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PROPELLANT TRANSFER: ATTACHED DEPOT

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Propellant transfer at an attached depot involves: 1) resupply tankers (dedicated launch from the ground or scavenging from the External Tank) to resupply the depot: 2) depot storage and supply tanks (attached, free-flyer or tethered) from which liquid hydrogen and liquid oxygen are transferred to fill the space-based OTV; and 3) the space-based OTV which is resupplied with cryogens from the depot. Liquid storage and supply, thermal control and transfer/resupply requirements for an attached depot are listed, and technologies defined. The specific fluid management elements and approaches for an attached depot are defined. The Cryogenic Fluid Management Facility (CFMF) Shuttle attached-payload test bed, scheduled for a mid-1988 first launch, will provide much of the needed technology.

Three elements are involved in the propellant transfer operation associated with an attached depot — a resupply tanker, a space station depot and a user system such as a space-based OTV. The technologies that are involved for each are shown on this chart. Liquid storage and supply is an element of each one of these systems as is thermal control. For the resupply tanker the thermal control period is relatively short, on the order of several days. For the space station depot the thermal control is relatively long, on the order of several months, perhaps 90 days or 180 days. For the space-based OTV the thermal control requirement is of intermediate length, perhaps on the order of several weeks. The space station depot not only must be resupplied by the resupply tanker, but in turn is the supply source for transferring propellant to the space-based OTV. The space station depot must be resupplied and also must be a supply source. For the OTV, resupply to initiate the next mission is accomplished prior to the mission. Fluid transfer is key to the space basing of OTVs.

ON-ORBIT CRYOGENIC FLUID MANAGEMENT

RESUPPLY TANKER (RT) (DEDICATED OR STS SCAVENGING)	SPACE STATION DEPOT (SSD) (ATTACHED, FREE FLYER OR TETHER)	SPACE-BASED OTV (SB OTV)
• LIQUID STORAGE AND SUPPLY	• LIQUID STORAGE AND SUPPLY	• LIQUID STORAGE AND SUPPLY DURING MISSION
• THERMAL CONTROL (RELATIVELY SHORT TERM ~ SEVERAL DAYS)	• THERMAL CONTROL (RELATIVELY LONG TERM ~ SEVERAL MONTHS)	• THERMAL CONTROL (INTERMEDIATE TERM ~ SEVERAL WEEKS)
	- - - - - - - - - - - - -	
	• RESUPPLY/TRANSFER CAPABILITY INCORPORATED IN DESIGN	• RESUPPLY TO INITIATE NEXT MISSION - FLUID TRANSFER CAPABILITY KEY TO SPACE-BASING

Figure 1

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The functions that make up cryogenic fluid management are liquid storage and supply, thermal control and fluid transfer and resupply. Liquid storage and supply involves liquid acquisition devices that acquire the liquid in low-g, and retain it in a position to be transferred as single-phase liquid using capillary or fine-mesh screen acquisition devices. Thermal control can either be passive or active, and fluid transfer involves receiver tanks as well as a transfer line.

DEFINITION - IN-SPACE CRYOGENIC FLUID MANAGEMENT (CFM)

- LIQUID STORAGE/SUPPLY (LS/S)
  - ACQUISITION/RETENTION
  - SINGLE PHASE LIQUID EXPULSION
- THERMAL CONTROL (TC)
  - PASSIVE SYSTEMS
  - ACTIVE SYSTEMS
- FLUID TRANSFER/RESUPPLY (FT/R)
  - RECEIVER TANK
  - TRANSFER LINE

Figure 2

This chart lists some of the fluid management requirements for an attached or free-flier depot. Fluid acquisition devices are designed to feed single-phase liquid down to low residuals, on the order of several percent of the loaded volume. Relatively high volumetric flow rates may be required to transfer propellant to an OTV in a several-hour transfer period. We would like not to have an imposed gravity or settling as part of the transfer operation because some systems may be limited by having special low-gravity requirements. The depot must incorporate adequate meteoroid protection. A key technology is the ability to gauge the mass of liquid in the supply and receiver systems so we can determine when it is time to stop the resupply operation. Two particularly important requirements involve contaminant or particle buildup in the tank over time when we are running basically a filling-station type operation, and the impact that slosh forces generated by liquid moving within the tank systems may have upon attitude control.

The purpose of the thermal control system is to minimize boil-off losses. Some studies have indicated a 90-day resupply time period is a reasonable operational criterion, in which case the thermal control system should be designed to provide up to 180 days for a contingency storage period assuming the resupply launch does not occur as planned. One attractive thermal control approach is to integrate the entire hydrogen-oxygen system by using a coupled heat exchanger which allows the boiloff from the hydrogen system to thermally condition the oxygen system to prevent or minimize the boiloff of oxygen.

From a fluid transfer and resupply technology standpoint, the capacity is needed to top partially full tanks. This is consistent with the concept of making the resupply operation somewhat similar to a filling station operation, where we would not empty the tanks every time we were ready to refill, but merely top a tank that had already been filled and partially used. Mass gaging is again a very key technology when we consider how we are going to control the operations of transferring fluid from one tank to another, knowing when we have completed the transfer process. It is important that we minimize rapid venting in the vicinity of the space station or other payloads. It may be that separate catch tanks are required for reliquefaction if venting of vapors, in particular non-condensibles, is damaging to payload elements. Resupply on 90-day intervals has already been discussed. Diagnostics for efficient operational control and safety will also be a part of any transfer system.

ATTACHED OR FREE-FLYER DEPOT FLUID MANAGEMENT REQUIREMENTS

- LIQUID STORAGE AND SUPPLY
  - SINGLE-PHASE LIQUID FEED TO LOW RESIDUALS (~ 2 PERCENT)
  - RELATIVELY HIGH VOLUMETRIC FLOW RATES (FILL OTV IN SEVERAL HOUR TRANSFER OPERATION)
  - NO IMPOSED GRAVITY/SETTLING REQUIREMENTS
  - INCORPORATE ADEQUATE METEOROID PROTECTION
  - GAUGE MASS TO DETERMINE TIME FOR RESUPPLY
  - DESIGNED FOR ADEQUATE SUPPLY PRESSURE TO TRANSFER FLUID
  - MINIMIZE CONTAMINANT AND PARTICLE BUILD-UP IN TANK OVER TIME
  - MINIMIZE SLOSH AND ITS IMPACT ON SPACE STATION ATTITUDE CONTROL
- THERMAL CONTROL
  - PROVIDE 180 DAYS OF STORAGE, MAINTAINING DESIRED SATURATED CONDITIONS (QUALITY OF LIQUID WITH TIME)
  - MINIMIZE BOILOFF LOSSES
  - INTEGRATE THERMAL CONTROL OF ENTIRE HYDROGEN/OXYGEN SYSTEM (COUPLED HEAT EXCHANGER APPROACH)
- FLUID TRANSFER/RESUPPLY
  - PROVIDE CAPABILITY TO TOP PARTIALLY FULL TANKS
  - GAUGE MASS/METER MASS FLOW TO CONTROL OPERATIONS
  - MINIMIZE NEED FOR RAPID VENTING INTO SPACE OF SIGNIFICANT QUANTITIES OF VAPOR (INCLUDING NON-CONDENSIBLES). MAY REQUIRE SEPARATE 'CATCH TANKS' OR RELIQUEFACTION.
  - RESUPPLY ON 90-DAY INTERVALS
  - INCORPORATE DIAGNOSTICS FOR LEAK DETECTION, OPERATIONAL CONTROLS, ETC.

Figure 3

This chart shows a depot concept with a coupled tank thermodynamic vent system. In this concept we refrigerate at the liquid hydrogen tank vapor-cooled shield. Circulators and a radiator panel are included as part of the heat rejection system. Hydrogen is fed as single-phase fluid from the total communication acquisition device, through an expander where it becomes two-phase fluid, and into a thermodynamic vent heat exchanger. The heat exchanger is attached to the vapor-cooled shield. Once the fluid reaches the end of the heat exchanger on the vapor-cooled shield, it is routed to a heat exchanger that could either be on the liquid oxygen supply tank or on the shield around the tank. The hydrogen is then vented overboard or reliquified. By coupling the heat exchanger of the hydrogen tank to the oxygen tank we can minimize or prevent the boiloff of oxygen.

DEPOT CONCEPT-COUPLED TANK WITH REFRIGERATION AT LH_2 TANK VCS

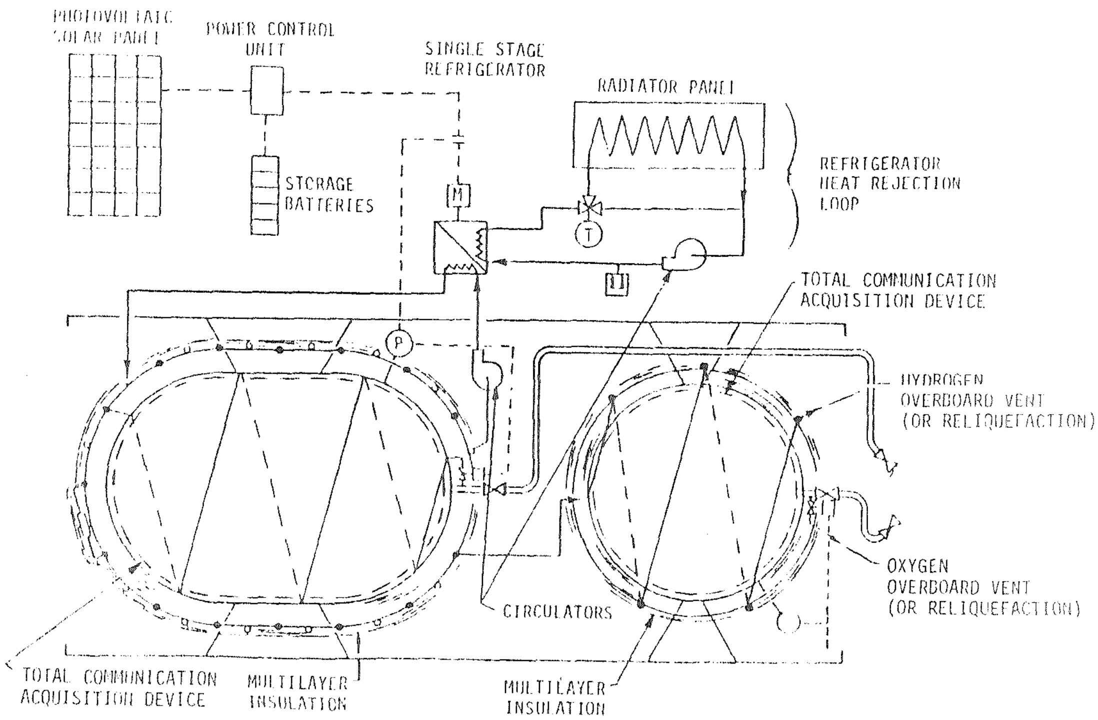

Figure 4

A prioritization of the cryogenic fluid management technologies relative to the resupply tanker, the space station depot and the space-based OTV was performed. This chart shows the various categories that were considered and a description of the prioritization criterion for each. Category one includes technologies that must be addressed as an enabling technology. Category two contains technology items which must be addressed for efficient design, such as minimizing weight, minimizing losses of fluid such as boiloff losses, or maximizing performance. Category three includes technologies which provide an intermediate performance gain. Categories four and five represent technology categories which can either be designed around with minimum impact or are not required for the application.

REQUIREMENTS PRIORITIZATION CATEGORIES

CATEGORY	DESCRIPTION
1	ITEM MUST BE ADDRESSED - ENABLING TECHNOLOGY
2	TECHNOLOGY MUST BE ADDRESSED FOR EFFICIENT DESIGN (MIN WEIGHT, MIN LOSSES, MAX PERFORMANCE, ETC.)
3	TECHNOLOGY WHICH PROVIDES INTERMEDIATE PERFORMANCE GAINS
4	TECHNOLOGY REQUIREMENTS THAT CAN BE DESIGNED AROUND WITH MINIMUM ADVERSE IMPACT
5	TECHNOLOGY NOT REQUIRED FOR APPLICATION

Figure 5

The liquid storage and supply technology priority assessment is shown for the resupply tanker, the space station depot, and the space-based OTV. For fluid management systems direct outflow with settling for the space-based OTV is an enabling technology. A total communication device which allows contact of the liquid in all locations of the tank is an enabling technology for the space station depot because settling would be disruptive to the stabilization of the space station. Autogenous pressurization is an enabling technology for the depot because the interjection of a non-condensible pressurant, such as helium, to assist in transferring the cryogen from the space station to user tanks, is disruptive to resupplying the depot as a partially full tank. The filling of a partially full tank is discussed in more detail on a later chart that addresses the transfer/resupply priority assessment. Mass gaging and instrumentation are key technologies for the resupply tanker and the depot because of the control required for the transfer process.

LIQUID STORAGE/SUPPLY TECHNOLOGY REQUIREMENTS PRIORITY ASSESSMENT

	APPLICATIONS		
	RT	SS DEPOT	SB OTV
• FLUID MANAGEMENT SYSTEMS			
ACQUISITION/EXPULSION SYSTEMS			
DIRECT OUTFLOW WITH SETTLING	5	5	1
TOTAL COMMUNICATION DEVICE	2	1	5
PARTIAL COMMUNICATION DEVICE	5	5	2
PRESSURIZATION SYSTEMS			
AMBIENT HELIUM	2	2	2
CRYO-COOLED HELIUM	2	2	2
AUTOGENOUS	3	1	3
SLOSH CONTROL SYSTEMS	4	2	3
- - - - - - - - - - - - - - - - -			
• ADDITIONAL TECHNOLOGY ISSUES			
START TRANSIENTS	4	4	3
OUTAGE/PULLTHROUGH	3	3	3
MASS GAGING/INSTRUMENTATION	1	1	2
NON-CONVENTIONAL TANKAGE	3	5	2

Figure 6

A total communication acquisition device is shown schematically in this chart. Fine-mesh screen channels form the total communication device, allowing communication with all regions of the tank. In low-g the liquid tends to fill in between the tank wall and the channel, and therefore allows expulsion to a very small residual. Channel devices similar to this have been considered for applications to tanks as large as 14-foot in diameter. Even with the low surface tension of liquid hydrogen good expulsion efficiencies are obtainable.

TOTAL COMMUNICATION LIQUID ACQUISITION DEVICE

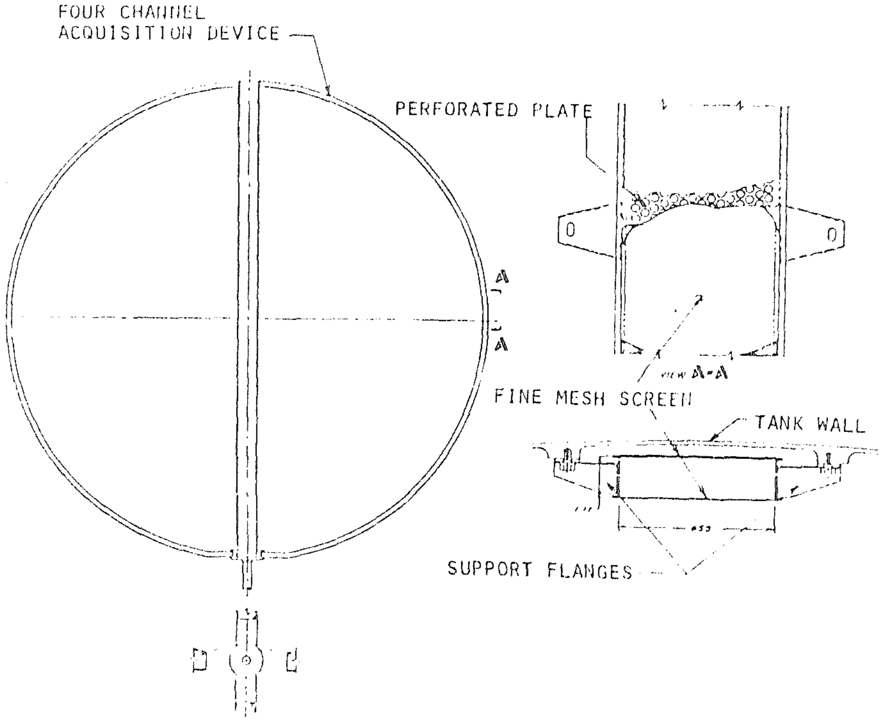

Figure 7

The technology priority assessment for thermal control is shown here. For the resupply tanker, thermal protection systems that will allow efficient ground operation and lightweight tankage for launch operations would include purged MLI and foam underneath the purged MLI. The foam underneath the purged MLI allows gaseous nitrogen rather than gaseous helium to be used as the purge gas and this decreases the heat flux by about a factor of six while the tanks are loaded and still on the ground. Internal and external heat exchangers as part of thermodynamic vent systems are key technologies in terms of effective thermal control and minimizing boiloff losses.

Some additional thermal control technology issues are listed here. One important issue is the degradation that may occur over time with the insulation system. Insulation can be designed to a prescribed requirement and if that insulation degrades significantly over time severe thermal performance impacts will result.. It is important to pay attention to contamination, meteoroid impacts, atomic oxygen degradation on the insulation performance. Thermal conditioning of the outflow is also important to preserving the quality or condition of the fluid that is being transferred from the resupply tanker into the depot or from the depot into the space-based OTV.

THERMAL CONTROL TECHNOLOGY REQUIREMENTS PRIORITY ASSESSMENT

	APPLICATIONS		
	RT	SS DEPOT	SB OTV
• THERMAL PROTECTION SYSTEMS			
VACUUM JACKET/INSULATION (DEWAR)	4	3	5
PURGED - MLI	1	3	3
FOAM - MLI	1	3	3
• THERMAL MANAGEMENT SYSTEMS			
THERMODYNAMIC VENT SYSTEMS			
- INTERNAL HEAT EXCHANGER	3	1	1
- EXTERNAL HEAT EXCHANGER (INCLUDING VAPOR-COOLED SHIELD)	3	1	1
- COUPLED HEAT EXCHANGER (VENT FREE STORAGE)	3	3	2
- PARA-TO-ORTHO CONVERSION	3	2	2
DIRECT TANK VENTING WITH SETTLING	5	5	2
REFRIGERATION SYSTEMS	5	3	3
• ADDITIONAL TECHNOLOGY ISSUES			
INSULATION REUSABILITY (NON-DEWAR)	1	4	2
INSULATION DEGRADATION (WITH TIME)	5	1	1
SUPPORTS/LINES/PENETRATION HEAT LEAKS	2	2	2
THERMAL ACOUSTIC OSCILLATIONS	3	2	2
CONVECTION CONTROL	4	2	2
THERMAL CONDITIONING OUTFLOW	1	3	1

Figure 8

This chart illustrates schematically the tanker concept with a total communication liquid acquisition device in the supply tank, and a depot which would also contain a total screen acquisition device. For the depot we have shown the hydrogen autogenous pressurant system which would be preferred considering the topping of a partially full tank by a resupply tanker. We would then preclude the problem of having to vent noncondensibles to precondition the tank and lower the pressure to allow the transfer process to occur. The resupply tanker could use a helium pressurant system to expel liquid in the tanks since it will be taken back to the ground, expelled and reconditioned for filling for the next resupply operation.

FLUID TRANSFER/RESUPPLY - TANKER TO DEPOT

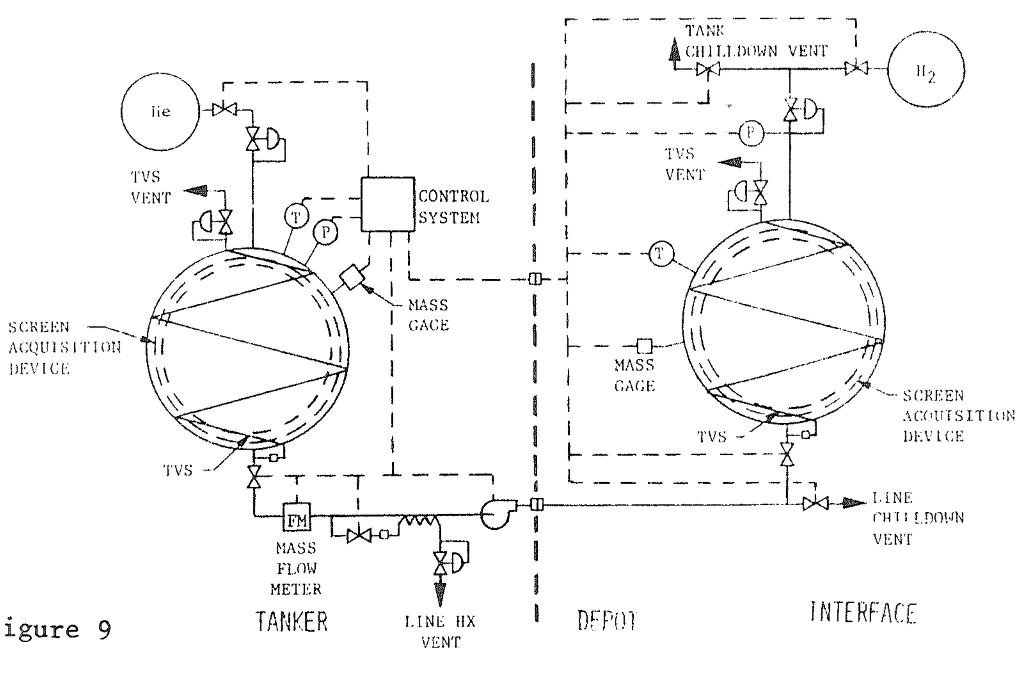

Figure 9

This chart depicts the depot and the space-based OTV. Again, the depot has a spherical tank with a total communication device and a gaseous hydrogen autogenous pressurant system. The space-based OTV would likely be non-spherical tank similar to the cylindrical tank shown, possibly having a start basket or partial acquisition device for fluid management. Elements of the system would again consist of mass gages and mass metering devices to allow us to control the operation and status when we had filled the system. The space-based OTV would likely have some kind of chill and fill system that would allow chilldown of the initially dry and empty tank prior to the filling of the tank. The filling of the tank would likely be accomplished by what's called a no-vent fill operation.

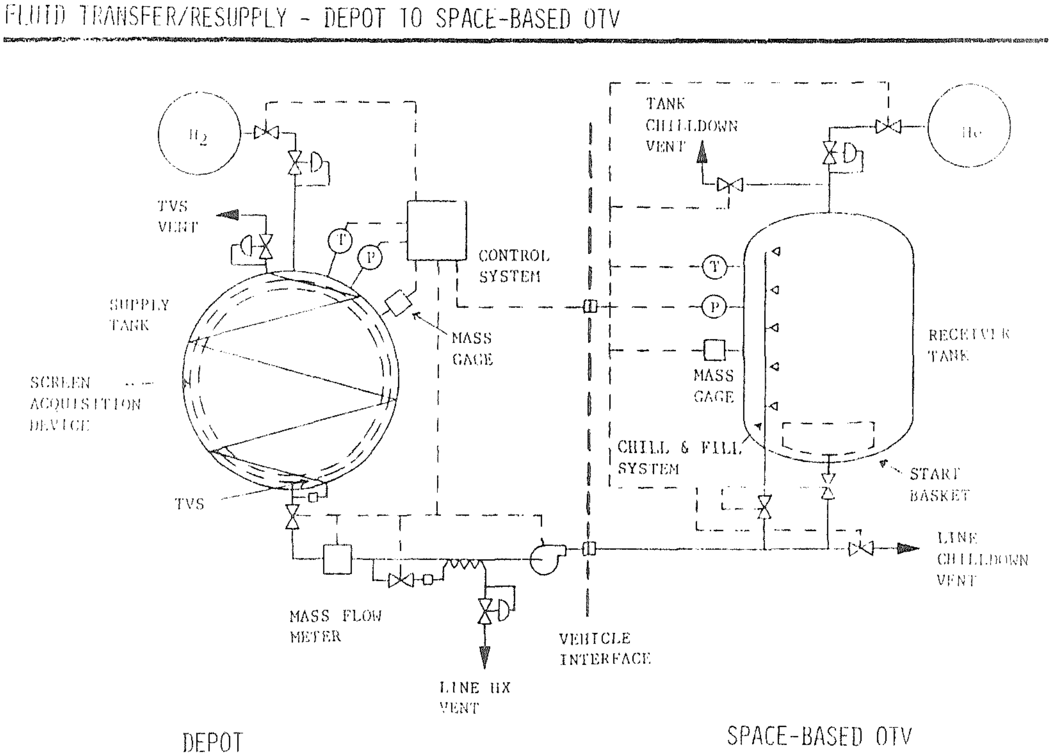

Figure 10

This chart shows fluid transfer/resupply technology requirements. If we have initially empty tanks, as we might have with a space-based OTV, then we would have to go through a childown prior to accomplishing a no-vent fill. For the space station depot we would likely be topping a partially full tank. No-vent fill is a preferred resupply technology and venting of noncondensibles is undesirable. Transfer line chilldown and quick disconnects represent technologies that are enabling for this kind of operation. As can be seen from this chart compared to the charts for liquid storage and supply and thermal control, there is much more enabling technology that is required.

The mass gaging and quality metering technology issues associated with fluid transfer and resupply are again identified as enabling. Long-term effects are important, but the storage periods for the space-based operations have not been clearly defined and the repeated cycling determination aspects have not been delineated. These could become enabling based on the particular operational scenarios proposed and implemented.

FLUID TRANSFER/RESUPPLY TECHNOLOGY REQUIREMENTS PRIORITY ASSESSMENT

	APPLICATIONS		
	RT	SS DEPOT	SB OTV
• RECEIVER TANK			
EMPTY			1
CHILLDOWN			1
ACQUISITION DEVICE FILL			1
VAPOR COLLAPSE			1
PURGE, NON-CONDENSIBLES			2
NO-VENT FILL			1
PARTIALLY FULL		1	
VENTING NON-CONDENSIBLES		2	
NO-VENT FILL		1	
VENTED FILL		2	
• TRANSFER LINE			
CHILLDOWN	1	1	1
QUICK DISCONNECT	1	1	1
• ADDITIONAL TECHNOLOGY ISSUES			
MASS GAGING	1	1	1
MASS/QUALITY METERING	1	1	1
PUMP VS. PRESSURIZED TRANSFER	2	2	2
LONG TERM EFFECTS			
REPEATED CYCLING DEGRADATION	3	3	3
CONTAMINATION	2	2	2

Figure 11

This chart summarizes the fluid management technology requirements based upon the previous prioritization assessment. The last item addresses an issue of scavenging propellant from the Shuttle External Tank (ET) following boost. Since topping a nearly full depot tank with propellant scavenged from the ET at different saturation conditions may be difficult, it may be required to handle scavenged propellants in separate tanks.

ATTACHED OR FREE-FLYER DEPOT FLUID MANAGEMENT TECHNOLOGIES

- TOTAL COMMUNICATION LIQUID ACQUISITION DEVICE
- AUTOGENOUS PRESSURIZATION
- INTERNAL AND COUPLED THERMODYNAMIC VENTS FOR THERMAL (PRESSURE) CONTROL AND PROPELLANT CONDITIONING
- THERMAL CONTROL SYSTEM PROTECTION FROM ENVIRONMENT (CONTAMINATION, ATOMIC OXYGEN, ETC) TO PREVENT DEGRADATION WITH TIME
- MASS GAUGING, INSTRUMENTATION, CONTROL SYSTEM AND DIAGNOSTICS
- MUST BE CAPABLE OF BEING RESUPPLIED AS A PARTIALLY FULL TANK AS WELL AS A DRY, WARM TANK
- DIFFERENT SIZE TANKS MAY BE REQUIRED TO HANDLE SCAVENGED PROPELLANT SINCE TOPPING NEARLY FULL DEPOT TANKS WITH PROPELLANT AT A DIFFERENT SATURATION CONDITION MAY BE DIFFICULT.

Figure 12

A Cryogenic Fluid Management Facility (CFMF) has been planned to obtain much of the data that has been discussed for attached depot operations. The purpose of the facility is to carry a reusable test bed into space attached to the Orbiter to obtain basic data on cryogenic fluid management. The facility uses liquid hydrogen as the test fluid and is designed for seven Shuttle flights. The detailed design of the facility is nearly complete, and mission planning is now proceeding for three flights. The facility will provide data to allow low-g verification of fluid and thermal models that encompass methods of integrating pressure control, liquid acquisition device and liquid transfer concepts. The experimental data will provide the data base for design criteria applicable to subcritical cryogenic systems in space and will provide the technology required to efficiently and effectively manage those cryogens.

CRYOGENIC FLUID MANAGEMENT FACILITY (CFMF)

DESIGN, FABRICATE, AND CARRY INTO SPACE A REUSABLE TEST BED WHICH WILL BE UTILIZED TO PROVIDE THE TECHNOLOGY REQUIRED TO EFFICIENTLY AND EFFECTIVELY MANAGE CRYOGENS IN SPACE

- LIQUID HYDROGEN TEST FLUID
- DESIGNED FOR SEVEN SHUTTLE FLIGHTS
  CURRENT MISSION PLANNING FOR THREE FLIGHTS
- LOW-G VERIFICATION OF FLUID AND THERMAL MODELS - METHODS OF INTEGRATING PRESSURE CONTROL, LIQUID ACQUISITION AND LIQUID TRANSFER CONCEPTS.
- ESTABLISHMENT OF DESIGN CRITERIA FOR SUBCRITICAL CRYOGENIC SYSTEMS IN SPACE

Figure 13

The Cryogenic Fluid Management Facility will provide enabling technology for the space station cryogenic fluid elements, and associated cryogenic users such as the space-based OTV. The emphasis of the facility is on liquid acquisition devices and thermodynamic vent systems and how they can be integrated together for effective storage and thermal control, and on liquid transfer and resupply operations. The seven-day Shuttle operation with an attached payload does not permit thorough testing of long-term storage effects. Current planning is for three missions with the first launch about mid-1988, and subsequent launches on six to nine month intervals.

CFMF APPLICABILITY TO CRYO FLUID MANAGEMENT TECHNOLOGY NEEDS

- CRYOGENIC FLUID MANAGEMENT FACILITY WILL PROVIDE ENABLING TECHNOLOGY FOR SPACE STATION CRYO FLUID ELEMENTS AND ASSOCIATED CRYO USERS SUCH AS THE OTV.
- EMPHASIS IS ON LIQUID ACQUISITION DEVICES, THERMODYNAMIC VENT SYSTEMS, AND LIQUID TRANSFER/RESUPPLY
- MAXIMUM SEVEN DAY SHUTTLE FLIGHT DOES NOT PERMIT THOROUGH TESTING OF LONG TERM STORAGE CONCEPTS.
- CURRENT PLANNING IS FOR THREE MISSIONS; FIRST LAUNCH ABOUT MID-1988

Figure 14