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ADVANCED LONG TERM CRYOGENIC STORAGE SYSTEMS

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Long term, cryogenic fluid storage facilites will be required to support future space programs such as the space-based Orbital Transfer Vehicle (OTV), Telescopes, and Laser Systems. An orbital liquid oxygen/liquid hydrogen storage system with an initial capacity of approximately 200,000 LB will be required. The storage facility tank design must have the capability of fluid acquisition in microgravity and limit cryogen boiloff due to environmental heating. Cryogenic boiloff management features, minimizing earth-to-orbit transportation costs, will include advanced thick multilayer insulation/integrated vapor cooled shield concepts, low conductance support structures, and refrigeration/reliquefaction systems. Contracted study efforts are underway to develop storage system designs, technology plans, test article hardware designs, and plans for ground/flight testing.

INTRODUCTION:

Advanced, long term orbital cryogenic storage systems (Figure 1)include thick multilayer insulation (MLI)/integrated vapor cooled shields (VCS), low conductance support structures, and reliquefaction systems. An orbital storage system should be designed for safety, reliability, and long term thermal performance. Passive cryogenic fluid storage and active cryogenic boiloff management, or a combination of both, are being studied to determine the optimum system design.

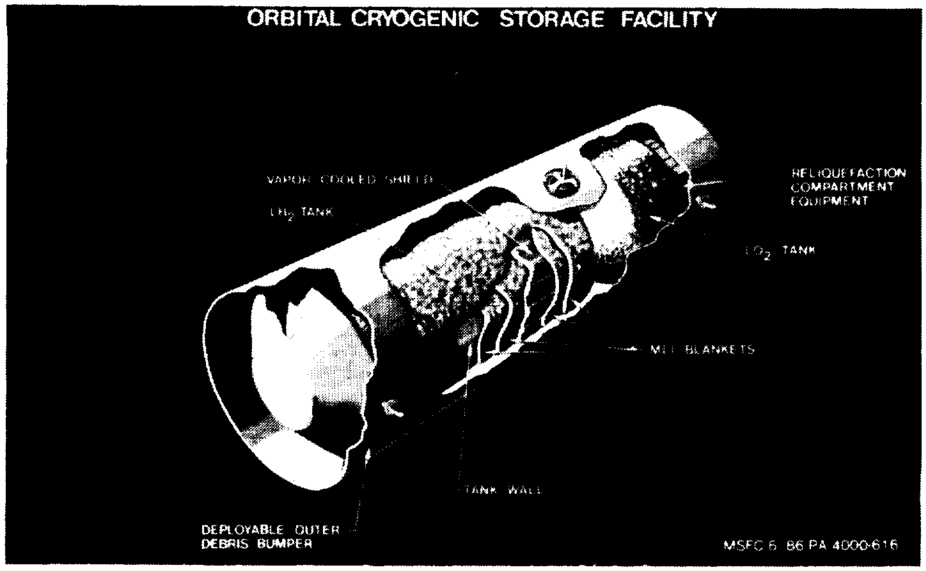

FIGURE 1.

SYSTEM DESCRIPTION:

An orbital cryogenic storage facility system will rely on the long term performance of various subsystems (Figure 2). Cryogenic fluid boiloff management features will include the following:

Thick multilayer insulation (MLI) systems consist of thin radiation shields (metallized polymeric film) separated by low-conducting spacer materials (Dacron, Nomex, nylon). Cryogenic storage will require multiple layers of MLI with fabrication/assembly techniques that minimize seam heat leaks.

The design of a vapor cooled shield (VCS) resembles a dual pass heat exchanger. Assuming liquid hydrogen/liquid oxygen (LH_2/LO_2) the VCS is most effective when using a thermodynamically coupled tank configuration. Saturated vapor (boiloff) is removed from the LH_2 tank and routed in the VCS around the tank to intercept heat leaks. After the vented fluid leaves the LH_2 tank VCS, it is routed to the LO_2 tank VCS to perform the same heat leak intercept function.

The thermodynamic vent system (TVS) performs a dual function. The primary function is to regulate tank pressure through controlled escape of saturated vapor (boiloff). Additionally, when used in conjunction with a VCS, the TVS provides the saturated vapor from the liquid storage tank.

LONG TERM CRYOGENIC STORAGE FACILITY
100,000 LB_M LH_2/LO_2 CAPACITY

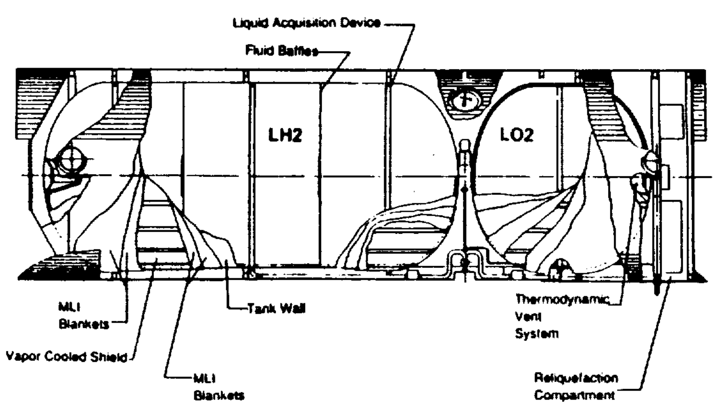

FIGURE 2.

Tank support struts are a key element in the thermal design of a cryogenic storage system. Various composite materials with high strength and low conductivity properties are under investigation for use as support structures. Other options include configurations of orbital disconnect struts where highly efficient struts are complimented by larger struts for support during launch loads.

A reliquefaction system would be designed to reliquefy the boiloff of propellants. Reliquefaction would eliminate the need for any external system venting of saturated vapor. Reliability, along with power, weight, and volume requirements are areas of development for space based reliquefaction systems.

Propellant storage conditions should be optimized with respect to safety, complexity, and cost. On orbit storage of propellant at lower than normal (15-20 psia) saturation pressures will allow thin walled tanks resulting in weight savings. However, to operate at reduced tank pressures (approximately 5 psia) thermal conditioning of delivered propellant is required. The least complex method of propellant delivery to orbit is in the 15-20 psia saturation pressure range due to ground handling and stress loading on the tanks during ascent. The delivered propellant would then require on-orbit thermal conditioning if the facility storage pressure is less than the 15-20 psia. Figure 3 shows the amount of energy removal required per pound of LH_2 starting at 20 psia going to a 'conditioned' 5 psia. Figure 4 relates the reliquefaction power required to perform the 'conditioning' for various LH_2 quantities. Judging from the energy requirements, storage conditions at pressures of 15-20 psia, assuming commonality between users, are required. The case for LO_2 conditioning is similar.

SPECIFIC ENERGY REMOVAL REQMT TO LOWER SUPPLY LH_2 PRESS. TO OTV TANK PRESS.

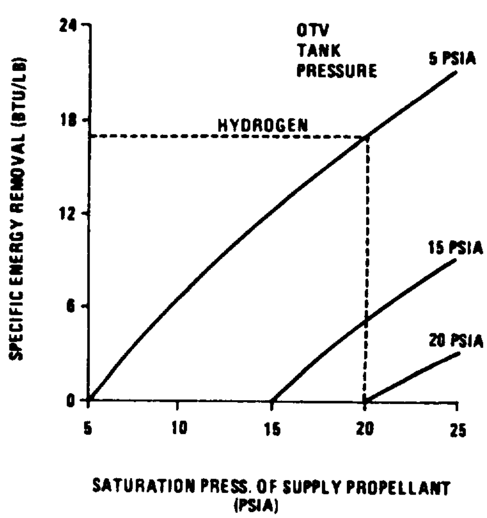

FIGURE 3.

RELIQUEFIER ENERGY REQUIRED TO CONDITION LH_2

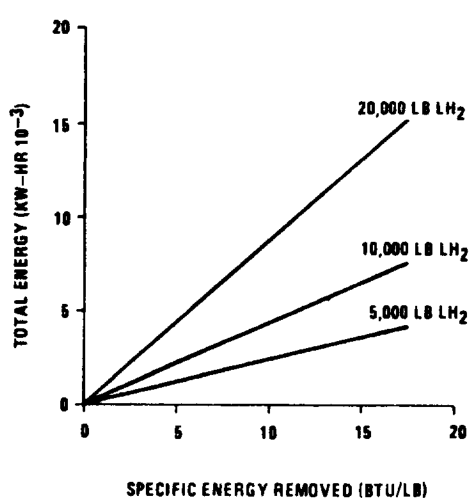

FIGURE 4.

A subsystem of a long term storage facility is the VCS. In Figure 5, the effect of adding a VCS to the LH_2 tank is shown. The parametric data is based on a 100,000 lb LH_2/LO_2 facility. The trend established shows a greater than fifty percent (50%) reduction in LH_2 boiloff due to the addition of the VCS. The distance the VCS is located from the tank wall has an effect on the LH_2 boiloff (Figure 6). With 4 inches of MLI, a 10 percent reduction in boiloff can be achieved by locating optimally the VCS (2 inches from the tank wall).

EFFECT OF H_2 VCS ADDITION TO LH_2 TANK

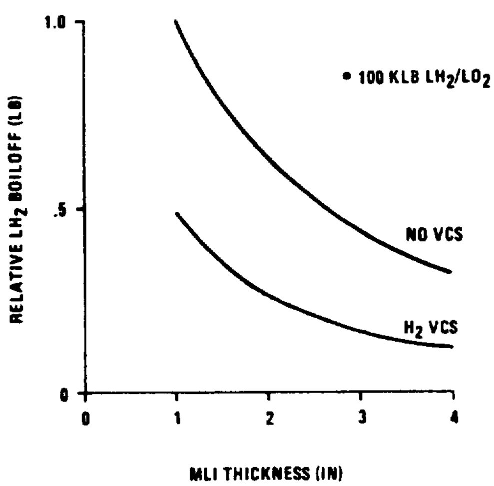

FIGURE 5.

EFFECT OF H_2 VCS LOCATION IN LH_2 TANK MLI

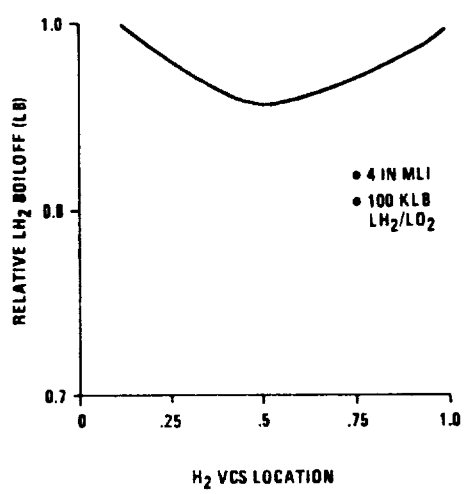

FIGURE 6.

A dual VCS H_2 system on the LH_2 tank can improve the thermal performance by 40 percent over a single VCS. Figure 7 shows the results of varying the locations of the two shields on the hydrogen tank. The curves suggest that the preferred locations for the inner and outer shields are 30 and 66 percent of the distance from the tank wall to the outer insulation surface. Figure 8 shows the effect of varying the H_2 VCS location on the oxygen tank. Approximately 75 percent of the distance from the LO_2 tank wall results in the lowest LO_2 boiloff.

SELECTION OF DUAL H_2 VCS LOCATION

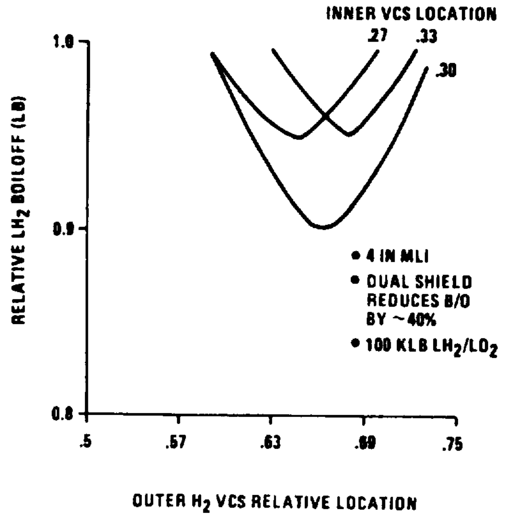

FIGURE 7.

EFFECT OF H_2 VCS LOCATION IN LO_2 TANK MLI

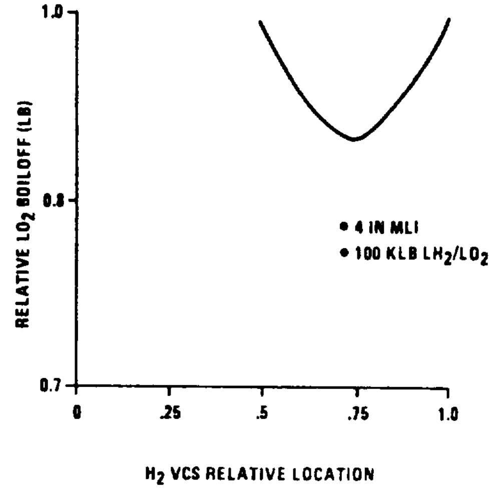

FIGURE 8.

A para-ortho hydrogen converter exploits the endothermic reaction of transforming para hydrogen into a para-ortho mixture. As saturated hydrogen vapor (boiloff) exits the LH_2 tank VCS, it is approximately 100 percent para. However, prior to entering the LO_2 tank VCS a catalyst bed speeds up the natural para-ortho conversion process and yields a para-ortho mixture. The conversion to the higher energy state absorbs energy and results in approximately a 40 percent increase in the hydrogen heat capacity (Figure 9). Therefore, the hydrogen vapor temperature in the VCS is reduced resulting in approximately 10 percent savings in LO_2 boiloff (Figure 10).

PARA/ORTHO CONVERSION OF HYDROGEN

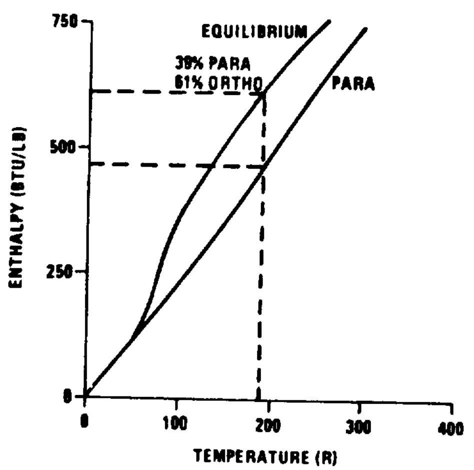

FIGURE 9.

EFFECT OF ADDING PARA/ORTHO CONVERTER

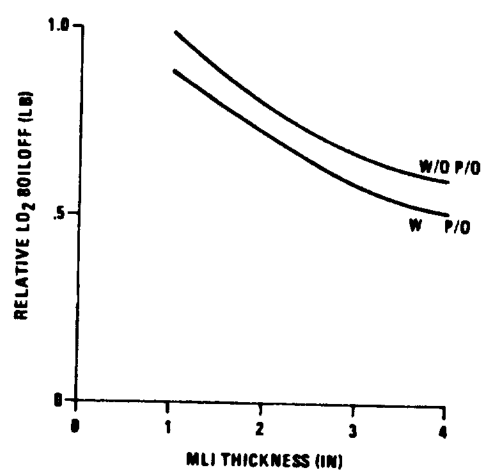

FIGURE 10.

A cryogenic reliquefaction system must meet the long requirements of safety, reliability, performance, and cost. Several refrigeration cycles are currently under development to meet future design criteria. Table 1 identifies characteristics of some of the more established cycles currently under development. Figures 11 and 12 plot critical parameters of the refrigeration cycles discussed below.

The Stirling refrigerator has been developed for long life performance utilizing magnetic bearings to suspend the reciprocating compressor and expander. This 2 stage system has demonstrated the potential for reliable operation and has good power utilization efficiency.

TABLE 1

SURVEY OF SMALL, LONG-LIFE REFRIGERATORS

CYCLE	MANUFACTURER	RATED TEMP. (°K)	CAPACITY (W/PT)	POWER INPUT (WATTS)	VOL. (ft^3) / WEIGHT (lb_m)	HOURS TO DATE	LIFE LIMITING COMPONENT	DEVELOPMENT STATUS	COMMENTS
STIRLING (SPRING SUSPENDED)	RUTHERFORD APPLETON LABS OXFORD	80°K	1 W	60	-- / 11 LB W/O ELECT.	6,000	UNKNOWN	LIFE TESTING	VERY SIMPLE AND LIGHTWEIGHT
STIRLING (MAGNETICALLY SUSPENDED)	PHILIPS	65°K (40-110)	5 W (0 - 10)	220	(40x10x10) 2.31 ft^3 /	SYSTEM; 6500 MECH PARTS; 18,000	ELECTRONICS IN DC-DC CONVERTER	MECHANICAL TESTS TO 18,000 HOURS (ELECTRONICS TO 2500 HRS & IMPROVING)	ADDITION OF MAG. BRGS. MAKES LONG UNATTENDED OPERATION POSSIBLE. (2-STAGE UNDER DEVELOPMENT)
R^3 BRAYTON (2-STAGE)	A.D. LITTLE	12,60	1.5 @ 12K 40 @ 60K	2670	17.4 / 465	7,000 (MECHANICAL COMPONENT TESTS)	EXPANDER	3-STAGE UNIT UNDER DEVEL. @ WRIGHT; LARGER CAPACITY	GAS BEARINGS PROBLEMS WITH EXPANDER @ 7000 HR
TURBO-BRAY (2-STAGE)	GARRETT-AIRESEARCH	20, 90	20 W @ 20, 90K	5,000	22 / 390	-	FOIL SUPP. GAS BEARINGS	FOIL/GAS BEARING RELIABILITY & He GAS RETENTION	INFORMATION ON REFRIG. TEMPERATURE IS CLASSIFIED AND UNAVAILABLE FOR LATEST MODEL
VUILLEUMIER	HUGHES	10,14,64	.15 @ 10K 1.9 @ 14K 8.3 @ 64	2100	5 / 181	31,000	MECHANICAL (PISTONS/CYL WEAROUT)	CURRENTLY DEVEL. LOW WEAR SEALS & RIDERS FOR LONG WEAR - MAKE UP GAS ALSO A PROBLEM	YEARS OF EXPER. IN FIELD FOR TACTICAL APPLICATIONS
MOLECULAR ABSORPTION	J.P.L.	27	0.65W	-	-	300	-	BREADBOARD TEST 3-UNIT $LaNi_5$	NEED HIGH PRESS. COMPRESSOR & HEAT INPUT (& 77K INT. STG. COOLING)
MAGNETIC	ASTRONAUTICS & LASL	20, 90	20 W 20K 20 W 90K	990 W	34 / 1,023	N/A	-	CONCEPTUAL	CONCEPTUAL DESIGN ONLY (SHOULD ACHIEVE 30 - 50% CARNOT)

There are two refrigeration systems under development utilizing Brayton cycles, the gas bearing rotary-reciprocating-refrigerator (R^3) and the turbo-Brayton. The R^3 has gas rotating bearings and a reciprocating compressor. This unit has the potential for long life, low wear, and reliable performance. The turbo-Brayton utilizes turbomachinery in a two stage expansion reversed cycle.

Vuilleumier refrigerators are basically Stirling cycles which utilize high temperature heat to drive the compression stage. These machines have accumulated many test hours.

Molecular adsorption refrigerators are in the development stages. Gaseous hydrogen is pumped at high pressure through heat exchangers and then expanded (using a Joule-Thomson valve) over a intermetallic hydride bed for cooling. The only moving parts of the system are self-regulating check valves.

Magnetic refrigeration is also in the early development stage. Materials that increase and decrease in temperature when alternately placed in a magnetic field drive this cycle. Such a system could be efficient, however many practical problems exist.

REFRIGERATOR POWER INPUT VS CAPACITY

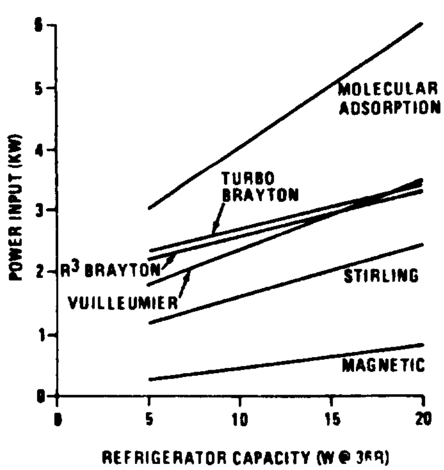

FIGURE 11.

REFRIGERATOR SYSTEM WT. VS. CAPACITY

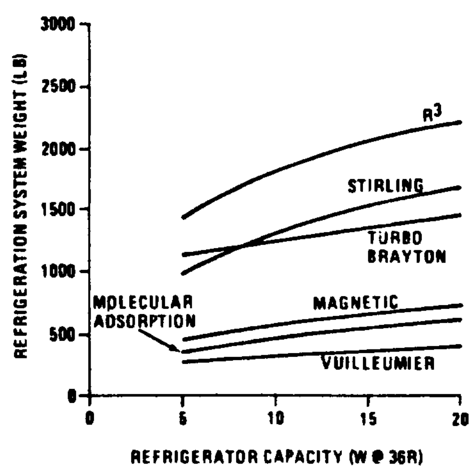

FIGURE 12.

Operational safety requirements will be a major factor in an orbital storage facility design. Various mission phases must be analysed with respect to hazard potential: Pre-launch (ground processing), launch, STS abort, and space based operations (propellant transfer, venting). Sensor and valve redundancies, meteroid bumpers, pressure/propellant tank structural structural margins, LH_2/LO_2 vents/disconnects separation distances, and electrical grounding are all design requirements of a storage facility. Table 2 outlines mission phases and potential hazards/solutions associated with each.

TABLE 2

HAZARD ANALYSIS

STS ABORT

- N/A – TANKS ARE LAUNCHED DRY

OPERATIONAL

- CRYOGENIC LEAKAGE
  - METEROID/DEBRIS SHIELDING TO PREVENT PUNCTURE
  - "ZERO-LEAK" CONNECTORS
  - VENT TRANSFER LINES/PURGE AFTER TRANSFER OP.
  - MAN RATED REDUNDANT FAIL OP/SAFE ON CRITICAL SYSTEMS (IF LOCATED @ MAN TENDED FACILITY)
- TANK OVERPRESSURIZATION
  - SUFFICIENT PRESSURE RELIEF VALVES (SIZE & LOCATION)
  - TANK SHOULD HAVE SUFFICIENT STRUCTURAL MARGINS 'LEAK BEFORE BURST'
- CRYOGEN CONTAMINATION
  - RELIEF VALVES W/PROTECTION TO PREVENT CONTAMINANTS

SPACE STATION ABORT

- SUFFICIENT PRESSURANT FOR LIQUID DUMP (ONE TANK)
- TANK HEATERS TO BOILOFF

SUMMARY:

A long term orbital storage facility will require several precursor 'experiments' in order to demonstrate system performance. Currently, the need exists for a multiphased technology demonstration program. The Cryogenic Fluid Management Facility (CFMF) experiment is planned for 1992 to demonstrate the areas of fluid transfer, mass gauging, and fill operations. A cryogenic storage experiment (short term test) is required as a precursor to long term Space Station testing. System performance (refrigerator, MLI/VCS) must be validated for withstanding launch loads and still performing on-orbit. Prior to facility IOC, a long term orbital system test would assure the necessary confidence in the storage design to begin space basing operations. Figure 13 summarizes the storage facility evolution. Table 3 is a partial listing of major programs supporting the technology requirements of long term orbital storage of cryogens.

LONG TERM ON–ORBIT CRYOGENIC STORAGE EVOLUTION

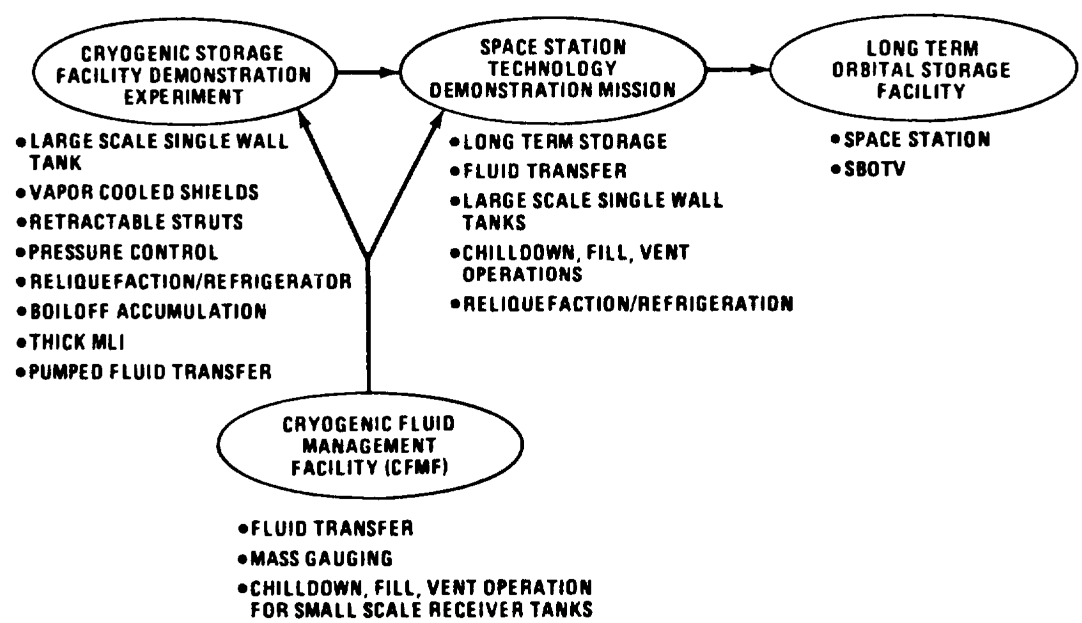

FIGURE 13.

TABLE 3

RELATED EFFORTS
(PAST AND ONGOING ACTIVITIES)

•THICK MULTILAYER INSULATION	AFRPL
•ADVANCED ORBIT – ORBIT VEHICLE STUDIES OTV, MOTV	MSFC
•ADVANCED CRYOGENIC TANK STRUCTURES	LaRC MSFC
•ADVANCED THERMAL PROTECTION SYSTEMS	LaRC MSFC JSC LRC
•CRYOGENIC INSULATION CRYOGENIC BREADBOARD (MSFC)	MSFC LRC LaRC
•PROPELLANT MANAGEMENT SYSTEMS CRYOGENIC BREADBOARD (MSFC)	MSFC JSC LRC
•CRYOGENIC FLUID MANAGEMENT FACILITY (CFMF)	LRC
•LONG TERM CRYOGENIC STORAGE STUDIES	MSFC LRC
•CRYOGENIC REFRIGERATOR DEVELOPMENT	JPL

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