This option also has the added benefit of being the same size of a tank as the present POS tanks. Therefore this size tank could be easily integrated into the existing EMU test bed, and secondary system could still be retained in initial systems to provide for a backup in case of a failure of the LOX subsystem. Since the decision on the tank size has not been finalized as of yet analyses were conducted for the last two options presented. The small tank option was not analyzed due to the fact that it was sized for a purge flow rate that was too small.

The results of the first set of analyses is presented in Figure 4.1-2 below. In this plot the pressure rise versus time for a heat leak of 1 Watt is presented. The two curves represent the two tank sizes analyzed. As predicted, the smaller tank will have a faster pressure rise rate. The smaller tank will rise to the vent setting in about 6 hours while the larger tank will reach this point after ~9.5 hours. This is in good agreement with the previously presented equations for pressure rise since the larger tank is ~ 50% larger than the smaller one. The predicted heat leak into the tank will be less than 0.5 Watts (1.75 Btu/hr) so the actual hold time after filling will be at least two times greater than the values shown here (and probably three or four times longer). Therefore either tank will be capable of reaching the required 8 hour hold time from filling to use of the system.

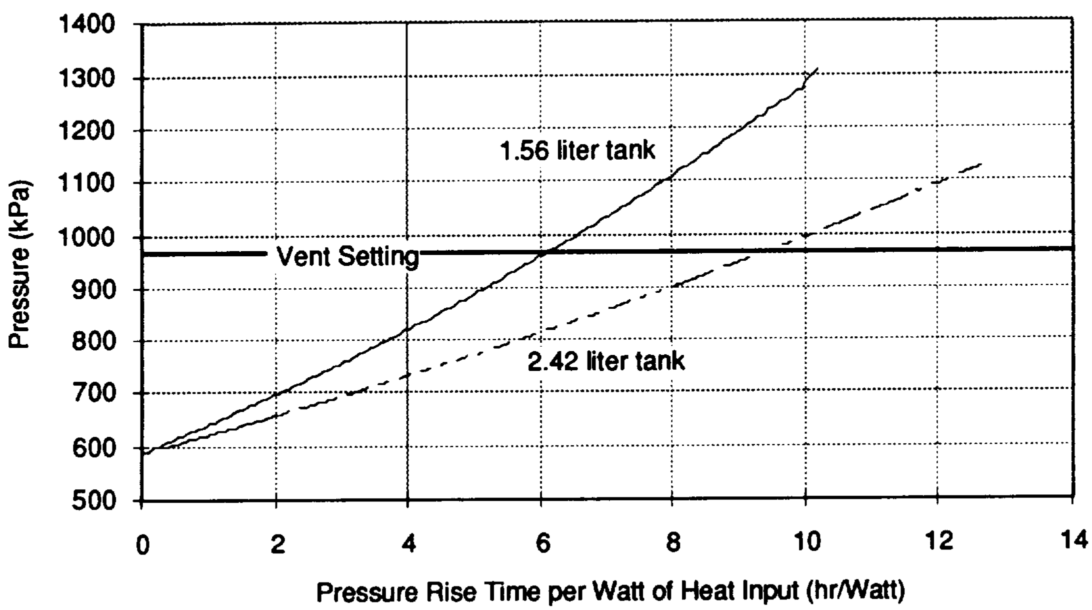

Figure 4.1-2 - Tank Pressure Rise for a Heat Leak of 1 Watt

The next analysis looked at the flow required to maintain a constant pressure for a fixed heat leak into the tank. The two previously discussed tanks were modeled with a heat leak of 1 Watt. Two cases were run for each tank, one with liquid outflow and one with vapor venting. The results of these analyses are presented in Figure 4.1-3. In this Figure the flow rate required to maintain a constant tank pressure is presented over the range of operating pressures. As can be seen from the plot there are only two curves, one for vapor venting and one for liquid outflow. This is because the vent rate or liquid outflow rate to maintain a constant tank pressure, for a fixed flow rate and tank liquid fill level, are independent of the tank volume. A quick review of the energy equation shows this to be true. For a fixed tank fill level the ratio of the liquid mass to the vapor mass is also fixed. If this ratio is fixed and the fluid properties are constant, then the required mass flow rate exiting the tank will remain constant. This result is especially well exampled by the special equation developed for vapor venting. This equation only relates the exiting mass flow rate to the input heat rate and does not account for any variation in the heat leak with the flow rate.

The plot shows that vapor venting is a much more efficient method of removing heat from a cryogenic tank. The predicted liquid outflow rate is much higher than the required vent rate, but this conclusion was expected. The results of this plot show that if the liquid flow is not used to intercept some of the heat leak, via the use of the liquid cooled shield (LCS), then pressure control for that tank will be very hard to obtain. If the previous maximum heat leak of 0.5 Watt is used here, then the vapor flow system will have a required boiloff rate of ~.001 kg/hr while the liquid system will have to outflow between .02 and .035 kg/hr (a value 20 to 35 times the vapor venting system). The liquid system will be come comparable to the vapor venting system if the net heat leak into the tank can be reduced to a value 10 to 35 times lower than the expected system performance. This can be accomplished via the use of a liquid cooled shield where the boiling of the liquid flow in a heat exchanger attached to the LCS will intercept much of the external heat leak before it has a chance to enter the tank.

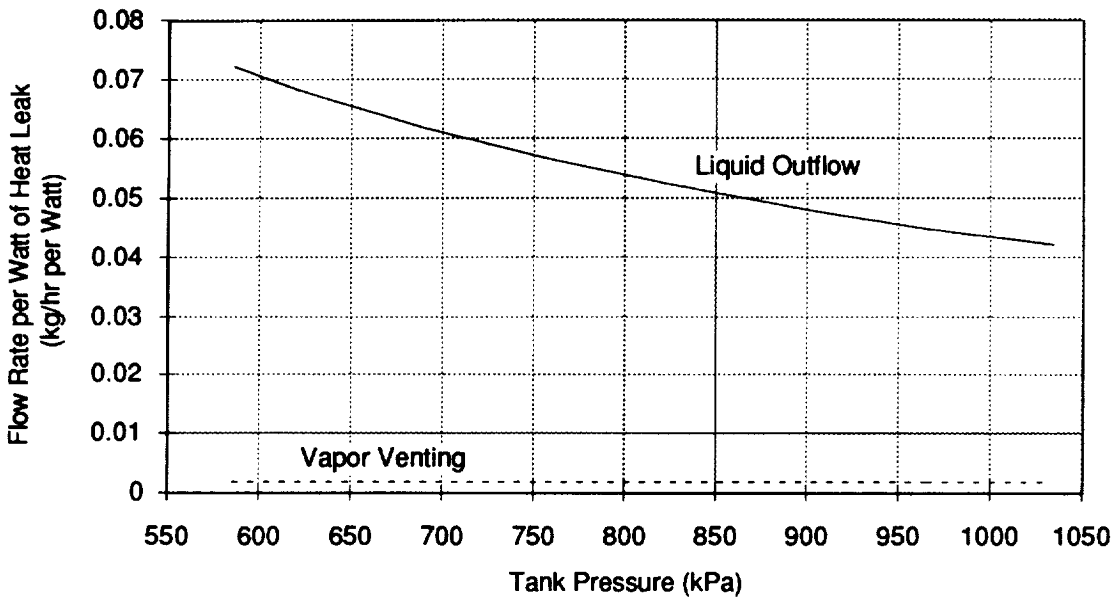

Figure 4.1-3 - Flow Rates Required to Maintain a Constant Tank Pressure for a 1 Watt Heat Leak

The tank pressure will decay during outflow if the flow rates exceed those required to offset the pressure rise due to the external environmental heating. To maintain a constant tank pressure excess heat could be applied to the fluid. In this case, a heater would be imbedded in the tank or would be mounted on the outside of the inner tank, thereby providing a good thermal contact with the fluid. An analysis was conducted to determine requirements for the heater power levels. This analysis consisted of simply scaling the previous results to determine the power required for a flow of 1 kg/hr. The results could then be scaled by the ratio of flow rates. The results are presented in Figure 4.1-4 which shows the required power for liquid outflow and vapor venting.

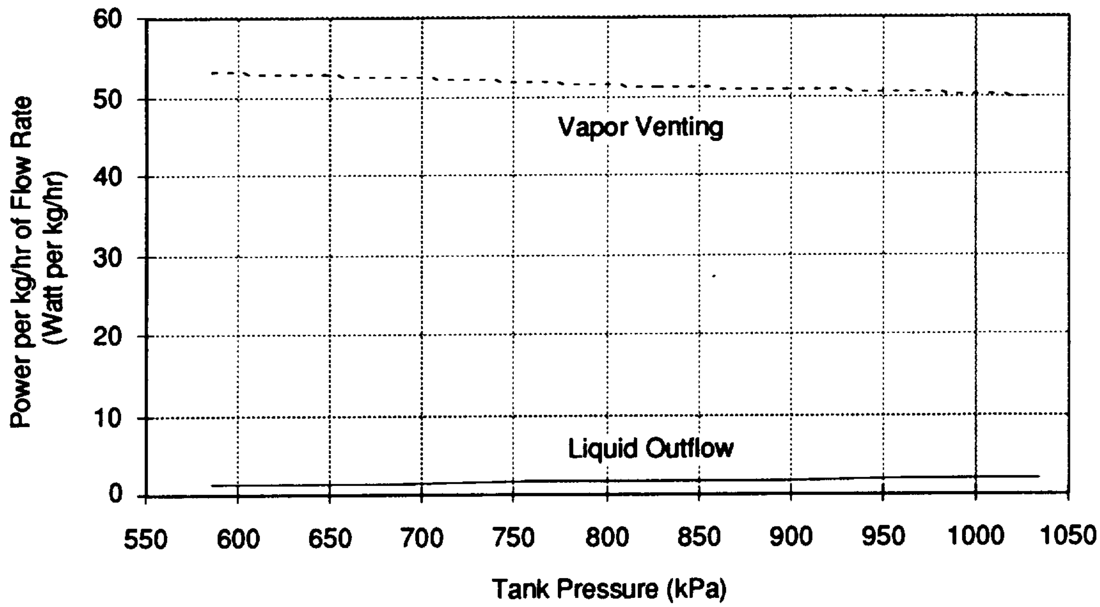

Figure 4.1-4 - Required Power to Maintain Constant Tank Pressure for a Vent Rate of 1 kg/hr

This curve shows that the vapor venting concept will require much more heat than the liquid outflow method. Another option is to allow for either liquid or vapor to exit the tank (the "don't care" approach). This concept is simpler due to the deletion of a liquid acquisition of positioning system, but it would require the heater to be capable of responding very quickly to the change in outflow fluid state. For the purge flow rate of 2.68 kg/hr the required power levels would have to vary between 3 to 5 Watts for liquid outflow and would have to quickly increase to 130 to 140 Watts for vapor venting. This would seem to be a serious drawback to this approach.

As mentioned before, the use of a liquid cooled shield would greatly reduce the required minimum flow rate for liquid outflow (the flow for a constant tank pressure). The analysis of a system including an LCS, or a vapor cooled shield (VCS) for that matter, is more detailed and complex since the heat leak into the tank is dependent on the flow rate. Therefore an integrated tank thermodynamic and insulation system model must be used. The thermodynamic model is simply the one previously described, where the heat leak is that predicted by the thermal model of the insulation system.

The thermal analysis of the insulation system is a well characterized task that simply requires the modeling of a serial and parallel heat transfer network. The modeling detail required is not too precise so only the heat leak due to the inner tank support straps, the fill and vent lines, and the radiation through the MLI blankets was included. Additional heat leaks, such as those due to the wiring or via radiation tunneling though the MLI seams, were not modeled since these affects will be secondary in nature. A schematic representation of the heat transfer network modeled is presented in Figure 4.1-5. Here the individual parallel heat transfer paths are shown all connecting between the inner tank, the LCS or VCS (depending on whether liquid or gas are venting), and the vacuum jacket of the tank. For ease of modeling only the steady state heat transfer rate is calculated and the inner tank and vacuum jacket temperatures are used as boundary conditions.

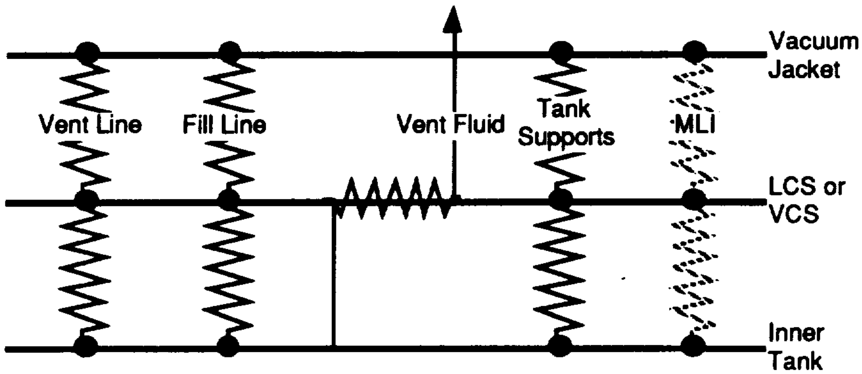

Figure 4.1-5 - Schematic Representation of the EMU LOX Tank Thermal Network Modeled

The heat leak through the support straps and the fluid lines was simply modeled as being due to conduction. An integrated average of the material conductivities was calculated between the two end point temperatures, and was used to model the heat transfer rate through the element. The heat transfer through the MLI is due to a combination of radiation between the individual layers and conduction through the spacer material. Using practices developed in earlier studies (References 4-1 and 4-2) the MLI was modeled with an equivalent conductance, to allow the analysis method for the MLI to be compatible with the solution of the other heat transfer rates. Many correlations for the effective conductance of MLI have been developed but the best found to date are provided in Reference 4-1. In this analysis it was assumed that the MLI would be double aluminized mylar (DAM) with double Dacron or silk spacers. Therefore the correlation for DAM with double silk spacers was used. A spreadsheet model was generated that would iterate on the LCS or VCS temperature until the predicted heat transfer rate into the cryogen and the required outflow rate to maintain the constant pressure had converged. A summary of the thermal system design parameters is presented in Table 4.1-1 below. In this Table the cross-sectional areas and lengths of the conduction parameters are presented along with information required to model the MLI system. In the spreadsheet it was assumed that there would be a conduction length of 1.27 cm (0.5 in) between the shield and the tank wall.

Table 4.1-1 - Design Parameters Used in the Thermal Analysis

Vent Line Cross Sectional Area	0.0993 cm^2	0.0154 in^2
Outflow Line Cross Sectional Area	0.0275 cm^2	0.0043 in^2
Support Strap Cross Sectional Area	0.1187 cm^2	0.0184 in^2
Vent Line Total Length	19.1 cm	7.5 in
Outflow Line Total Length	11.4 cm	4.5 in
Support Strap Total Length	5.1 cm	2.0 in
Tank Surface Area	4.26 cm^2	0.66 in^2
Shield Surface Area	6.45 cm^2	1.00 in^2
# MLI Layers	20	20
MLI Density	19.7 layers/cm	50 layers/in

Parametric runs were conducted to evaluate the required vent rate or liquid outflow rate to maintain a constant tank pressure. The Results of this analysis are presented in Figure 4.1-6 below. In this plot a difference in the performance between the two tank sizes is predicted, which is in contradiction to the previously stated result that the boiloff rate is independent of tank size for a fixed heat inflow rate and a fixed liquid fill level. This difference in this situation is that the resultant heat leak into both tanks is different due to the fact that the the smaller tank has less surface area to cover with the MLI.

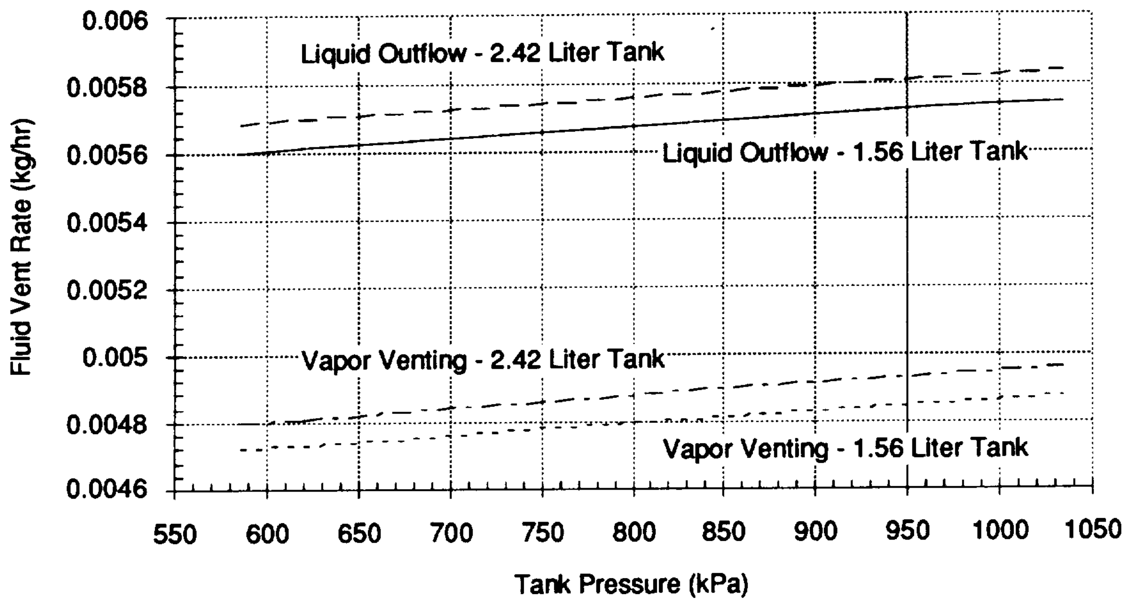

Figure 4.1-6 - Oxygen Vent Rates to Maintain Constant Tank Pressure with an LCS or VCS

This plot shows that the inclusion of an LCS has indeed reduced the required liquid outflow rate down to a value very near that predicted for the vapor flow. The maximum flow rate that would be required is less than .006 kg/hr (.013 lbm/hr) which is much lower than the minimum required operating flow rate of .023 kg/hr (.05 lbm/hr). Therefore the system required flow rate will always be greater than that required to maintain a constant tank pressure. This is a more attractive option than to have the minimum required flow rate be lower than that required to maintain constant tank pressure since it would require periodic of the EMU LOX system venting during operational usage, with a subsequent loss of fluid. The thermal system could be degraded to allow for a higher flow rate to maintain a constant tank pressure (i.e. design so that this flow rate is very nearly equal to the minimum required operating flow rate), but this would result in a less efficient thermal system design and would reduce the hold time from filling to use of the system.

The drawback to this approach is that the tank pressure may drop too much during outflow of the oxygen from the tank. If this were to occur, then the driving pressure for the outflow would decay resulting in a drop in supply flow rate to the EMU. To alleviate this possibility, tank heaters or an external pressurant source would be required. A final set of analyses were conducted to determine the amount of pressure reduction that would occur during a system outflow. Two conditions were run. The first is a nominal outflow at the average flow rate of 0.075 kg/hr (0.164 lbm/hr), which corresponds to the nominal metabolic rate during an EVA of 3410 Watts (1000 Btu/hr). The second case corresponds to the maximum outflow rate of 2.68 kg/hr (5.9 lbm/hr) which occurs during an emergency purge.

Both cases were modeled in the same manner as presented above, with one difference. This analysis required a transient model since the pressure decay rate is the parameter to be determined. The steady state model already developed could have been modified to perform this analysis but the limitations of a spreadsheet would make this very difficult. Instead the Martin Marietta developed program MMCAP (Martin Marietta Cryogenic Analysis Program) was used. This program is a general purpose cryogenic model that can be used to simulate liquid storage, inflow, outflow, and pressurization in conjunction with the solution of a thermal model of the insulation system. The program has been validated against numerous ground tests and also against the limited flight data that exists for cryogens. The main drawback of the use of MMCAP is that it does not model thermal stratification in the liquid very well. Since this aspect of the analysis will not be present in the EMU tanks, the use of MMCAP is fully justified.

The analysis results are presented in Figures 4.1-7 and 4.1-8. Figure 4.1-7 provides the results for the nominal outflow rate and Figure 4.1-8 the results for the purge case. The nominal outflow case was set with an initial pressure of 690 kPa (100 psia) while the purge flow was set to begin from the maximum pressure of 930 kPa (135 psia).

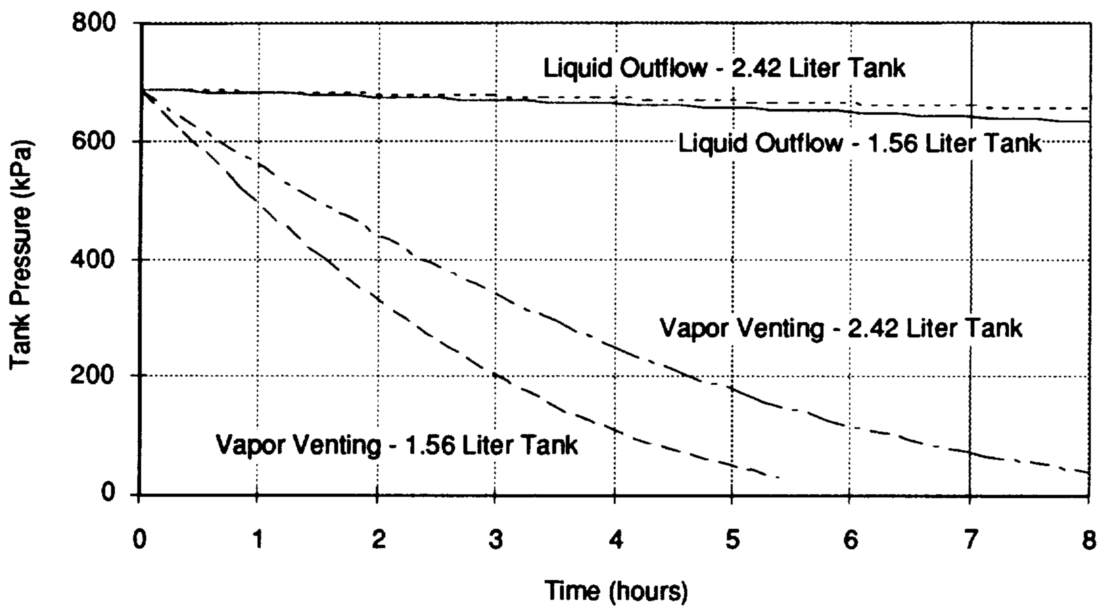

Figure 4.1-7 - Predicted Tank Pressures During Nominal Outflow

As can be seen from the plot, the vapor venting systems do indeed have a substantial pressure drop while the liquid outflow system pressure drop is very small over the 8 hour outflow time. The larger tank had a pressure reduction of ~650 kPa (94 psid) for the vapor venting case and ~34 kPa (5 psid) for the liquid outflow situation. The smaller tank had a larger pressure reduction of ~65 kPa (8 psid) for the liquid outflow situation and was not able to sustain the tank pressure for a vapor outflow. After ~5.5 hours the tank pressure had dropped below the minimum allowed setting of 35 kPa (5 psia) and it was assumed that the outflow would heave to cease. The extra pressure drop predicted for the smaller tank is due to the fact that the loaded fluid tank mass is less, so that the percent of the total loaded mass that was vented is greater for the smaller tank.

From this set of results the conclusion that a vapor only system would be impractical can be made. As the plot above shows, the pressure will drop drastically during the venting. The pressure reduction is due to the fact that the mass flow rate exiting the tank is much greater than that required to maintain a constant tank pressure (as shown in Figure 4.1-6 above). The liquid only outflow, on the other hand, has a much lower pressure drop rate due to the implications of the first law analysis. Due to the fact that the enthalpy of saturated liquid is much lower than the enthalpy of saturated gas, then the amount of energy removed for a fixed flow rate of liquid is much less than for the same flow of vapor. Since the liquid system has a lower energy removal rate than the vapor venting system, the pressure drop rate for the liquid outflow will also be much lower. The large pressure reductions that are seen with the venting approach will only become larger for flow rates that are greater than the average flow rate used in this analysis (i.e. the maximum purge condition). Two approaches could be used to maintain the tank pressure during a vapor only venting scenario. The first is to use a heater to maintain the tank pressure. This approach only adds complexity to the system and is better suited for the don't care method that does not have the requirement for a liquid positioning control device. The other approach would be to make that tank larger so that the percent removal rate of the vapor would be less. This option is not possible due to the size limitation of the system (and would result in an over-sized tank). These facts, along with the extra complexity of designing, manufacturing, and testing a low-g direct venting system, lead to the conclusion that the vapor only approaches will be impractical.

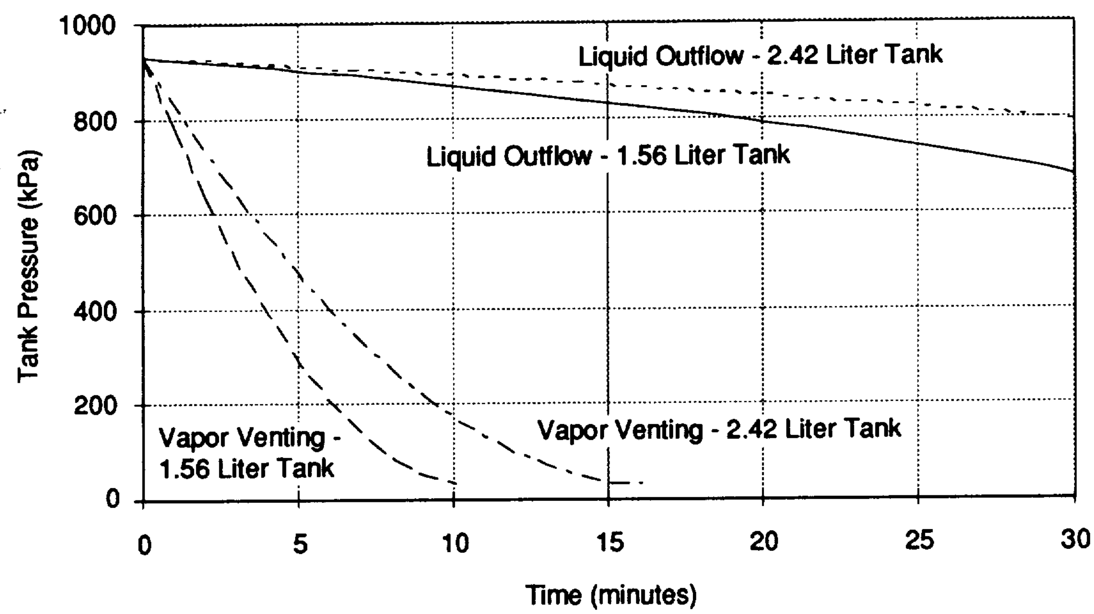

Figure 4.1-8 - Predicted Tank Pressures During the High Flow Purge Condition

The results of the maximum flow rate analysis show the difference between the liquid and the vapor venting concepts to an even greater extent. For both size tanks the vapor system would reduce the tank pressure below the minimum pressure before the 30 minute purge time has been reached. The liquid cases though have a pressure reduction of ~130 kPa (19 psid) for the larger tank and ~230 kPa (33 psid) for the smaller size tank. This level of pressure reduction during the outflow will still allow for the maintenance of the required purge flow rate for the entire 30 minute purge time.

4.2.1 <u>Initial Screening Results</u> -

The results of the thermodynamic analysis can be used to screen out all of the concepts that utilize a vapor only supply of oxygen. In addition other concepts were screened out as described in this section. In addition to the three concepts that utilize the vapor only approach to oxygen supply, there are three that combine this approach with a liquid outflow for the excess demand flow. These three concepts were developed in the case that the liquid only concepts would not be capable of providing the full range of flow rates required. Due to the fact the liquid only concepts have been proven to be thermodynamically sound, there is no need to combine that technology with one that requires a low-g liquid positioning device to allow for direct venting of the vapor. The vane device was also found to be impractical for the acceleration environment required. To maintain positive control over the liquid position in a 0.125 g-field, the vane spacing would have to be less than 0.18 mm (0.007 inches). This sizing between the vanes would be impractical to produce since the liquid fill fraction of the tank would be very low. For all of the above stated reasons the three liquid and vapor flow concepts were also deleted from the final review list. In addition, the supercritical storage system was deleted. This system would allow for the smallest storage volume, but it would also require the continuance of high pressure oxygen storage.

The results of the initial screening are summarized in Table 4.1-2 below. In the table the individual configurations are listed along with a brief description and the results of the initial screening. As can be seen from this Table, 7 of the original 16 concepts were deleted form the final review.

Table 4.1-2 Results of the Initial Configuration Screening

Configuration	Description	Results of Initial Screening
1	Conventional TVS system providing vapor only flow	Delete from review - Not thermodynamically possible without heater
2	Conventional TVS system providing const. vapor flow with demand flow provided by liquid	Delete from review - Too complex, concept requires LAD plus extra hardware
3	Vane type LAD system providing vapor only flow	Delete from review - not thermodynamically possible without heater, vane device cannot meet 1/8 g-level requirement
4	Vane type LAD system providing const. vapor flow with demand flow provided by liquid	Delete from review - vane device cannot meet 1/8 g-level requirement
5	Magnetic LAD system providing vapor only flow	Delete from review - Not thermodynamically possible without heater
6	Magentic LAD system providing const. vapor flow with demand flow provided by liquid	Delete from review - Too complex, concept requires LAD plus extra hardware
7	Magnetic LAD system providing liquid only flow onto LCS	Include in review
8	Liquid only outflow provided by LAD with LCS	Include in review
9	Don't care system with either liquid or vapor flow	Include in review
10	Bladder tank with LOX inside bladder	Include in review
11	Bladder tank with LOX outside bladder	Include in review
12	Diaphragm system with internal pressurization (blowdown system)	Include in review
13	Diaphragm system with external pressurization	Include in review
14	Bellows system with internal pressurization tank	Include in review
15	Bellows system with external pressurization tank	Include in review
16	Supercritical system	Delete from review - Concept is still high pressure, Concept does not push new technology

4.2 Final Configuration Screening

After the initial screening had reduce the original 16 configurations down to a list of 9, the detailed configuration trade was undertaken. This trade rated the relative merits of each concepts against a list of 11 ranking categories. The list of these 11 categories was then broken down into sub-categories to allow for a direct rating of each concept against finite criteria instead of subjective ones. Finally, each concept was evaluated against the set of criteria developed and a score for each category was generated. This score was summed up into a relative form to allow for comparison of the relative merits of each concept to be made.

4.2.1 Evaluation Criteria -

The first step of the rating process was to develop a list of categories against which the concepts would be evaluated. From individual inputs a list of 11 categories was generated that was found to be a good representation of the attributes required in the EMU SLOSSS storage tank. The list of 11 categories is provide in Table 4.2-1 below. In this Table the category title and a short definition is provided. The categories are presented in order of important to the system (from highest to least).

Table 4.2-1 Ranking Categories Used in the System Selection Trade

1) Total System Volume / Usable LO2 Volume -

2) Robustness - Ability of the system to hold-up to extended use and certain amounts of abuse (impact resistance, etc.)

3) Complexity / Interface - Amount of complexity required to develop unit and interfaces with EMU.

4) Serviceability - Requirements for orbital servicing of the system.

5) Gaugeability - Ability to determine the amount of LOX stored in system.

6) Storage Life - Time from fill to initial usage that LOX can be stored without venting.

7) Testability - Requirements for qualification testing of unit.

8) Expulsion Efficiency -

9) Logistics Costs - Fluid and equipment requirements for servicing of system.

10) Servicing Integration - Amount of crew, fluid, and electrical interaction required for servicing system.

11) Development Required Before Breadboard Usage - Level of technology maturity of concept.

This list provides a good set of top levels attributes against which the concepts could be reviewed, but it does not allow for the details of the design to be evaluated. To allow for an objective review to be conducted, the 11 categories were broken down into sub-categories. For example, the category of robustness was broken down into four areas, each of which are elements that make a system robust. The four categories used were the number of active components in the system (since these components would be most likely to fail), the life cycle of the system (since this would define the replacement period of the tanks), the number of failure modes specific to that concept (which is a rating of the complexity of that concept compared to any other), and the number of cold components (those within the vacuum jacket of the tank), since they would be the most difficult to replace. The same approach was taken for each category that required further definition (expulsion efficiency is a straightforward parameter and therefore defined the entire category).

The rating scheme was also developed at this time. Using an approach that was successfully employed in contract NAS7-754 (Reference 4-3) it was decided that each of the 11 categories would have a maximum rating of 1.0 (with 1.0 being the best and 0.0 being the worst). This value then became the maximum rating for each category and the sub-categories were given their own allotments that would as a sum add up to a maximum of 1.0. For example, the robustness sub-categories were given allotments of 0.3 for the number of active components, 0.2 for the life cycle, 0.3 for the number of failure modes, and 0.2 for the number of cold components. Any component could, as a maximum, be assigned values in each sub-category that were equal to the individual allotments. If a certain concept was lacking in one area (it had one cold component for example) then a certain amount would be deducted from the category maximum of 1.0 (the cold component would have subtracted 0.1 from the allotment of 0.2, resulting in robustness rating of 0.9). Table 4.2-2 presents a summary of the sub-categories used in the ranking. The allotments for each along with a description of the sub-category and the reduction criteria are presented.

Table 4.2-2 Sub-Categories Used in the Ranking Analysis

1) Total System Volume / Usable LO2 Volume -	Maximum Rating of 1.0
Ratio of the minimum Vtank / Vliquid to the concept's Vtank / Vliquid (so concept with minimum will have value of 1.0).	
2) Robustness -	Maximum Rating of 1.0
a) # Active Components - # of components other than valves in the system	Maximum Allotment of 0.3 reduce by 0.1 for each
b) Life Cycle Limited - Life cycle must be > 100 fills	Maximum Allotment of 0.2 reduce by 0.2 if not
c) # Failure Modes Specific to Concept - Heater failure would be considered here, but tank leakage would not since it applies to all concepts	Maximum Allotment 0.3 reduce by 0.1 for each FM
d) # Cold Components in System - Components inside vacuum jacket	Maximum Allotment of 0.2 reduce by 0.1 for each one
3) Complexity / Interface -	Maximum Rating of 1.0
a) # of Solenoid Valves in System -	Maximum Allotment of 0.5 subtract 0.1 for each
b) Pressure Control Concept - Is pressure controlled actively or passively	Maximum Allotment of 0.5 subtract 0.5 if requires active

Table 4.2-2 Sub-Categories Used in the Ranking Analysis (Continued)

4) Serviceability - Maximum Rating of 1.0

a) Crew Interaction During Filling - Maximum Allotment of 0.5
0.5 for minimal, 0.3 for moderate, and 0.1 for high

b) Automation of Fill is Possible - Maximum Allotment of 0.25
0.25 if yes, 0.0 if no

c) Topoff of LOX is Possible - Maximum Allotment of 0.15
0.15 if yes, 0.0 if no

d) Tank Wall Mass to Volume Ratio - Maximum Allotment of 0.1
LOX chilldown mass parameter 0.1 for minimum ranging to 0.0 for maximum

5) Gaugeability - Maximum Rating of 1.0

Three gauging concepts have been defined subtract 1/3 for each one not possible

6) Storage Life - Maximum Rating of 1.0

Found that storage life was not determined by concepts, but instead by the thermal design of the tank system. Thus all concepts get a rating of 1.0.

7) Testability - Maximum Rating of 1.0

a) Ground Testing - Maximum Allotment of 0.5
0.5 if -1g testing possible, 0.3 if can simulate -1/8 g, 0.1 if +1g testing possible

b) KC-135 Testing - Maximum Allotment of 0.5
0.5 if not required, 0.3 if needed for supporting data, 0.1 if only way possible

8) Expulsion Efficiency - Maximum Rating of 1.0

0.0 for expulsion efficiency of 95% or less, then add 0.2 for each % higher than 95%

9) Logistics Costs - Maximum Rating of 1.0

Cannot get specific numbers for this value without detailed analyses, so will provide relative rating.
1.0 if relatively minor (one fluid w/ low chilldown mass)
2/3 if moderate (two fluids w/ low chilldown mass, or one fluid w/ high chilldown mass)
1/3 if relatively high (two fluids w/ high chilldown mass)

Table 4.2-2 Sub-Categories Used in the Ranking Analysis (Concluded)

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10) Servicing Integration - Maximum Rating 1.0

a) Number of Fluids Requiring Refill - Maximum Allotment of 0.3
reduce by 0.3 for two fluids

b) Support Equipment Requirements - Maximum Allotment of 0.4
0.4 if simple support system, 0.2 if complex system

c) Power Requirements - Maximum Allotment of 0.3
reduce by 0.1 for each powered system

11) Development Required Before Breadboard Usage - Maximum Rating of 1.0

1.0 if concept ready for breadboard testing
0.5 if concept tested but requires more work prior to breadboard testing
0.0 if untried concept or materials

4.2.3 Inputs to Ranking Analysis -

The next step consisted of objectively evaluating each concept to generate an input list for the ranking. Each design was studied and reviewed to determine the obvious input parameters (i.e. number of components, expulsion efficiency, etc.). There were certain areas though that could not be reviewed in detail without the need for much analytical time and effort. A good example of this is the crew interaction sub-category of the servicing category. Without a full design of the servicing system and analysis of the requirements for crew interaction, only generalizations can be made. It was determined that there would be three levels of interaction; high, moderate, and low. Each system was evaluated to determine into which of these three groupings it would fall. The extremes were easy to determine (such as a small, single fluid tank requiring a simple no-vent fill process as compared to a large, two fluid system requiring multiple vents to ensure a bladder had been seated properly prior to filling) while the intermediate levels were more esoteric. There were a few other areas of review that were similar to these, but a consistent approach was taken in all cases.

The inputs to the ranking for each concept are discussed in detail below with a summary of the actual inputs used in the ranking presented in Table 4.2-3.

Concept 7 : Magnetic Acquisition of Liquid - The magnetic system will be very simple in design and requires the minimum total tank volume. Assuming the system would be spherical (which is a good point from which to compare system size performance) the entire system volume (not including the valves or the conditioning heat exchanger since these components will be common to all systems) is 3.87 liters (236 cubic inches). Since the liquid volume will be 1.56 liters (95.2 cubic inches) the ratio of the two volumes works out to 2.48. A review of the concept schematics presented in section 3.0 shows that there is only one active and one cold component, the electromagnet. There is only one concept specific failure mode, the loss of power to the magnet, and the life cycle limit of the concept should be much greater than 100 fills. The system has only one solenoid valve per tank, for isolation, and it is capable of passive pressure control.

The servicing aspects of the system are a little hard to detail at this time but general approaches can be reviewed. The servicing will involve a charge-hold-vent chilldown followed by a no-vent fill of the tank. Both of these operations have been verified experimentally by ground testing but there is no orbital servicing experience to ensure that the methods will work. Since supporting data is not available for all of the proposed filling methods, the review must proceed assuming that the proposed methods will work. Compared to all of the concepts, this one will require the minimal amount of crew involvement. The chilldown and no-vent fill process could be fully automated to allow for minimal crew impacts, with the level of automation dependent on the amount of effort that will be put into the servicing equipment. For this system topoff is possible and the tank will have a comparably small mass to volume ratio (with the only increase over the minimal case being the extra mass of the magnetic coils).

During the study three concepts were developed that will possibly allow for gauging of the LOX mass in the tank. The first is to simply meter the outflow and to integrate the metering data. This will allow for a tracking of the vented fluid to be accomplished, thereby providing a measure of the fluid mass in the tank. Another concept is to utilize the magnetic behavior of LOX to allow for mass gauging. By placing an electrical coil on the tank wall, the inductance in the coil will be affected by the LOX mass in the tank. Thus, the coil inductance could be used to measure the amount of fluid in the tank. One final approach will only work with positive displacement devices (namely the bellows concepts). If the position of the bellows can be detected, then a measure of the fluid volume can also be made. This concept is capable of using two of the three gauging methods developed. As was stated previously the choice of concept does not drive the hold period, only the insulation system design will.

One of the main drawbacks to the magnetic approach is the additional testing that must be performed to verify that the concept will work. The best test approach would be to drain the tank while inverted. In this case the system would be capable of withstanding a -1 g acceleration field, and would have little problem meeting the 1/8 g requirement. The magnetic LAD would not have the force capable of performing an inverted outflow so low-g testing would be required. This would involve the use of a KC-135 test facility, or an equivalent option, which is a serious drawback to the choice of this concept. If the 1/8 g requirement can be satisfied by the design then the expulsion efficiency will be very close 100%. Per the definition of the logistics costs this system will require minimal consumables during servicing. This concept also has minimal service integration requirements. Finally, the concept will require further development prior to use in the breadboard, since the theoretical feasibility of the concept has only recently been established.

Concept 8 : Capillary Screen Acquisition of Liquid - This concept is also very simple in design and requires the minimum total tank volume, resulting in the same volume ratio as concept 7 (2.48). A review of the concept schematic shows that there are no active or cold components. There is only one concept specific failure mode, leakage or failure of the screen, and the life cycle limit of the concept will be much greater than 100 fills. The system has only one solenoid valve per tank, for isolation, and it is capable of passive pressure control.

The servicing aspects of the system are the same as those defined for concept 7 with the addition of the fact that this concept will have the minimal mass to volume ratio. This concept is also capable of using two of the three gauging methods developed. As was stated previously, the choice of concept does not drive the hold period, only the insulation system design will. Expulsion efficiencies for LAD are typically very high, but due to the small size of this tank, the relative size of the LAD will be much greater. Therefore an expulsion efficiency of 97% was assumed, but the actual performance of the system might be better.

The screen mesh chosen for the LAD is capable of supporting a 17.8 cm (7 inch) column of liquid oxygen. The tank design will likely result in a 30.5 cm (12 inch) inner tank length, so inverted testing can be performed until the tank liquid has drained to the ~40% fill level. At this time the hydrostatic head will cause the liquid to fall out of the LAD, resulting in a cessation of the outflow. The LAD will be more than capable of meeting the 1/8 g requirement though. Testing under one-g can be accomplished by tilting the tank at an angle that will produce a hydrostatic head equivalent to the level that would be seen in space. Finally, screen channel LAD's are a very mature technology that have many hours of ground test experience with cryogens. Their application to space systems has not been proven yet, but the technology is ready for breadboard integration.

Concept 9 : Don't Care System - This concept is simple in design and requires the minimum total tank volume, resulting in the same volume ratio as concept 7 (2.48). A review of the concept schematic shows that there is only one active or cold component, the tank heater. There is only one concept specific failure mode, failure of the heater, and the life cycle limit of the concept will be much greater than 100 fills. This concept has the drawback of requiring an active control system that will cycle the heater to maintain the tank pressure within a prescribed range.

The servicing aspects of the system are the same as those defined for concept 7 with the addition of the fact that this concept will have a mass to volume ratio that will be slightly increased by the heater (it could in fact be lower than the other options if the heater is only a coil of wire). This concept is also capable of using two of the three gauging methods developed. As was stated previously the choice of concept does not drive the hold period, only the insulation system design will. This concept also has an expulsion efficiency of 100% by design, since either liquid or vapor outflow can be accommodated.

The testing of this concept will be more detailed since the expulsion of either liquid or gas can be simulated separately, but not at the same time. The only method of achieving a variable outflow quality would be to conduct the testing in a KC-135. This concept is ready for integration into a breadboard since there is in reality no new technology being developed.

Concept 10 : Collapsing Bladder - This concept is more detailed and requires a larger system volume due to the ullage space required and the addition of the pressurization system. The total system volume works out to 4.52 liters (275.8 cubic inches) resulting in a system volume ratio of 2.90. A review of the concept schematic shows that there is one active component, the regulator, and one cold component, the bladder. There are two concept specific failure modes, leakage or failure of the bladder and failure of the regulator. The concept will likely have a life cycle limit of less than 100 fills, due to the brittleness of the polymeric bladder material at cryogenic temperatures. The system has two solenoid valves per tank and it is capable of passive pressure control.

The servicing aspects are more detailed with this kind of system. First off, two fluids (LOX and GHe) must be serviced. The LOX fill is much more difficult due to the inclusion of the bladder system. To ensure vapor free outflow from the tank the liquid side must be filled 100% with subcooled liquid. To achieve this fill level the system must be cooled to a colder temperature prior to the chill, requiring more chilldown liquid mass. In addition, the position of the bladder must be assured prior to the fill to prevent any creases or folds to develop during the filling of the tank. Finally the GHe placed in the tank must be pre-chilled to prevent any heat transfer from the ullage to the liquid side of the system. All of these extra servicing steps will require more crew involvement in the servicing of the system. The transfer can still be automated, but the degree of automation will be somewhat less than for other concepts. From all of this it was decided that this concept will require a moderate amount of crew involvement. The bladder tank can be topped off but this will require the use of a back-pressure regulator on the ullage side to prevent the system pressure from dropping and the subsequent formation of helium bubbles in the LOX, due to the permeation through the bladder material of the pressurant gas. This concept is also capable of using two of the three gauging methods developed. The storage life will not be affected by the design of the bladder system due to the loading option chosen. To allow for heat storage after filling the tank will be filled with subcooled liquid. During the hold period the liquid will be allowed to swell due to the change in density of the liquid. Therefore some room must be built into the bladder to account for the liquid volume change. Analysis has shown that if the liquid is allowed to swell 5% then the hold period following the fill will be ~27 hours, which is in the ball park of the estimated hold time for other options. Previous analysis of collapsing bladder systems have shown an expulsion efficiency of 97%.

This system will be very easily flight qualified since the liquid can be expelled while the tank is in an inverted position. Using the logistics cost defined previously the system will have a moderate level of logistical requirements. The filling requirements for amount of fluid and support equipment will be greater than the first three options discussed. Finally, the concept is not ready for breadboard integration since there are no bladder materials in existence that can withstand the cryogenic operating temperatures.

Concept 11 : Expanding Bladder - This concept is exactly the same as the previous one except that the liquid is stored on the outside of the bladder. The servicing requirements for this concept are greater due to the fact that the bladder must be fully collapsed prior to or during the filling of the system. The potential for folding or cracking of the bladder will be greatly increased during this operation. There may in fact be the requirement to visually inspect the bladder prior to filling (through a fiber-optic system) to ensure it has been fully collapsed. Topoff is possible but not likely for this concept. The expanding bladder design will have a higher expulsion efficiency of 98% though. All other inputs are the same as for concept 10.

Concept 12 : Diaphragm with Blowdown Pressurization - This concept is also detailed and requires a larger system volume due to the large ullage space required for the blowdown. The total system volume works out to 4.69 liters (286 cubic inches) resulting in a system volume ratio of 3.00. A review of the concept schematic shows that there are no active components and one cold component, the diaphragm. There is only one concept specific failure mode, leakage or failure of the diaphragm. Due to the brittleness of the polymeric diaphragm material at cryogenic temperatures, the life cycle limit of the concept will most likely be less than 100 fills. This conclusion is supported by the fact that ambient temperature diaphragm tanks have a very low life cycle. The system has one solenoid valve per tank and it is capable of passive pressure control.

The filling concept is the most detailed of any of the concepts. The liquid side must be charged with subcooled LOX (to allow for the extended hold time) and then charged with the high pressure helium to provide the blowdown pressurization source. The ullage must be pre-cooled prior to the filling to prevent any heat transfer across the diaphragm. The chilldown mass for the system will be somewhat greater due to the extra wall mass and the mass of the diaphragm. This process could be automated but it would require a very sophisticated system. Topoff of the system is not possible due to the fact that the helium pressurant will come out of solution during the expulsion. As the tank pressure drops, the helium that has permeated through the diaphragm and has dissolved in the liquid will form vapor bubbles that may become of significant size. These vapor bubbles must be purged from the liquid prior to filling and the only method to achieve this is to drain the tank prior to filling the system. The predicted expulsion efficiency is 99%. Other operational concerns with the diaphragm systems will be similar to the bladder concepts.

Concept 13 : Diaphragm with External Pressurization - This concept is similar to the previous one except the pressurization system is external to the LOX tank. The total system volume is the same as for the bladder systems with a resultant ratio of 2.90. A review of the concept schematic shows that there is one active component, the regulator, and one cold component, the diaphragm. There are two concept specific failure mode, leakage of the regulator and leakage or failure of the diaphragm. As with the other diaphragm concept, the system will be severely life cycle limited. The system has two solenoid valves per tank and it is capable of passive pressure control.

The filling concept is the same as that developed for the bladder systems, except that the difficulty in configuring the diaphragm prior to fill is less than for the bladder systems. The predicted expulsion efficiency is 99%. Other operational concerns with the diaphragm systems will be similar to the bladder concepts.

Concept 14 : Bellows System with Internal Pressurization - This concept is a more robust system but requires a larger system volume due to the size of the bellows. The total system volume works out to 8.41 liters (513 cubic inches) resulting in a system volume ratio of 5.56. The system volume is so much greater due to the need to have this concept be a cylindrical system (since the bellows can only be manufactured as a cylinder). A review of the concept schematic shows that there is one active component, the regulator, and two cold components, the bellows and regulator. There are two concept specific failure mode, cocking or failure of the bellows and failure of the regulator. Since the bellows is of all metal construction, the life cycle limit of the concept should be greater than 100 fills. The system has 1 solenoid valve per tank and it is capable of passive pressure control.

The filling concept is the same as for the other positive expulsion systems. The chilldown and fill will be conducted as prescribed previously with the knowledge that the bellows will require the most chilldown liquid mass and more intense monitoring during the fill process (to ensure that the bellows does not twist or bend). Since the pressurant will be stored in a cold condition the fluid must be chilled prior to filling the helium tank. The process can be automated and topoff is indeed possible for this system (although it would require more servicing equipment than other systems). The bellows systems definitely have the maximum mass to volume ratio of all of the concepts.

The addition of the bellows allows for the addition of another gauging option to be studied. The end of the bellows will move during the outflow in a linear manner. A position sensor on the end will provide a good measure of the stored liquid mass if no bubbles form in the liquid side. Extra volume will be built into the bellows to allow for liquid swelling during the hold period, resulting in a hold period greater than the required 8 hours. The bellows type systems should have an expulsion efficiency of ~97%.

A review of the filling operations shows that this concept will require the maximum amount of logistical support (two fluids being serviced and maximum chilldown mass). In addition the servicing equipment will be complex due to the need to fill the system 100% full of liquid and the need to pre-chill the helium prior to fill. The bellows concepts are ready for breadboard integration since bellows do exist that will meet the requirements for the breadboard. Further work will be required to make a flight weight bellows though since they are presently very massive.

Concept 15 : Bellows System with External Pressurization - This concept very similar to the previous concept except for the fact that the pressurant will be stored external to the LOX tank. The total system volume is still 8.41 liters (513 cubic inches) resulting in a system volume ratio of 5.56. A review of the concept schematic shows that there is one active component, the regulator, and one cold component, the bellows. There are two concept specific failure modes, cocking or failure of the bellows and failure of the regulator. This system will also have a life cycle limit of more than 100 fills. The system has 1 solenoid valve per tank and it is capable of passive pressure control. Operational concerns are the same as for the other bellows system except that the need to fill the helium tank with cold gas is deleted.

The individual inputs were all compiled and used to generate the list of inputs presented in Table 4.2-3 below. The Table is self descriptive and reflects the comments made in the previous section.

Table 4.2-3 Input List for the EMU SLOSSS Tank System Ranking

Rating Categories	Ranking Factor	7	8	9	10	11	12	13	14	15
1 System Volume / Usable Volume		2.48	2.48	2.48	2.9	2.9	3	2.9	5.56	5.56
2 Robustness										
# Active Comps		1	0	1	1	1	0	1	1	1
Cycle Limit < 100		y	y	y	n	n	n	n	y	y
# Failure Modes		1	1	1	2	2	1	2	2	2
# Cold Components		1	0	1	1	1	1	1	2	1
3 Complexity / Interface										
# Valves		1	1	1	2	2	1	2	1	1
Passive Pressure Control System		y	y	n	y	y	y	y	y	y
4 Serviceability										
Crew Interaction (1-min, 2-mod, 3-max)		1	1	1	2	3	3	2	3	2
Automation Possible		y	y	y	y	y	y	y	y	y
Topoff Possible		y	y	y	y	y	n	y	y	y
Mass / Volume Ratio (1-min to 0 - max)		0.8	1	0.8	0.8	0.8	0.6	0.6	0	0
5 Gaugability (number of options)		2	2	2	2	2	2	2	3	3
6 Storage Life (1-unlim, 0 - 0.0)		1	1	1	1	1	1	1	1	1
7 Testability										
Ground Testing (1-invert, 2-tilt, 3-1g)		3	2	1	1	1	1	1	1	1
KC-135 Testing (1-none, 2-some, 3-all)		3	1	2	1	1	1	1	1	1
8 Expulsion Efficiency		100	97	100	97	98	99	99	97	97
9 Logisitic Costs (1-min, 2-mod, 3-max)		1	1	1	2	2	2	2	3	3
10 Service Integration										
# of Fluids		1	1	1	2	2	2	2	2	2
Support Equip Reqs (1-min, 2-max)		1	1	1	2	2	2	2	2	1
# Power Reqs		1	1	1	1	1	1	2	1	1
11 Readiness for Breadboard Use		3	1	1	3	3	3	3	1	1

4.2.2 Ranking Results -

After the input list was generated the ranking process was conducted. A spreadsheet was built using the ranking criteria described in section 4.2.1. The spreadsheet uses the inputs to generate the rankings for each category. This is shown in the following example. If a 2 were input for the gaugeability category (meaning that 2 of the 3 proposed methods for gauging were applicable to this concept) then the spreadsheet would place a 0.67 in the entry for that concept under ranking category 5. Once the individual ratings for each of the 11 categories was generated for each concept, the spreadsheet would multiply the category weighting against the rating for that category (for example if the gaugeability weighting was 4 then the resultant weighted rating for the example above would be 2.67). Next the weighted ratings for each of the 11 categories would be added up to generate a summed, weighted ranking for each concept. Finally, the summed ranking would be normalized so that the sum of the final rankings would add up to 100. Since there were 9 concepts being ranked, this resulted in an average ranking of 11.11. Any system with a higher normalized ranking that this value would be above normal and any with a lower value would be below normal.

The keys to this approach are the weightings used for each of the 11 categories. The 11 categories have been presented in the order of most to least important, but that is all that is known about their relative important to the final results. Three different weighting systems were used to ensure that the importance of each category could be studied. First an equal rating of 1 was used. This weighting assumed that all of the categories were equally important. Second a weighting of 11 to 1 was used. This weighting placed the most importance on the volume ratio by stating that it was 11 times more important than the final category. This top heaviness of the weightings is not likely to provide a true picture of the best system. Finally, a three level weighting was developed. This ranking approach is used extensively in the Quality Function Deployment (QFD) methodology that has seen widespread usage this last decade. The idea is to break the categories into three discrete groupings; the most important, those of moderate importance, and the least important. Each group gets a weighting of 3, 2, and 1 respectively. It was decided that categories 1 through 4 were the most important and would get a weighting of 3, categories 5 through 7 were of moderate importance and would be weighted with a 2, and the rest would have a weighting of 1. Rankings were conducted with all three sets of weighting factors to determine which system best meets the needs of the program.

The ranking results are presented in Figure 4.2-1 and Table 4.2-4. The Figure presents the results plotted up for each of the three rankings conducted. As can be seen from the Figure the choice of the weighting used did not have a great effect on the results of the ranking. In all three cases concept #8 came out the top rated system with concepts #7 and #9 trading spots between second and third place. The place where each concept fell did vary somewhat with the choice of weightings used, but the general placement of the results shows a steady pattern. As can be seen on the plot, the top three concepts were consistently well above the others.

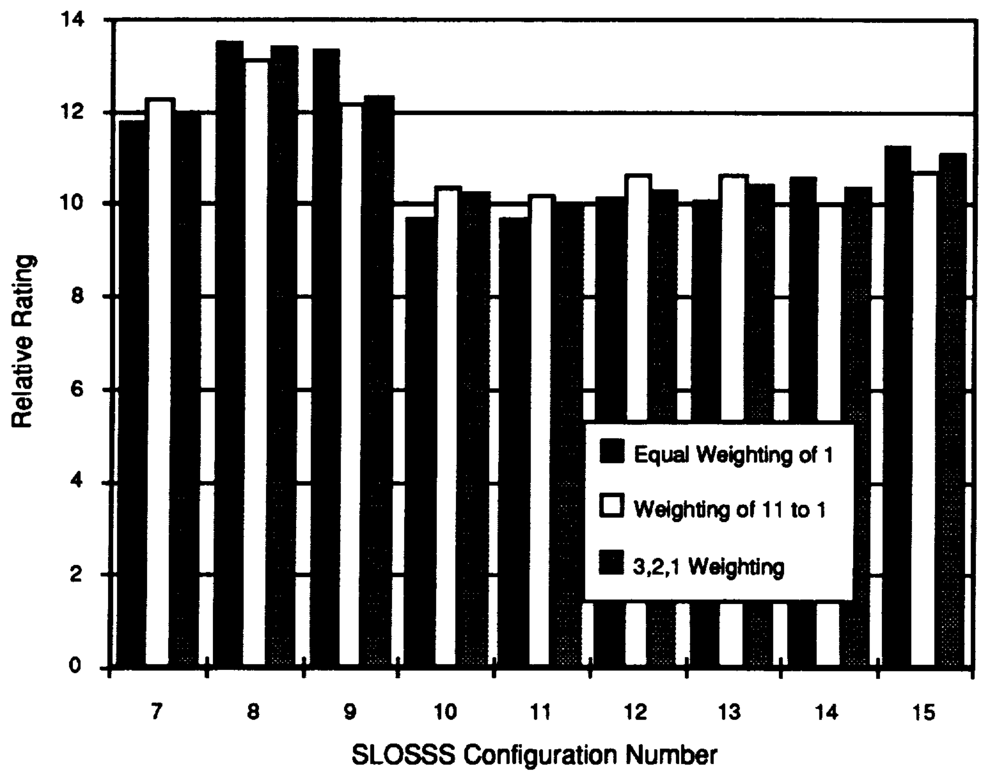

Figure 4.2-1 Results of the EMU SLOSSS Storage System Ranking

Table 4.2-4 provides the details for the ranking using the 3,2,1 weighting scale. The spreadsheet table is provided showing the calculated ratings for each category and sub-category along with the resultant relative ranking. The details for the 3,2,1 weighting are provided since they present the best representation of the relative importance of the categories used to rate the systems.

Table 4.2-4 Results of the 3,2,1 Weighted Ranking

Rating Categories	Ranking Factor	Concepts Reviewed in SLOSSS Study								
		7	8	9	10	11	12	13	14	15
1 System Volume / Usable Volume	3	1	1	1	0.86	0.86	0.83	0.86	0.45	0.45
2 Robustness	3	0.7	0.9	0.7	0.3	0.3	0.5	0.3	0.5	0.6
# Active Comps		0.2	0.3	0.2	0.2	0.2	0.3	0.2	0.2	0.2
Cycle Limit < 100		0.3	0.3	0.3	0	0	0	0	0.3	0.3
# Failure Modes		0.1	0.1	0.1	0	0	0.1	0	0	0
# Cold Components		0.1	0.2	0.1	0.1	0.1	0.1	0.1	0	0.1
3 Complexity / Interface	3	0.9	0.9	0.4	0.8	0.8	0.9	0.8	0.9	0.9
# Valves		0.4	0.4	0.4	0.3	0.3	0.4	0.3	0.4	0.4
Passive Pressure Control System		0.5	0.5	0	0.5	0.5	0.5	0.5	0.5	0.5
4 Serviceability	3	0.98	1	0.98	0.78	0.58	0.41	0.76	0.5	0.7
Crew Interaction		0.5	0.5	0.5	0.3	0.1	0.1	0.3	0.1	0.3
Automation Possible		0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Topoff Possible		0.15	0.15	0.15	0.15	0.15	0	0.15	0.15	0.15
Mass / Volume Ratio		0.08	0.1	0.08	0.08	0.08	0.06	0.06	0	0
5 Gaugability	2	0.67	0.67	0.67	0.67	0.67	0.67	0.67	1	1
6 Storage Life	2	1	1	1	1	1	1	1	1	1
7 Testability	2	0.2	0.8	0.8	1	1	1	1	1	1
Ground Testing		0.1	0.3	0.5	0.5	0.5	0.5	0.5	0.5	0.5
KC-135 Testing		0.1	0.5	0.3	0.5	0.5	0.5	0.5	0.5	0.5
8 Expulsion Efficiency	1	1	0.4	1	0.4	0.6	0.8	0.8	0.4	0.4
9 Logisitic Costs	1	1	1	1	0.67	0.67	0.67	0.67	0.33	0.33
10 Service Integration	1	0.9	0.9	0.9	0.4	0.4	0.4	0.3	0.4	0.6
# of Fluids		0.3	0.3	0.3	0	0	0	0	0	0
Support Equipment Reqs		0.4	0.4	0.4	0.2	0.2	0.2	0.2	0.2	0.4
# Power Reqs		0.2	0.2	0.2	0.2	0.2	0.2	0.1	0.2	0.2
11 Readiness for Breadboard Use	1	0	1	1	0	0	0	0	1	1
Relative Ranking		11.9	13.4	12.3	10.2	9.97	10.3	10.4	10.4	11.1

4.3 Ranking Conclusions

The ranking has shown that concept #8 is the best choice with which to continue the design and development of the EMU SLOSSS storage and supply system. The system is small, simple, and easy to service; which are three of the most important characteristics required of the final system to be integrated into a breadboard design. The other two options that came out near the top (the magnetic system and the don't care system) each have one major drawback. The magnetic system is not even fully developed yet and would require special low-g testing to validate the concept. The don't care idea requires the use of a heater and an active pressure control system, which increases the complexity of the system interfaces.

5.0 RECOMMENDED SYSTEM DESIGN

5.1 LOX Storage System Design

Storage system configuration 8 was selected during the final evaluation phase as the preferred system for further analysis and conceptual design for the breadboard system. Three options in sizing the tank were considered. The tank could be sized for primary oxygen mass requirements only, the tank could be sized to fit within the existing EMU envelop with the extra oxygen mass as margin, or the tank could be sized to supply both primary and emergency purge requirements without regard to installation in the EMU. The later option appeared to be preferred if the overall tank dimensions were not significantly greater than the existing primary tank dimensions. An estimate of oxygen mass requirements assuming normal and emergency use and various operational losses was prepared in order to determine tank sizes. It was found that both spherical and cylindrical tank configurations significantly exceeded the limits of the primary tank envelope. A further evaluation indicated that a cylindrical tank configuration equivalent to the current primary tank volume could be obtained if all of the primary oxygen requirement and only half of the emergency requirement were supplied. This would permit installation of the LOX tank into the volume presently available in the EMU. Furthermore, installation of two of these LOX tanks into the EMU would provide double the primary requirement and all of the emergency requirement. This arrangement is also desirable from a breadboard testing consideration. A single tank can demonstrate the operations required for filling, draining, and normal outflow as would be expected during a typical EMU mission. In additions, the higher flow rate requirements of the purge operation could also be simulated. The mass distribution upon which this sizing study was based is presented in Table 5-1.

Table 5-1 Oxygen Mass Distribution For Sizing the Breadboard Test Tank

Function / Item	Mass - kg	Mass - lbm	% Mass	Comments
Normal Usage	0.595	1.312	37.3	
Emergency - Purge	0.669	1.475	42.0	1/2 of Purge Flow
Safety Factor	0.080	0.176	5	Margin on Entire Mass
Gaging Error	0.032	0.070	2	
Loading Tolerance	0.048	0.105	3	Ullage = 7 ± 3 %
Boiloff - Max Hold	0.080	0.176	5	
Functional Checkout	0.032	0.070	2	
Liq. Acqusition Loss	0.016	0.035	1	
Residual Vapor	0.043	0.095	2.7	
Total	1.594	3.515	100	
Volume - liters	1.614			Based on Loading at
Volume - ft^3	0.057			689 kPa (100 psia)

A conceptual design of the breadboard tank based upon the above mass distribution has been prepared and is presented in Figure 5-1. The overall dimensions of the tank including the vacuum jacket are a diameter of 13.5 cm (5.3 inches) and a length of 36.1 cm (14.23 inches).

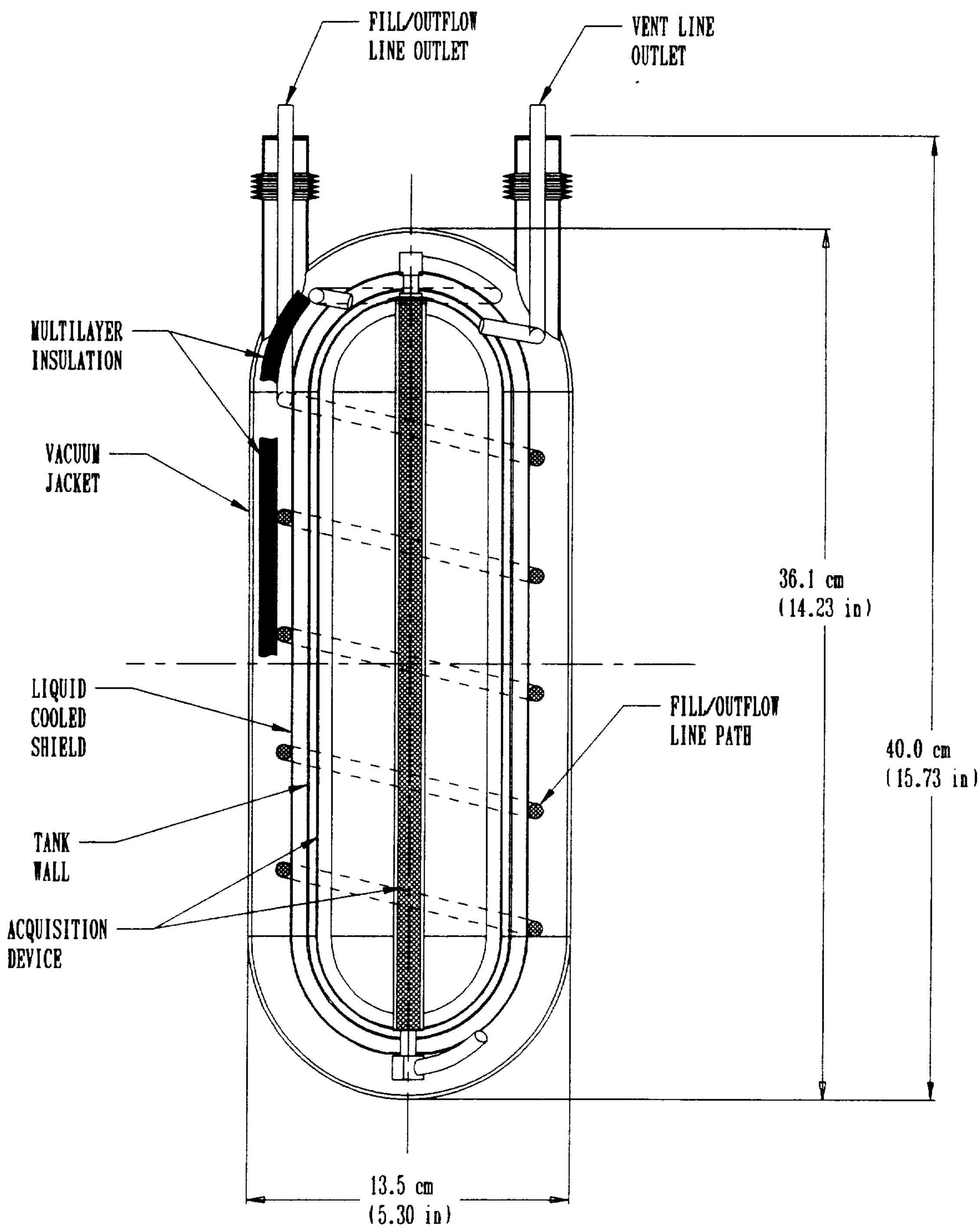

Figure 5-1 LOX Storage Tank Design

The maximum diameter that could be accomodated in the EMU envelope is 17.8 cm (7.0 inches) and the length of the primary tank is 36.3 cm (14.3 inches). This LOX tank design fits well within both of these limits. The design shown in Figure 5-1 includes the tank, a liquid acquisition device, a liquid cooled shield, multilayer insulation, a fill and drain line, a vent line, and a vacuum jacket. The liquid acquisition device employs four fine mesh screen channels, although the number of channels could possibly be reduced in the final tank design. The fill and drain line also serves as the outflow line during normal or purge flow operations. This line is attached to the acquisition device at the bottom of the tank and is coiled around and attached to the liquid cooled shield before exiting at the top of the vacuum jacket. The vent line is attached to the tank at the top and is thermally shorted to the liquid cooled shield before exiting at the top of the vacuum jacket. All fluid lines are 0.635 cm (0.25 inch) in diameter. The multilayer insulation is applied to the external surface of the liquid cooled shield. The estimated mass for this tank design is 3.7 kg (8.1 lbm).

5.2 EMU Integration Design Concepts

The replacement of the present high pressure gaseous oxygen supply in the present EMU with a cryogenic liquid oxygen system requires consideration of several significant integration issues. These result from the differences between the operating characteristics of the gaseous and cryogenic supply, and from changes in the approach to oxygen supply redundancy and fault tolerance which may accompany the change in storage mode.

5.2.1 Thermal Conditioning Approaches and Considerations-

The most significant impacts of the cryogenic oxygen supply arise in the need to vaporize and thermally condition the cryogenic liquid. These impacts are particularly severe for the failure scenarios associated with purge mode operation of the oxygen supply system, and may drive the configuration of the storage system chosen.

Heat input required to vaporize the liquid oxygen supplied from the storage tank and to heat it to an acceptable temperature for introduction into the EMU vent loop is shown at several oxygen make-up flow rates in Table 5-2 below. The effects of this heat removal on the temperature of the EMU vent loop or transport water loop under normal flow conditions are also indicated.

Table 5-2 Cryogenic Oxygen Thermal Conditioning Requirements

Condition	O_2 Flow kg/hr (lb/hr)	Heat Reqd W (BTU/hr)	Vent T Decrease °C (°F)	Water T Decrease °C (°F)
Min Metabolic	0.023 (0.05)	2.14 (7.3)	1.94 (3.5)	0.017 (.03)
Nominal	0.074 (0.164)	7.03 (24)	6.39 (11.5)	0.056 (0.1)
Max Metabolic	0.150 (0.33)	14.07 (48)	12.78 (23)	0.111 (0.2)
Ejector Purge	0.227 (0.5)	21.4 (73)	20 (36)	0.167 (0.3)
Purge	2.67 (5.9)	249.2 (850)	>222 (400)	1.95 (3.5)

As the table shows, the normal oxygen make-up flow can be readily conditioned by heat exchange with either the vent loop or the transport water loop in the EMU. In either case only limited effects on the bulk temperature of the EMU's working fluids would be expected, although for the vent loop, local generation of frost and condensate must be considered, and the heat exchanger location in the loop must be carefully evaluated. In general, the portion of the vent loop immediately upstream of the heat removal device is likely to be significantly superheated and therefore a favorable location from this perspective. The oxygen make-up flow rate required for an ejector type purge mode of operation is less than a factor of two larger than that required at maximum metabolic rate conditions and also causes only a modest decrease in loop fluid temperatures. The cryogenic oxygen flow rates associated with a full purge flow corresponding to the present EMU purge mode are much larger, and, as shown in Table 5-1, would have a severe effect on the vent loop temperature. For this scenario, only heat exchange with the transport water loop is viable without the input of considerable heat from an external source.

The consideration of thermal conditioning purge mode oxygen flows becomes more difficult when the EMU failure scenarios in which oxygen purge is required are considered. A dominant scenario for this contingency is the loss of vent loop flow associated with the failure of the fan, its drive motor, the motor control, or loss of electrical power. In this case, neither the vent loop nor the transport water flow is available as a heat source for thermal conditioning. Options considered for this scenario include the use of available thermal mass as a transient source, the recovery of the crewman's metabolic heat load through exchange with the oxygen leaving the EMU, and the provision of a supplemental source of heat for this contingency. The last of these appears to be the most desirable, but all entail appreciable penalties.

The use of thermal mass within the EMU as a transient heat source for purge gas conditioning offers the obvious advantage of simplicity. In evaluating this possibility, the present EMU was used as a guide. Although the design of an advanced EMU incorporating cryogenic oxygen storage would differ, it is likely that the general level of hardware integration and internal heat transfer would be similar. Sources of the heat which may be considered include the inventory of fluid resident in the heat exchanger normally used for thermal conditioning as well as the thermal mass of the heat exchanger and the EMU structure itself. For a 30 minute purge at the specified oxygen flow rate, approximately 448.4w (425 BTU) are required to condition all of the delivered gas to acceptable conditions. With an initial transport water loop temperature which could be as low as 15.56°C (60°F), approximately 7.71 kg (17 lbs) of water inventory in the heat exchanger would be required if the oxygen and water temperatures are to be maintained above 4.44°C (40°F). The resultant heat exchanger volume would exceed 6.55 liters (400 cubic inches). Even if as much as 70% of the water were allowed to freeze and the oxygen into the helmet permitted to be as low as 0°C (32°F), this inventory would have to be over 1.36 kg (3.0 lbm) of water. The poor heat transfer characteristics involved in this scenario would result in a substantial penalty in the metal weight and volume for this heat exchanger as well. The total volume would exceed 2.05 liters (125 cubic inches), and acceptable gas conditioning performance would be difficult to achieve. Study has revealed no practical means of exploiting the large total heat capacity of the PLSS for this purpose. Heat transfer among the components of the system is insufficient unless the delivered gas temperature is allowed to approach -28.9°C (-20°F), a value which is considered unacceptable.

Conceptually, it would be possible to recapture the heat removed from the crewman by heat exchange between the cryogenic oxygen supply stream and the gas exiting the EMU during purge operation. In practice, this approach entails serious compromise to the reliability of the purge and is deemed unacceptable. To achieve the required heat transfer, it is necessary that the exit gas be chilled by countercurrent heat exchange nearly to the temperature of the cryogenic oxygen leaving the storage vessel. As a result, not only would a substantial heat exchanger volume of 1.64 liters (100 cubic inches) be required, but the formation of ice in the heat exchanger is virtually guaranteed. The restriction of the flow of gas leaving the suit, and therefore the reduction of the supply of purge gas to the helmet below acceptable levels is highly probable.

The energy required for thermal conditioning of the purge gas represents approximately one third of the energy capacity of the present EMU electrical systems which would occupy a volume on the order of 0.82 liters (50 cubic inches) and weigh about 1.81 kg (4 lbs). The delivery of the heat from this battery could be through heaters incorporated into the heat exchanger normally used to thermally condition the oxygen at a modest weight and volume penalty. Due to the required high rate discharge and extremely infrequent use, it is likely that the optimum technology for this battery will be different from that for the principle EMU power source.

Heat exchange for thermal conditioning the cryogenic oxygen can be accomplished in a dedicated heat exchanger for that purpose or, alternatively, could be incorporated into the heat exchanger used to remove heat from the vent and transport water loops (the sublimator in the present EMU design). Each approach offers some advantages and could be preferred depending on the EMU evolutionary context in which cryogenic oxygen storage was implemented.

Advantages of integration with the vent and transport water heat exchanger include: 1) only the oxygen heat transfer surfaces and passages are added weight and volume, 2) provisions for the management and removal of condensate from the vent loop are already present, and 3) penalties on routing the vent or transport water plumbing are minimized. Its primary disadvantages lie in the complexity of the resulting component and in the potential packaging constraints which result. For use in an evolutionary modification to the present EMU, the impact of sublimator volume growth in the existing package is an added disadvantage for this approach. Preliminary calculations indicate that adequate heat transfer for all normal flows and for the ejector type purge operation could be provided by approximately a 0.16 liter (10 cubic inch) increase in the size of the present sublimator or the corresponding heat rejection component in an advanced EMU design. If the full purge flow is to be accommodated, the volume penalty for the heat exchanger is estimated to be approximately 5 times as large and, as noted above, an auxiliary heat source for purge operation appears necessary. A logical consequence of this approach is the use of a common thermal conditioning heat exchanger for redundant cryogenic storage subsystems; valving for redundancy management would interface the cryogenic, two-phase fluid upstream of the heat exchanger.

The use of a dedicated heat exchanger for oxygen thermal conditioning would permit both the storage and thermal conditioning hardware to be located within the volume presently occupied by the primary (and possible secondary) oxygen supplies. This would require more complex routing of transport water flow, but would allow the integration of cryogenic oxygen storage with minimum impact on other EMU systems. The total volume impact is somewhat greater, however. Estimated heat exchanger volume to address normal and ejector purge operational conditions is approximately 0.41 liters (25 cubic inches). In this approach, the use of separate heat exchangers for redundant storage subsytems is practical although the heat exchanger volume penalty would be doubled. This would permit the management of the redundant supplies using active components downstream of the conditioning heat exchangers. The back-up system could be readily brought on-line by a drop in system pressure as is the case in the present EMU SOP.

5.2.2 Redundancy Management - Sizing Considerations-

Based on the above discussions of cryogenic oxygen storage system design and thermal conditioning considerations, it is appropriate to consider the overall impact of the use of cryogenic oxygen storage within the context of several different approaches to redundancy and fault tolerance in addition to that implicit in the study baseline conditions. By requiring a peak flow delivery rate for purge of 2.68 kg/hr (5.9 lb/hr), the study baseline requirements imply that the cryogenic oxygen system under study will fully replace both the normally used primary oxygen supply and the emergency use secondary oxygen supply included in the present EMU. As indicated above, the total system design characteristics for a cryogenic oxygen supply are significantly different for the normal and purge use parameters. Consequently, examination of alternative integration approaches in which the cryogenic supply replaces only the primary supply, or only a portion of the function of the SOP may be beneficial in defining the best overall concept and in fairly evaluating the utility of this technology for an EMU.

Several possible approaches to the use of cryogenic oxygen storage in the EMU are compared on Table 5-3 below. These encompass the range of possibilities from a fully redundant replacement

Table 5-3 EMU Cryogenic Oxygen Storage Redundancy Management - Sizing Options

Option	EMU Volume Impact	EMU Support Impact	EMU Operational Impact
Fully Redundant - Mission and Purge	+5.74 liters (+350 cubic inches)	Maximum Cryo Usage for Cool-Down Need to Off-load Large Volume of Cryo Oxygen	Possible Loss of Purge Reliability Increased Complexity With Supplemental Heating for Purge
Redundant - Sized for Purge in Each Tank	-1.31 liters (-80 cubic inches)	High Cryo Usage for Cool-Down Need to Off-Load Large Volume of Cryo Oxygen	Possible Loss of Purge Reliability Increased Complexity With Supplemental Heating for Purge
Redundant - Sized for Mission and Purge as Total Capacity	-2.95 liters (-180 cubic inches)	High Cryo Usage for Cool-Down Need to Off-Load Large Volume of Cryo Oxygen	Possible loss of Purge Reliability Dual Failure (Fan + Cryo Subsystem) Yields Reduced Purge Duration
Redundant - Sized for Mission in Each tank Plus Conventional SOP	-5.08 liters (-310 cubic inches)	Less Cryo Usage for Cool-Down Need to Off-Load Unused Cryo Oxygen High Pressure SOP Recharge Required After Emergency Use	Increased Mission Reliability or duration - Can Continue Normal Operation with Loss of One Cryo Storage Sub-system
Redundant - Sized for Mission and Ejector Mode Purge as Total Capacity	-4.42 liters (-270 cubic inches)	Less Cryo Usage for Cool-Down Need to Off-Load Less Unused Cryo Oxygen High Pressure SOP Recharge Not Required for Most Failure Scenarios	
Non-Redundant - Sized for Normal Mission Use Only Plus Conventional SOP	-9.01 liters (-550 cubic inches)	Lease Cryo Usage for Cool-Down No Need to Off-Load Unused Cryo Oxygen (Vent Residuals) High Pressure SOP Recharge Required After Emergency Use	

for both the primary oxygen system and SOP, to the simplest possible non-redundant replacement for the primary oxygen supply only. The volume comparison shown reflect the combined volume estimates for the cryogenic storage subsystem, and the thermal conditioning hardware in comparison to the high pressure oxygen tankage replaced. The present design baseline thus comprised 7.87 liters (480 cubic inches) in primary oxygen tankage, and 2.95 liters (180 cubic inches) of storage volume in the SOP. Impacts on system plumbing and structure and questions of packaging efficiency are neglected in this preliminary comparison.

As the table shows, the benefits to the EMU design in terms of net packaging volume vary widely depending on the approach to redundancy management which is taken. The greatest net volume benefit is realized with a design which provides a single primary supply using cryogenic storage and a conventional high pressure gas secondary oxygen supply. This approach will provide essentially identical reliability and safety of operation to that achieved with the present EMU design. Depending on the state of development of emerging high pressure electrolysis technologies, this approach could provide the best over-all approach for an advanced EMU. Alternatives which address most failure scenarios through the use of a lower flow rate ejector purge operation impose limited volume penalties and may be attractive if satisfactory high pressure SOP recharge capabilities do not emerge.

5.2.3 System Monitoring and Control-

Fluid Level Gauging-One of the most critical parameters that must be monitored during the operation of the EMU is the mass of oxygen remaining in the supply system. The current approach employed in the EMU is to monitor storage tank pressures during the EVA. Since the storage tank volumes are known and the gaseous oxygen temperature is nearly constant during operation, the pressure will be proportional to the residual mass in the tank. In a liquid system, measurement of pressure or rather pressure differentials is practical for mass determination only when gravity is sufficient to provide orientation of the liquid mass in the tank and thermal effects are not suffiicent to produce significant stratification in the liquid. Such an approach is currently in the small LOX tanks used to supply oxygen to medical patients requiring oxygen therapy. Other methods currently employed in ground operations to measure liquid mass in cryogenic tanks include point level sensors, capacitance probes, and load cells. All of these methods can be used because of the consistent orientation of the liquid in the tank. In the low gravity environment of space, accelerations due to vehicle drag are insufficient to overcome surface tension forces and provide orientation of the liquid. Furthermore, accelerations generated by astronaut movement are both random and insufficient to provide a steady orientation of the liquid. Therefore, differential pressure measurements together with the other mentioned techniques cannot be used for mass measurement in the storage tank. There are presently, two methods that appear as possible candidates for gauging the mass remaining in the storagae tank. The first of these is based upon the magnetic properties of oxygen. If the magnetic core of a coil is changed, the inductance of the coil will change accordingly. If a coil is wound on the LOX tank, changing the mass of LOX in the tank may result in an inductance change in the coil that may be correlated with quantity of mass present in the tank. The possiblity of using this inductive sensing technique is currently being investigated in an in-house development program and is being monitored closely.

A second method for gauging the mass remaining in the tank is to utilize an integrating flow meter located at the outlet of the thermal conditioning heat exchanger. This will allow tracking of the vapor consummed and provide an indication of the mass remaining. The reason for locating the meter at the outlet of the heat exchanger is to avoid the possiblity of two phase flow that could occur at the inlet side of the heat exchanger. Pressure and temperature measurements would also be required at the flow meter inlet for density determination. This measuring technique would have to be verified with signifcant ground testing. To support this test, a small capacitance probe can be installed in the center of the tank beween the outlet and forward end manifolds of the liquid acquistion device in the breadboard test tank to correlate the mass outflow from the tank with the measured vapor flow in the flow meter.

Normal Operating Controls-The control of the operation of the oxygen supply system with cryogenic storage is not inherently complex. For some system architectures, it can be as simple as the oxygen control system included in the present EMU, and is not found to present insurmountable challenges for any of the system configurations under study. The introduction of a cryogenic oxygen supply will modify system heat flows to some degree, however, and may interact with crew comfort and thermal control. In particular, the effects of lower temperature flow during purge operation should be evaluated. Detailed study is in order for the development of a flight hardware design, but is not felt to be required for the present technology development/feasibility study since no major effect on the ultimate practicability of the technology is foreseen.

At its simplest, cryogenic oxygen supply system operational control consists of manually activated shut-off valves and pressure regulators like those in the present system. Proper design of the storage tank for the acquisition and delivery of liquid provides acceptable tank pressures throughout the anticipated operating duty cycles without the need for active control. Adequate control of the delivered gas temperature can be achieved through the design of the heat transfer components and the normal regulation of temperatures in the EMU's primary transport loops.

The integration of this simple control concept into a nonredundant oxygen supply system is illustrated schematically in Figure 5-2. The location of the storage shut-off valve close to the tank allows it to serve effectively to minimize the volume of external lines which are unnecessarily chilled during tank thermal conditioning in preparation for filling. As suggested on the schematic, the shut-off valve could be a three way valve used for the tank chill and fill operations as well. It is likely that, as in the present EMU design, two different regulated pressures will be desired to accommodate the delivery of feed or make-up water to a transport loop or other uses at a pressure above that of the primary ventilation loop. This is reflected in the schematic although other design solutions are possible.

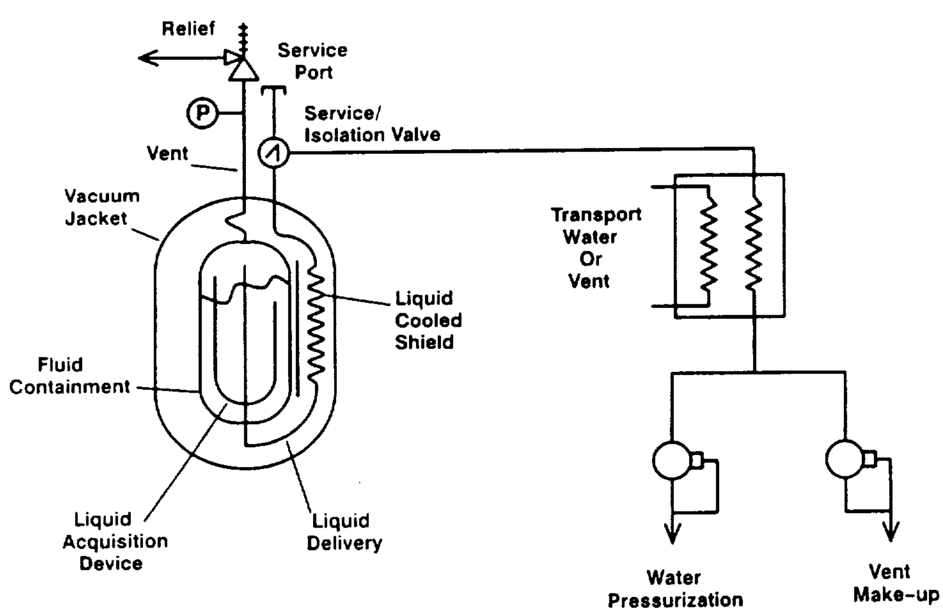

Figure 5-2 Simple Cryogenic Supply Schematic

The incorporation of redundancy into the cryogenic oxygen system can complicate the control system appreciably, although relatively simple redundant systems can be conceived. The degree of complication depends on the extent of redundancy desired and the presence or absence of multiple operating modes for each of the redundant systems.

If the thermal conditioning hardware as well as the storage subsystems are redundant, the redundancy can be managed simply by having the back-up system flow through its own pressure regulator(s) set at a lower outlet pressure than that (those) of the primary system. This approach is exactly analogous to the redundancy management approach between the primary oxygen supply and SOP in the present EMU. It has the virtue of including redundancy in the pressure regulator, a relatively high failure rate component. In this case, the back-up system, or both systems, may be designed to accommodate the normal purge flow operation specified by appropriately sizing the storage tank and the thermal conditioning hardware and by incorporating an appropriate power source for purge flow heating. The power source itself could be redundant, or in the interests of limiting weight and volume, a single source could be arranged to supply either of the two redundant systems on demand.

Figure 5-3 illustrates schematically a redundant system embodying this control approach. Control of the auxiliary heaters for purge operations is shown by simple thermostats although more sophisticated systems could be employed. The series-parallel redundant arrangement shown provides protection against overheating or loss of heating capability due to a single thermostat failure, but may not provide sufficient performance given the narrow range between normal operating temperatures and the acceptable purge temperature limits. Because of the very large ratio between the purge flow rate and the normal make-up flow requirements, it could prove desirable to size the normally operating regulator for a peak flow rate below that required for the purge and provide and additional, higher flow, component with a lower regulating pressure for the purge operation.

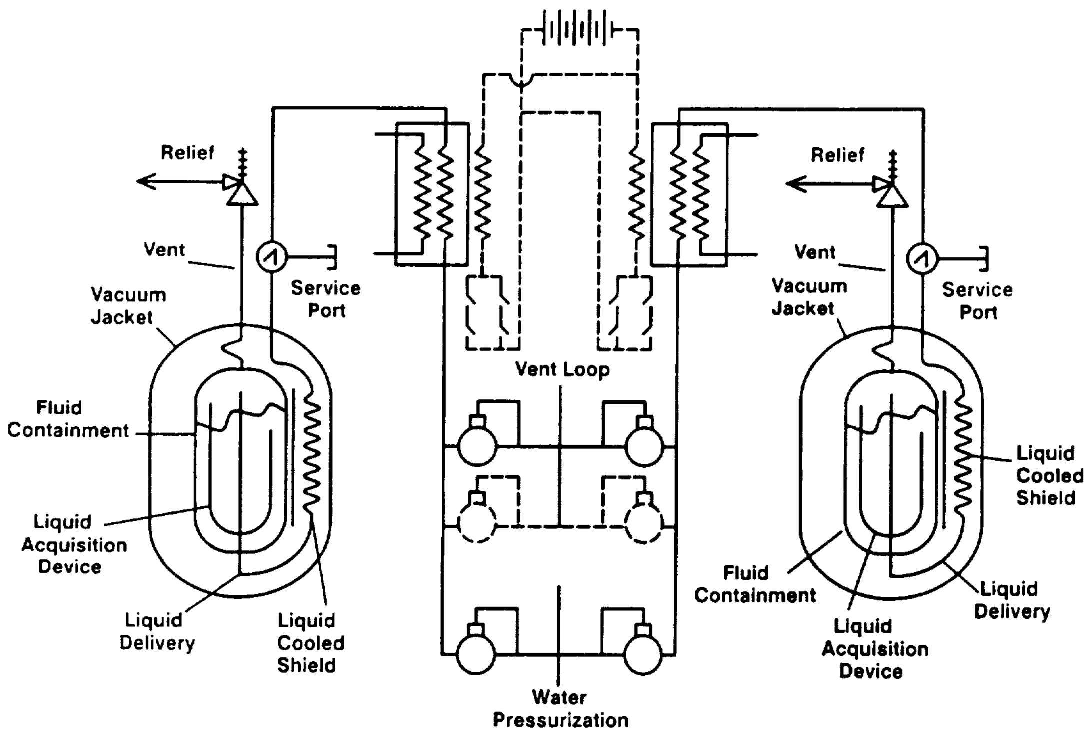

Figure 5-3 Redundant system With Purge Capability

The volume savings attainable by using a single thermal conditioning heat exchanger will be purchased at the price of additional control complexity. In this case, a common pressure regulator (or regulators) will pass the flow from both storage subsystems, and the simple expedient of different pressure settings cannot be used to pass the responsibility from on system to another in the event of a fault. It will be necessary to sense the loss of flow from the primary system and, based on that signal, actuate valves in the cryogenic fluid lines between the storage tanks and the heat exchangers to shut off the primary and connect the back-up system to the thermal conditioning hardware. This can be accomplished either through electronic sensing and electromechancial actuation, or directly by pneumatic control of the valves. The latter could be desirable from the standpoint of simplicity, reliability, and independence from other EMU failure modes, but may be difficult to manage on start-up or restart conditions or during unexpected pressure fluctuations. Figure 5-4 illustrates such a system concept. Redundant pressure regulators are shown since total loss of oxygen supply due to a single regulator failure would most assurdly be unacceptable.

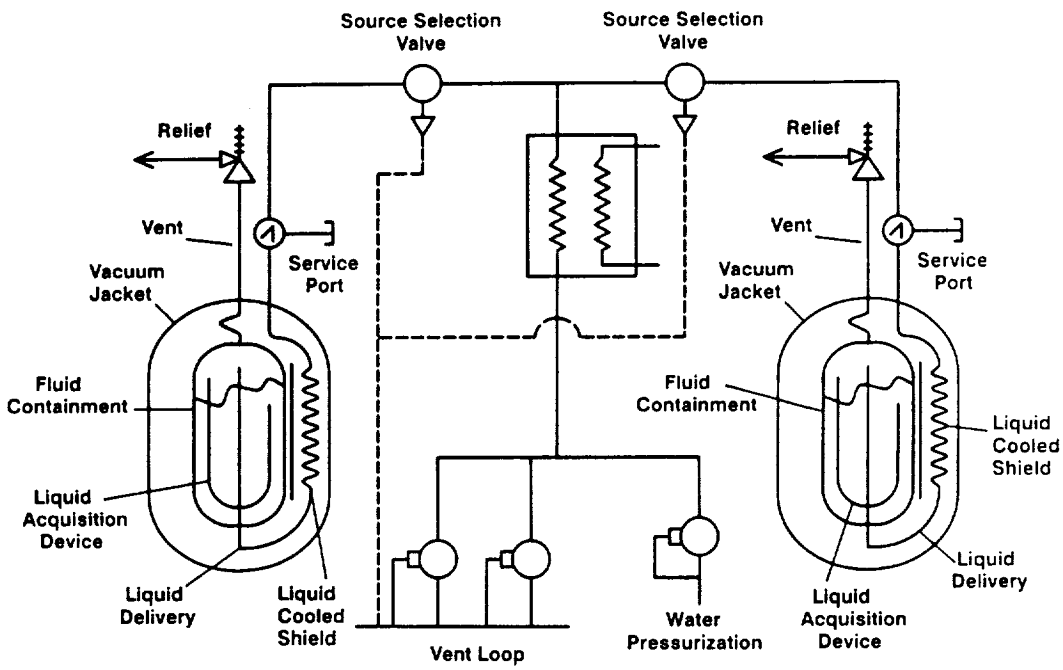

Figure 5- 4 System With Storage Redundancy Only

The provision of an ejector purge mode of operation introduces additional control challenges. The ejector purge mode flow rate is close to the maximum metabolic requirement, and the energy required for successful ejector pumping of the vent loop is expected to be close to the total available from the source flow. Consequently, it will be necessary to positively shut down the normal low pressure supply when the ejector purge mode is entered. Further, this must be accomplished in the absence of normal EMU electric power and control functions since this is precisely the scenario the purge is required to address. Possibilities to effect this control include provision of mechanically actuated valves in the feed lines to the normal and the ejector purge pressure regulators. A shut-off valve on the inlet to the purge mode regulator could be mechanically actuated to open and a corresponding valve on the normal regulator to close when the appropriately sized ejector purge discharge valve was manually opened by the crewman. More highly automated approaches are conceivable and would impose fewer constraints on the mechanical integration and packaging of the system, but introduce possible safety critical failure modes which would require careful study.

Fault Detection and Monitoring-Substitution of a cryogenic oxygen supply will affect the fault detection and monitoring provisions appropriate for the EMU oxygen feed system, but will not introduce any major technical challenges beyond that discussed with respect to fluid level gauging above.

For the storage tank itself, temperature and pressure measurements become redundant rather than complementary as they are in a conventional high pressure storage system. They could be used to cross check each other, but either provides a measure of the temperature of the fluid in the tank, and almost no information as to the quantity. Of the two parameters, pressure is less subject to local variations and errors due to lead conduction, etc. and would therefore generally be preferred. An indication of too low a pressure or temperature may reflect depletion of the fluid in the tank, an abnormal withdrawal rate, or failure of the liquid acquisition device resulting in the withdrawal of vapor from the tank. In any case, this information is indicative of a condition which should lead to the transfer of operation to the back-up supply if available. An excessive temperature or pressure would indicate an excessive stand time without fluid withdrawal or failure of the tank insulation. It should be accompanied by operation of the tank vent relief valve to limit pressures to a safe level. A pressure indication above the relief valve setting could indicate a critical safety problem requiring immediate attention (although normal practice is to design relief valves to preclude fail-closed modes).

Monitoring of the fluid delivery and conditioning system downstream of the storage tank(s) should include the measurement of the temperature and pressure of the conditioned oxygen gas supplied to the pressure regulator as well as the regulated pressure in the ventilation circuit itself. The temperature measurement will provide the detection of icing or other conditions which degrade heat transfer to the oxygen and which could precipitate secondary failures from abnormal temperatures in the pressure regulator or at the make-up inlet to the ventilation loop. Measurement of regulator inlet pressure will provides confirmation of acceptable end to end performance of the oxygen supply system, and direct measurement of a safety critical parameter. In systems where redundancy is managed through regulator pressure settings, this parameter may also serve as an indicator of the transition from primary to back-up modes of operation.

Where electrical power is used to supply heat for oxygen thermal conditioning during purge, a sensed indication of current draw in that system is also of considerable importance. The occurrence of any current draw under normal operating conditions would indicate a failure condition requiring maintenance action, and would also indicate the need to recharge or replace the heat supply battery.

5.3 System Servicing and Support

A review of the basic requirements for servicing the LOX tanks was conducted during the study. Because of the low gravity environment under which the tanks must be filled, the no-vent fill process appears to be the most practical method to be used at this time. Assuming the tanks are at ambient temperature, they must be precooled to some low temperature value so that tank overpressure conditions do not occur when the no-vent fill process can be initiated. This low temperature value has been referred to as a target temperature. It is significant in that the residual heat remaining in the tank wall at that temperature can be absorbed by the incoming liquid heat capacity without an excessive warming of the liquid bulk and a corresponding rise in vapor pressure. The target temperature does not have to be at the temperature of the incoming fluid. To accomplish the precooling or chill down of the tanks, a procedure known as a charge-vent cycle may be employed. In this procedure, a small quantity of liquid is admitted to the tank . As this quantity is vaporized, heat is absorbed from the tank wall, liquid acquisition device, liquid cooled shield, insulation and lines. The vapor is then vented to a vacuum and the injection process is repeated. When the tank temperature is at or below its target value and the tank vapor has been evacuated, the no-vent fill process can be initiated. As the name implies, the tank loading procedure will be carried out with the tank vents closed. A slight tank pressure rise will be expected as the incoming liquid compresses the ullage vapor. This no-vent fill method of tank loading has been demonstrated under an IR&D program at Martin Marietta using liquid nitrogen which has thermal properties similar to oxygen. A special fill and drain port is not provided in the tank design so that filling and draining of the tanks will be accomplished through the normal outflow line. This procedure allows for cooling of the acquisition device, the liquid cooled shield and the associated plumbing in addition to the tank material.

To satisfy the requirements for chilldown and no-vent filling of the LOX tanks, a preliminary system schematic has been developed for the servicing system. This schematic, presented in Figure 5-5, illustrates the LOX servicing unit, EMU Primary Life Support System and the interface between the two systems. The servicing system unit consist of a vacuum jacketed LOX storage dewar, a gaseous oxygen pressurization system, and associated valves and plumbing for both ground servicing and flight operations. For flight operations, the storage dewar will contain a liquid acquisition for deliver of liquid to the system interface. It was assumed in preparing the schematic that two LOX tanks were to be used in the primary life support system. Each of these tanks are equipped with their own fill and vent lines so that either sequential or parallel fill operations may be conducted. However, only two interface connections, one for filling and one for venting, are provided. Instrumentation requirements include pressure measurements in the servicing unit plumbing and wall temperature and liquid gauging measurements in both tanks. A liquid flow meter is also included in the LOX supply line to the interface.

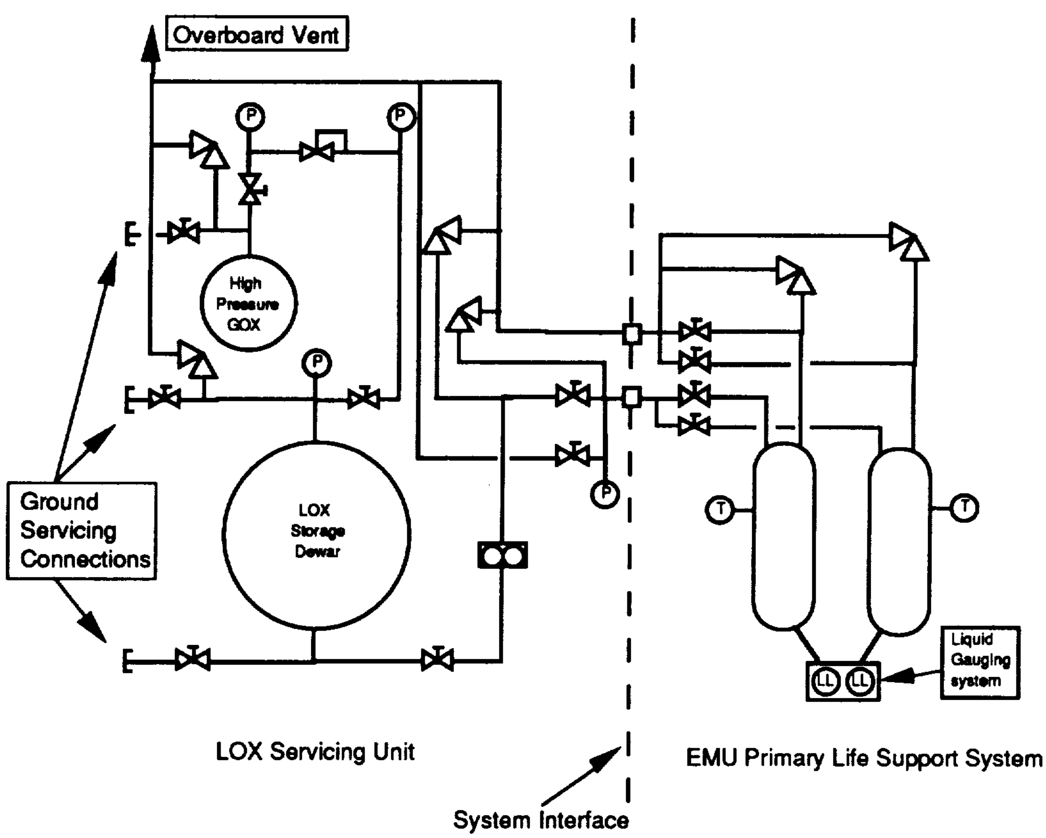

Figure 5-5 EMU LOX Servicing System

5.4 Breadboard System Design

A breadboard test program can provide useful information and data for the design and integration of a LOX storage system into the EMU. Four major issues that must be investigated by this program are the demonstration of the storage tank outflow characteristics, the demonstration of thermal conditioning operation, development and verification of a liquid gauging system, and the development of LOX tank servicing procedures. While the breadboard testing will be done under a one-g environment, the possible use of the breadboard system hardware in a flight experiment is also a factor that can influence its design.

To address these issues, a preliminary schematic of the breadboard system has been prepared and is presented in Figure 5-6. This schematic was developed for the recommended storage system concept. A single tank is employed in the system, since both normal and purge outflow requirements and can be demonstrated. Thermal performance can also be evaluated. One concern in using the recommended design is that when the tank is mounted vertically, as indicated in the schematic, complete liquid expulsion will not be demonstrated because of hydrostatic pressure limitations present in the one-g environment. A preliminary pressure loss analysis of the liquid acquisition system indicated that channel frictional and screen flow losses are negligible, even at the highest purge flow rate. The hydrostatic pressure difference is the dominating loss, but this is not surprising at the high g-level. Complete expulsion can be demonstrated if the storage tank centerline is tilted approximately 55 degrees to the vertical so that the hydrostatic pressure limit is reached at the end of the expulsion process. An alternative to tilting the test tank is to reduce the length with the corresponding reduction in stored liquid mass. Further analysis to establish the final tank design is required.

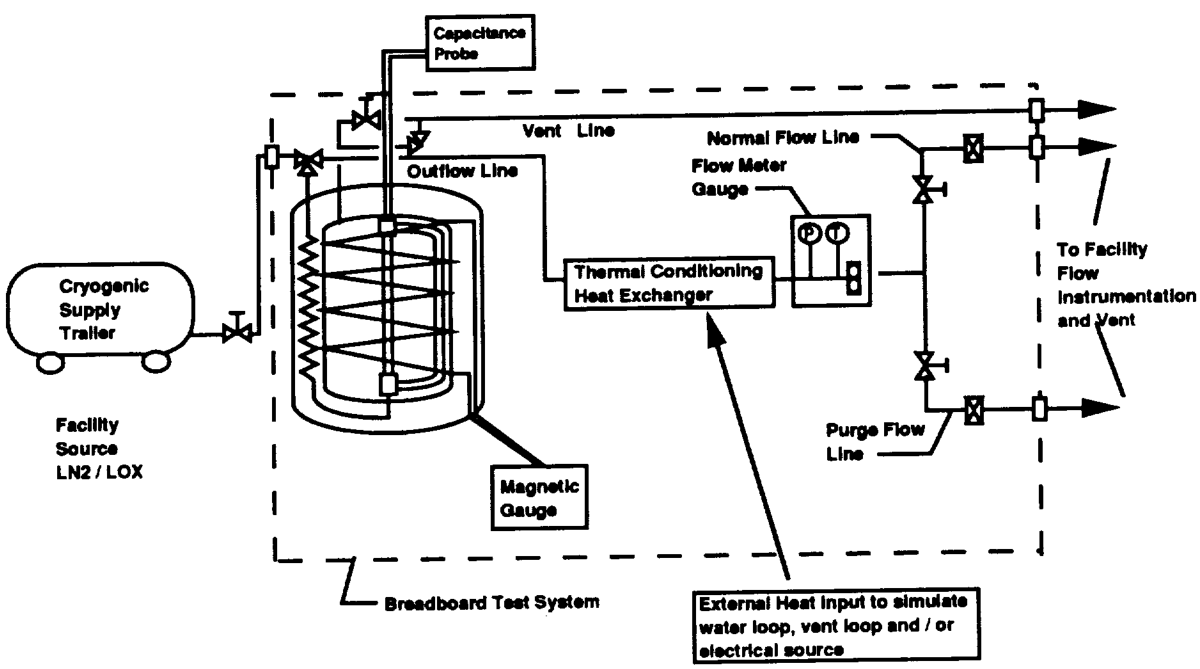

Figure 5-6 Breadboard Test System Schematic

The schematic also shows a thermal conditioning heat exchanger system. The preferred configuration for the system is unknown at the present time. More study and design effort is required. Various sources of heat have been identified in the discussion in a previous section of this report and are also indicated in the schematic.

The third major issue is the development and evaluation of a gauging technique for use in the system. Two approaches that have been identified previously in this report are the magnetic system and the integrated flow system. Both of these systems have been identified in the schematic. To support the evaluation of these systems, a capacitance probe for measuring liquid level in the tank is shown installed between the upper and lower manifolds of the acquisition device. During outflow, this probe will provide data for evaluating the performance of the two candidate gauging systems.

Servicing operations, specifically the filling of the LOX storage tank, makes up the fourth major issue to be addressed by the breadboard test system. For filling the tank in space, the preferred approach is to use a charge-vent cool down process followed by filling of the tank with the vent closed (i.e. no-vent fill). The charge vent process required injecting small quantities of liquid into the tank, allowing vaporization to occur, and then venting the vapor to a vacuum. This vaporization and venting process removes heat from the tank, acquisition device, liquid cooled shield, insulation, and tubing. The charge-vent process is repeated until tank temperatures are at a value that will permit filling the tank under no-vent conditions with only a small permissible increased in temperature. The capacitance probe in the tank will also support development of the tank filling procedures.

Complete instrumentation required in the breadboard system is not shown in the schematic. Tank pressure and pressures at various points fin the plumbing system would be defined and incorporated when the design is more firmly established. Temperature measurements on the tank wall, liquid shield, and outflow and thermal conditioning heat exchanger lines would also be required.

It is recommended that testing be accomplished with both liquid nitrogen and LOX. Initial testing with nitrogen provides a thermal shock test for all hardware and plumbing and can be used to verify testing procedures. The only issue that cannot be addressed with nitrogen testing is the magnetic gauging technique. Ultimately, LOX must be used in developing that system.

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16. Abstract

The storage of life support oxygen in an Extravehicular Mobility Unit in the liquid state offers some advantages over the current method of storing the oxygen as a high pressure gas. In the first place, storage volume is reduced because of the increased density associated with liquid. The lower storage and operating pressures also reduce the potential for leakage or bursting of the storage tank. The potential for combustion resulting from adiabatic combustion of the gas within lines and components is substantially reduced. Design constraints on components are also relaxed due to the lower system pressures.

A design study was performed to determine the requirements for a liquid storage system and prepare a conceptual design. The study involved four separate tasks. The first was to identify system operating requirements that influence or direct the design of the system. The second task was to define candidate storage system concepts that could possibly satisfy the requirements. An evaluation and comparison of the candidate concepts was conducted in the third task. The fourth task was devoted to preparing a conceptual design of the recommended storage system and to evaluate concerns with integration of the concept into the EMU. The results of this study are presented in this report.

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