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LONG TERM CRYOGENIC STORAGE FACILITY SYSTEMS STUDY

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The LTCSFSS is a Phase A study of a large capacity orbital propellant depot for the space based, cryogenic orbital transfer vehicle. The study is being performed for Marshall Space Flight Center by General Dynamics Space Systems Division and has five principal objectives:

1) Definition of preliminary concept designs for four storage facility concepts

2) Selection of preferred concepts through the application of trade studies to candidate propellant management system components

3) Preparation of a conceptual design for an orbital storage facility

4) Development of supporting research and technology requirements

5) Development of a test program to demonstrate facility performance

The initial study has been completed, and continuation activities are just getting underway to provide greater detail in key areas and accommodate changes in study guidelines and assumptions.

A total of eighteen major trade studies were performed, leading to the selection of both an all-passive concept and a total reliquefaction concept for managing cryogen boiloff. The all-passive concept may be preferred if the facility is located on a free-flying platform; the total reliquefaction concept may be preferred if its located on the Space Station.

Eighteen enabling technology needs were identified and task plans prepared along with cost and duration estimates. They total about $12 million and range from two to six years duration.

Several testing options were identified for reducing the technical risk associated with fielding the orbital propellant depot. On the bases of risk reduction, schedule compatibility and cost, an option was selected that involves performing a short term orbital flight experiment in the Orbiter cargo bay with a subscale, integrated hydrogen storage and transfer system.

The four propellant storage concepts are very similar: all route hydrogen boiloff through vapor-cooled shields (VCSs) on the hydrogen and oxygen tanks. Concepts 1, 2 and 3 store both hydrogen and oxygen boiloff in high pressure accumulators, whereas Concept 4 reliquefies all boiloff and returns it to the tanks. Concept 2 has an additional shield that is connected to a refrigerator. Concepts 1, 2 and 3 use high pressure accumulated oxygen boiloff for oxygen tank autogenous pressurization during OTV tanking. Concept 4 uses a liquid pump and heat exchanger to provide autogenous oxygen pressurization. Concept 3 is the only concept using high pressure accumulated hydrogen for hydrogen tank autogenous pressurization. The other concepts use a pump and heat exchanger.

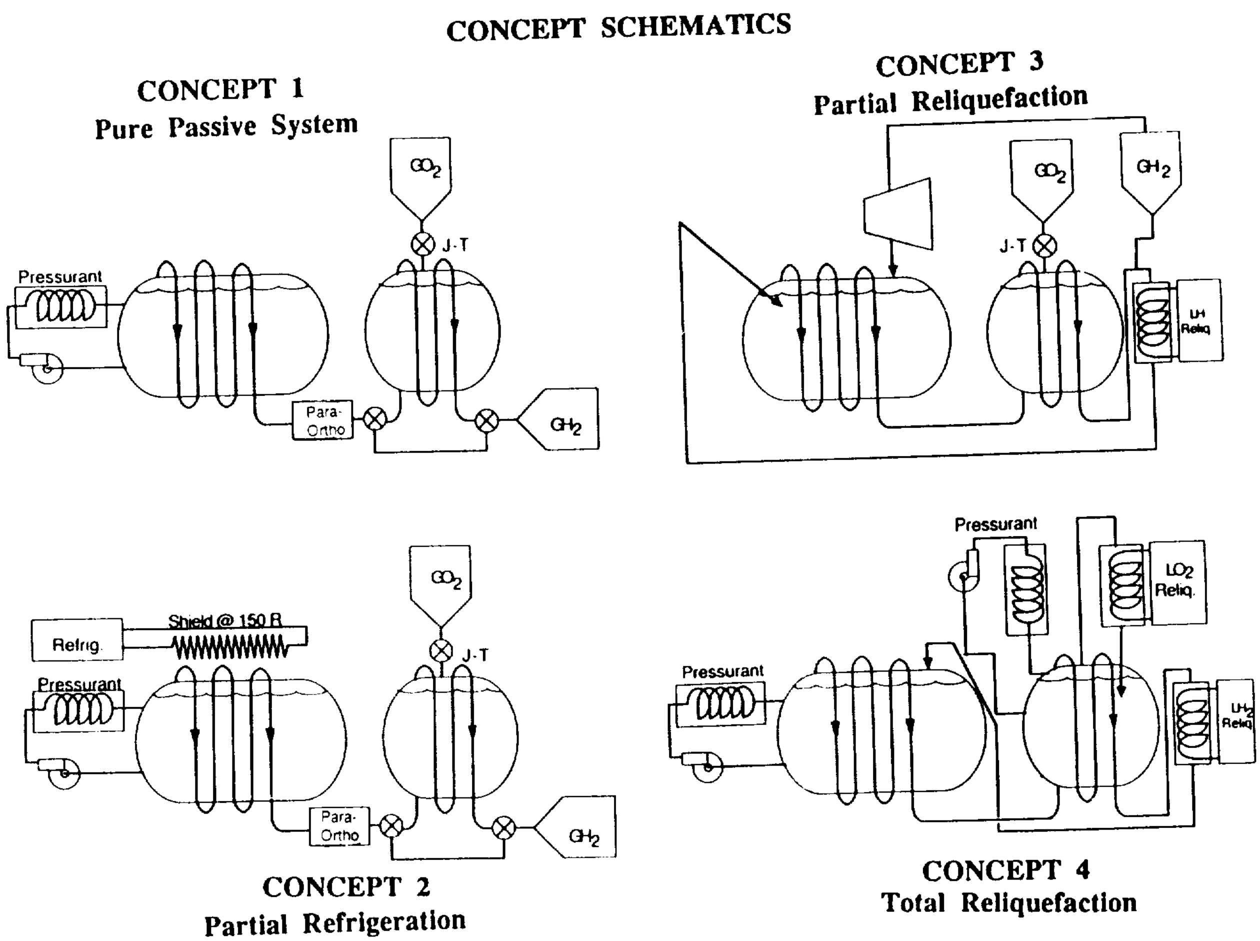

Figure 1

Eighteen trade studies were performed at the subsystem and component levels, leading to the selection of preferred approaches and overall system concepts. The system consists of two 100,000 lb capacity tank sets attached to the windward side of the growth Space Station. Passive thermal features to limit tank heating include 4 inches of multilayer insulation, hydrogen vapor-cooled shields surrounding both hydrogen and oxygen tanks, and permanent low conductance composite struts. The external cover around the tank set is periodically changed as the solar coating degrades. Tank liquid is acquired in microgravity using a screen channel capillary device and transferred using autogenous tank pressurization and liquid pumps. Tank pressure is controlled with a thermodynamic vent system. OTV tanks are preconditioned using a charge/hold/vent cycle and then filled without venting. Refrigerator and reliquefaction systems are based on the magnetic suspension free piston Stirling refrigerator. Micrometeoroid and debris protection will be provided by an inner structural shell to which the tank support struts are attached and by a thin outer bumper. The tank sets will be launched dry and will store propellants at a pressure of 20 psia. Boiloff that is not reliquefied will be stored in high pressure accumulators and periodically transported away by the OMV for venting.

TRADE STUDIES

TRADE	RESULT
System layout	Two 100 klb tanksets attached to Space Station
Tank configuration	Cylindrical, 2219 aluminum alloy tanks
Passive insulation configurations	4 inches of coated DAK/Dacron net
Structural support schemes	Permanent composite struts (<.05Qtot)
VCS configurations	Hydrogen shields on both tanks
Thermal coating degradation effects	Periodically change solar cover
Fluid acquisition systems	Screen channel capillary LAD
Pressure control systems	Thermodynamic vent systems on both tanks
Fluid transfer options	Autogenous pressurization & liquid transfer pumps
System thermal preconditioning requirements	Use charge/hold/vent and no-vent fill
Refrigeration/reliquefaction systems	Magnetic Stirling refrigerator
Operational/safety requirements	Safety waivers required
Propellant loading/unloading requirements	Pump and heat exchanger for tanker pressurization
Instrumentation and controls	Mass gauging and two-phase flowrate are developmental
Micrometeoroid/debris protection	Cylindrical shell with outer bumper
Launch condition	Launch tank set empty and warm
Boiloff storage and utilization	High pressure storage, OMV transport & vent
Propellant storage condition	20 psia least facility cost; 5 psia best obtained by ground conditioning

Figure 2

Each tank set contains 100,000 lb of propellants. The diameters of each are 14.5 ft in order to fit in the Orbiter cargo bay. The lengths of Concepts 2, 3 and 4 are 50.0 ft while Concept 1 is 53.5 ft long. The dry weight of Concept 1 is 27,800 lb with the other concepts being 3,300 to 3,980 lb heavier. The hydrogen and oxygen loss rates and electrical energy use depend on the thermal insulation system features. Estimates for each concept assume 4.0 in. total MLI thickness, and that a hydrogen VCS is used for both the hydrogen and oxygen tanks. Concepts 1 and 2 employ a para/ortho catalytic converter in the hydrogen vapor line between the two vapor-cooled shields, and Concept 2 has a refrigeration shield outboard of the VCS on the hydrogen tank.

None of the concepts have any net oxygen loss since Concepts 1, 2 and 3 allow just enough boiloff to provide the accumulated oxygen for tank pressurization during OTV tanking. Concept 4 reliquefies the oxygen boiloff. Concepts 1 and 2 have 315 and 207 lb/month, respectively, of accumulated high-pressure hydrogen boiloff that must be discarded.

Concept 4, the total reliquefaction concept, requires an average power of about 2 kW to run the reliquefaction system. Concept 3 requires 3,570 kWh/month of electrical energy, most of which is used to run the hydrogen reliquefaction system. This concept suffers excessive hydrogen boiloff because it uses stored hydrogen boiloff for pressurization during OTV tanking. The high boiloff is caused by the enthalpy of superheat of the pressurant, which thermally equilibrates with liquid in the tank during the approximately two-hour OTV tanking operation. Its other negative effect is that the rising tank saturation pressure caused by thermal equilibration increases the pressure of the tanked OTV hydrogen, requiring heavier hydrogen tankage on the OTV.

CONCEPT SUMMARY

	Concept 1	Concept 2	Concept 3	Concept 4
Boiloff management method	Passive	Refrig.	Partial Reliq.	Total Reliq.
Propellant capacity (kg)	45,400	45,400	45,400	45,400
Diameter (m)	4.42	4.42	4.42	4.42
Length (m)	13.3	15.2	15.2	15.2
Dry weight (kg)	12,600	14,400	14,300	14,100
MLI thickness (mm)	102	102	102	102
Coupled VCS	Yes	Yes	Yes	Yes
Refrigeration shield	No	Yes	No	No
Para/ortho converter	Yes	Yes	No	No
Hydrogen loss, (kg/mo)	143	93.9	0	0
Oxygen loss (kg/mo)	0	0	0	0
Electrical energy use (kWh/mo)	146	365	3,570	1,430
(Pumps & Compressor kWh/mo)	146	111	226	17
(Refrigeration kWh/mo)	0	254	3,344	1,414

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Figure 3

The concept selection criteria are safety, reliability, cost, performance and development risk, with safety given the greatest emphasis.

Concept 4 is the only concept that does not require storage of boiloff, and on this basis has a significant safety advantage.

Refrigerators and high pressure compressor trains have been assumed to have equivalent reliability. Since Concepts 2 and 3 have both refrigeration and compressor equipment, they should be at a disadvantage to Concepts 1 and 4.

Concept 4 has a life cycle cost advantage over the other concepts, although Concept 1 has the lowest IOC cost. If ground rules were to change that currently limit venting of boiloff, Concept 1 could become the clear cost winner.

Concepts 1 and 2 have hydrogen boiloff that must be disposed of and they therefore have lower overall performance than Concepts 3 and 4. Concept 3 uses over twice the electrical energy of Concept 4 and thus Concept 4 is regarded as having the best performance.

CONCEPT SELECTION

RELATIVE RANKING*

CRITERIA	CONCEPT 1 PASSIVE	CONCEPT 2 REFRIG.	CONCEPT 3 PARTIAL RELIQ.	CONCEPT 4 TOTAL RELIQ.
Safety	2	2	2	1
Reliability	1	2	2	1
Cost	2	3	4	1
Performance	3	3	2	1
Development Risk	1	3	3	2
TOTALS	9	13	13	6

* 1 is the best rating

Figure 4

The Concept 1 all-passive facility concept includes a single boiloff disposal module affixed at the aft end of one of the tank sets. Four spheres, each five feet in diameter, store gaseous hydrogen boiloff and one 3.5-foot diameter sphere stores the gaseous oxygen boiloff. These vessels are sized to accumulate the 90-day period boiloff plus some contingency for two 100,000 lb capacity tank sets. The other tank set does not have a boiloff disposal module.

The boiloff disposal module is periodically detached and transported away from the Space Station by the OMV and is non-propulsively vented to space.

LONG TERM CRYOGENIC STORAGE FACILITY

All-Passive System Concept with Boiloff Disposal Module

100,000 lb_m Capacity

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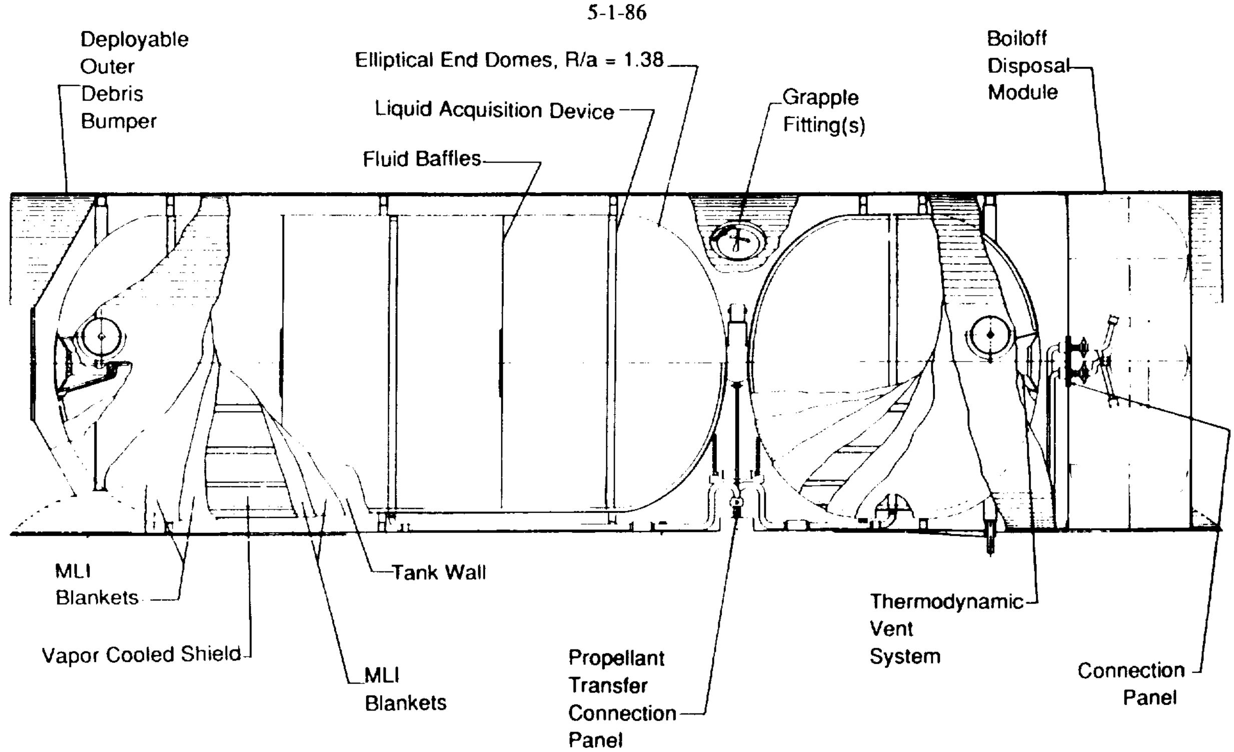

Figure 5

Most of the primary structural elements of the Concept 4 total reliquefaction system are the same as discussed for the all-passive facility. The differences are primarily in the aft bulkhead enclosure where modifications have been made to mount the reliquefaction equipment. Within this compartment are the hydrogen and oxygen pressurant heat exchangers and pumps, the reliquefier and condenser units, and the power conditioning equipment module. All components have been mounted on a graphite epoxy composite isogrid frame to isolate warm side components from cold side cryogenic storage tanks. An access way through the center of the frame is provided since there are doors on the elliptical bulkhead ends of both the hydrogen and oxygen tanks for access to interior on-orbit serviceable and replaceable components, such as the mass gauging instruments, mixers, etc.

A large two-piece door on the aft compartment provides access to the interior equipment modules and serves as the inner component of the two-part micrometeoroid/debris bumper system. Equipment within has been modularized after the design of similar SSP system elements to utilize space servicing tool systems.

LONG TERM CRYOGENIC STORAGE FACILITY

Total Reliquefaction System Concept

100,000 lb_m Capacity

5-1-86

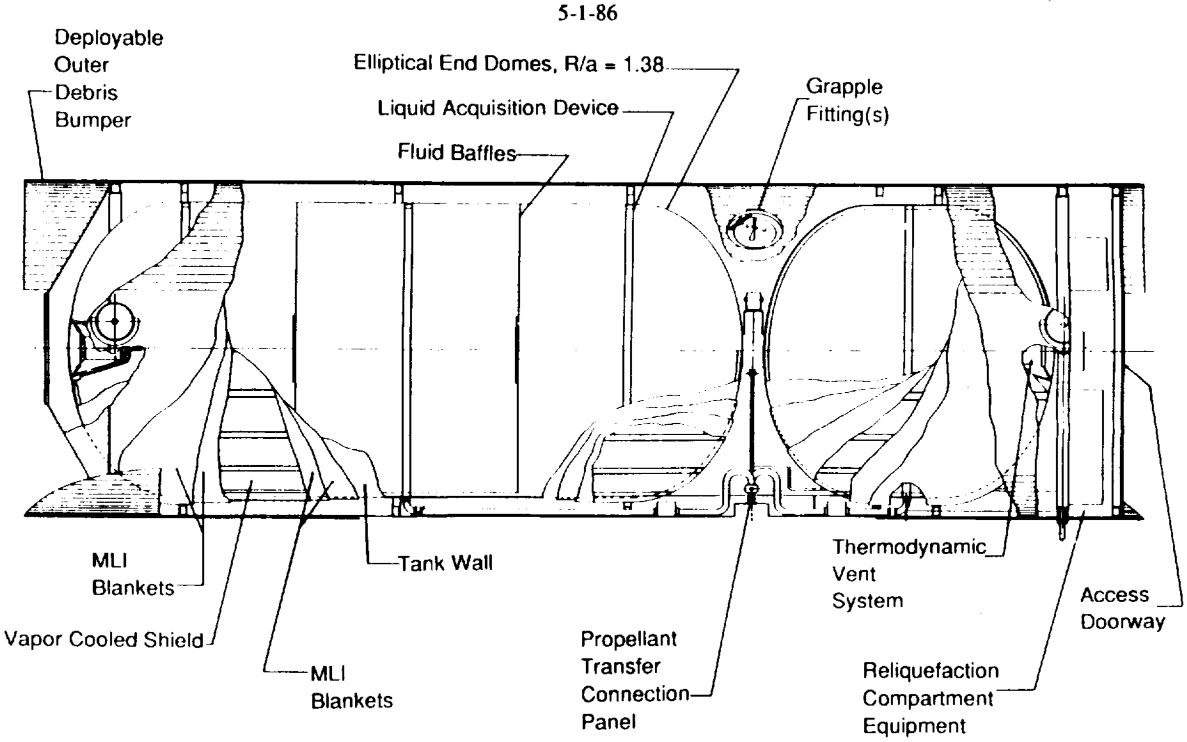

Figure 6

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This schematic of the hydrogen fluid subsystem for a single tank set illustrates the features necessary to meet functional requirements and the redundancy necessary to provide single failure operational/dual failure safe capability. Steady-state venting from the system can only occur after at least two failures, provided that redundant power supplies are available. Operationally, the system has been designed to perform long-term fluid storage, tank pressurization for fluid transfer, depot tank or OTV tank prechill, and depot tank or OTV tank no-vent fill.

Two important features of the hydrogen system are the line evacuation subsystem and the prechill bleed subsystem. The line evacuation subsystem reduces the pressure of the fluid in the lines that penetrate the MLI/vapor-cooled shield boundary, minimizing the heat input through these lines. The prechill bleed subsystem is used to remove the fluid from the prechill accumulator in a controlled manner in between OTV servicing operations.

CONCEPT 1: PURE PASSIVE SYSTEM, LH2 FACILITY

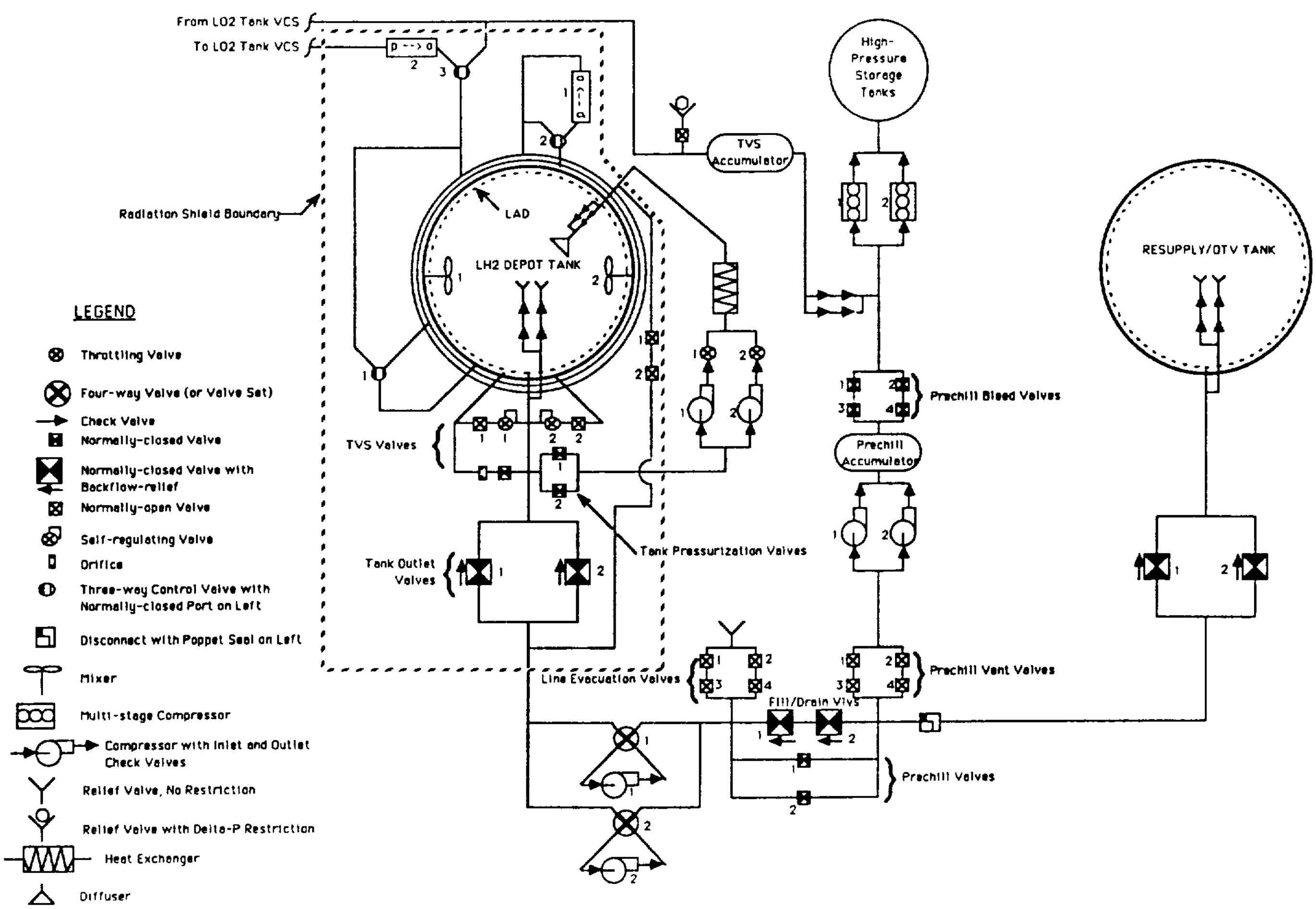

Figure 7

The refrigeration subsystem required for reliquefaction of boiloff uses separate hydrogen and oxygen refrigerators in order to provide the best thermodynamic performance and to permit separate control over the hydrogen and oxygen streams.

The oxygen refrigerators are single-stage devices that provide cooling for both desuperheating and condensing the oxygen boiloff. The hydrogen refrigerators are two-stage devices that provide desuperheating on the first stage and condensing on the second stage. The refrigerators are magnetic suspension, free piston, Stirling machines that are hermetically sealed and use gaseous helium as the refrigerant. Condensate pumps return the condensed liquid to the storage tanks, and circulation pumps provide cooling for both the refrigerators and their control electronics. The refrigerators are heat sinked to the Space Station thermal bus.

CONCEPT 4 REFRIGERATION SYSTEM

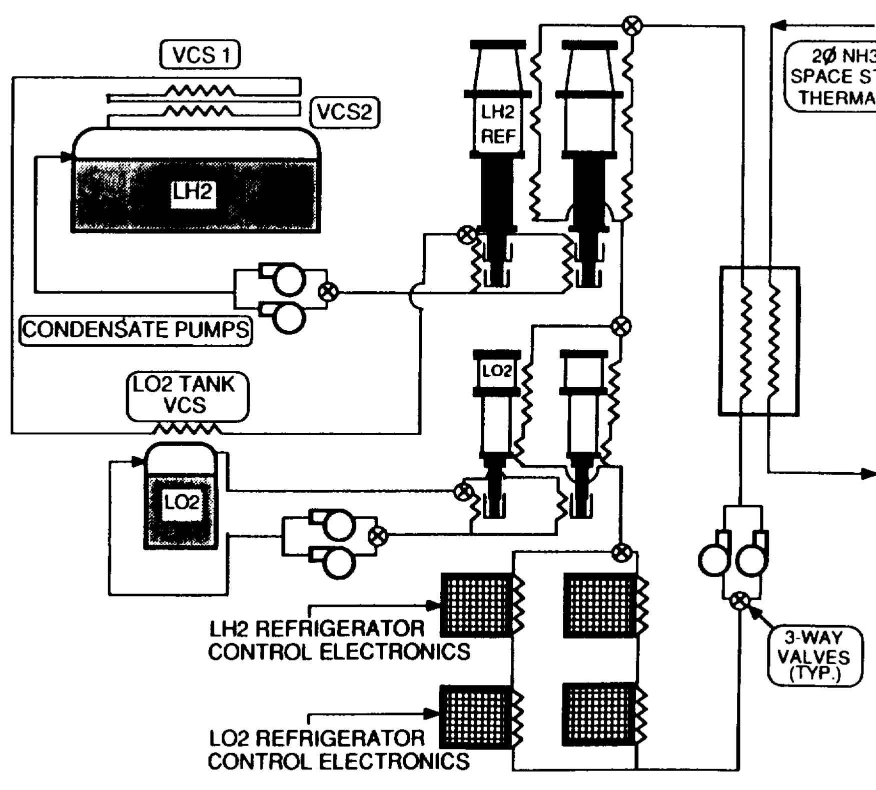

Figure 8

The four storage facility concepts identified during the preliminary concept definition were further defined during the trade studies. The features of the four concepts were reviewed to identify enabling technologies that require research and development prior to making final design option commitments.

Each technology was reviewed to determine its status and identify ongoing efforts to further its development. On the basis of its criticality and status, a justification for further development was prepared along with a brief technical plan, resource estimates and schedule. The estimates were scaled to achieve performance characterization through ground-based components, and include neither on-orbit testing (other than material samples) nor development of flight-qualified components.

Eighteen technology tasks were identified; five tasks were not priced and scheduled because they are to be carried out in connection with the Cryogenic Fluid Management Flight Experiment (CFMFE) program. The costs total $12.18 million and the task durations range from two to six years. The tasks are essentially independent and could be carried out in parallel, if necessary.

TECHNOLOGY DEVELOPMENT CANDIDATES [1]

	Time Req'd Years	Cost $1000
Thick MLI System Development	5	600
VCS Thermal/Structural Integration	3	900
Scaleup and Demonstration of Low Conductance Structural Support	3	400
Para/Ortho Converter Configuration Development[2]	6	280
Solar Thermal Coating Screening and Qualification	4	800
Liquid Acquisition Device Demonstration	CFMFE	
Pressure Control System Demonstration	CFMFE	
Pressurization System Demonstration	CFMFE	
Cryogenic Liquid Transfer Pumps	3	500
Transfer Line/Receiver Tank Chilldown and Fill	CFMFE	
Refrigerator Development[3]	5	5100
Zero-g LH_2/LO_2 Condenser Development[4]	3	450
Zero-g Mass Gauging	CFMFE	
Leak Detection Methods	3	650
Penetration Data Base Development to Support Micrometeoroid/ Debris Shield Design	2	400
Development of Low Conductive Fluid Lines	3	750
Fluid Baffling for Tanks	3	800
Boiloff Storage Compressor Development[5]	3	550
	Total Cost	$12.18M

(1) Exclusive of on-orbit testing
(2) Para/ortho converter not required for Concepts 3 and 4
(3) Refrigerator nor required for Concept 1
(4) Zero-g condenser not required for Concepts 1 and 2
(5) Boiloff storage compressor not required for Concept 4

Figure 9

Storage facility technical risk has been identified by summarizing the critical design and performance issues of individual components. The technical risk is due to uncertainty that components will perform their functions as well as intended. Testing components in representative environments would reduce performance uncertainties and verify design concepts and models. Risks at the component level have been identified as low, medium or high depending on the uncertainty that the component would perform as intended. This risk assessment forms the basis for defining a risk reduction testing program.

STORAGE FACILITY RISK ASSESSMENT

STORAGE FACILITY COMPONENT	CRITICAL DESIGN ISSUES	COMPONENT PERFORMANCE RISK
Tank	• Fluid sloshing and orientation in μ-g env. - Ullage location - Baffle design	Med
	• Tank failure mode	Low
Tank Support Structure	• Dynamic response to launch environment	Med
	• Dynamic interaction with space station	Low
Tank Support Struts	• Support of launch loads	Med
	• Thermal performance	Med
Multiple Layer Insulation (MLI)	• Insulation layup & thermal performance	Med
	• Insulation degradation due to launch	Med
	• Degradation due to atomic oxygen and contamination on orbit	Med
Tank Set Solar Selective Cover	• Coating degradation on orbit	Med
	• Shield thickness and material	Low
Radiator	• Performance	Med
	• Coating degradation on orbit	Med
Micrometeoroid & Debris Shields	• Material and thickness	Med
	• Performance	Med
Vapor-Cooled Shield (VCS)	• Support during launch	Med
	• Thermal performance	Med
Para to Ortho Converter	• Performance	Med
	• Operating life	Low
	• Filtering requirement	Low
Penetrations: Inst. & Plumbing	• Thermal performance	Med
Warm Tank Chilldown	• Procedure - Spray nozzle configuration - Liquid flowrate and duration - Time for temp to reach equilibrium - Number of gas venting steps	Med
	• Zero-g performance	Med
Thermodynamic Vent System (TVS)	• Thermal performance	Med
	• Zero-g performance - Heat transfer from fluid in tank	Med
Stratification / Hot Spot Management	• Mixing needs / Mixing strategy	Med
	• Zero-g performance	Med
Liquid Acquisition Device (LAD)	• Zero-g performance - Residual liquid fraction - Vapor break through vs. flowrate - Maximum flow rate vs. tank liquid % - Pressure drop	Med
	• Long term perf. (corrosion in LOX)	Med

Figure 10

STORAGE FACILITY RISK ASSESSMENT (continued)

STORAGE FACILITY COMPONENT	CRITICAL DESIGN ISSUES DESIGN ISSUES	COMPONENT PERFORMANCE RISK
Pressurization System	• System requirements & performance	Med
	• Zero-g performance - Diffuser performance - Optimum flowrate and temperature	Med
Liquid Pumps	• Operating life	Med
	• Zero-g performance	Low
Refrigerator	• Thermodynamic efficiency and life	High
	• Zero-g performance	Low
Boiloff Condenser	• Thermal performance	Med
	• Zero-g performance	Low
Boiloff Compressor	• Operating life	High
	• Zero-g performance	Low
Low Heat Leak Valves	• Operating life	Med
	• Thermal performance	Med
Disconnects	• Fluid leakage, Pressure drop	Med
	• Force and alignment requirements	Low
	• Thermal performance (heat leak)	Low
Mass Gauging	• Performance	High
	• Zero-g performance	Med
Control System	• System performance, Operating life, & response to component failure	Med
No-Vent Fill	• Procedure	Med
	• Zero-g performance - Ullage condensation rates - Fluid mixing requirements	Med
Transfer Line Chilldown	• Procedure	Low
	• Zero-g performance	Low

Figure 10 (Cont.)

The objective of the test program is to reduce the technical risk associated with fielding an orbital propellant depot. A methodical approach to test program definition was taken by identifying technical risks to the component level, analyzing test article size considerations and defining six test options.

The options were evaluated based on the risk reduction they provide, their compatibility with the overall development schedules for the full scale orbital storage facility, the Space Station and the OTV, and test option cost.

The option recommended involves subscale integrated system testing with hydrogen both on the ground and for a short period on orbit. Extended ground tests would be conducted with active components, liquid acquisition device degradation in liquid oxygen would be investigated, and MLI, solar coatings, and micrometeoroid shield materials would be given extended exposure in low earth orbit.

The recommended test program is estimated to cost $150 million. Contributing to this cost is the extra hardware required for Shuttle qualification of components, and the extensive tasks associated with Shuttle integration of the test hardware.

TEST PROGRAM

OBJECTIVE

- **Reduce The Technical Risk Associated With Fielding An Orbital Propellant Depot**
  - Operating life of active components
  - Zero-g fluid management technology
  - Thermal performance
  - Integrated system performance
  - Degradation of materials on orbit

APPROACH

- Identify techical risks down to component level
- Determine scale of test articles
- Define testing options
- Evaluate options based on resulting risk reduction, schedule compatibility, and cost

CONCLUSIONS / RECOMMENDATIONS

- $150 Million overall cost
- Schedule considerations point towards short term orbital test
- Shuttle qualification requires extra hardware
- Shuttle integration is an extensive task

Figure 11

A contract change order has extended the period of performance through August, 1987, and revised some of the guidelines and assumptions for the study. Additional emphasis was placed on facility interface requirements, cost analyses, and test planning.

CONTRACT CHANGE ORDER

- Extends period of performance through August, 1987
- Revises guidelines and assumptions
  - Dual keel Space Station
  - Orbiting platform
- Requests preliminary interface requirements document
- Requests discounted cost analyses
- Requests preliminary test plan

Figure 12