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ACTIVE COOLING REQUIREMENTS FOR PROPELLANT STORAGE

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Recent NASA and DOD mission models have indicated future needs for orbital cryogenic storage and supply systems. Cryogens required will include hydrogen and oxygen. Tank sizes will vary from 32 ft^3 to 1800 ft^3 for applications ranging from Space Station on board propulsion to Space Station Orbital Transfer Vehicle (OTV) propellant storage. The storage durations may vary from a few hours for such missions as OTV Low Earth Orbit (LEO) to Geosynchronous Equatorial Orbit (GEO) transfer and resupply, to several years for mission such as Space Station station keeping and space-based laser systems. There is strong economic incentive for reducing the boiloff losses for long duration missions. It has been proposed that refrigeration be investigated to reduce the heat load to the tanks and thereby minimize boiloff.

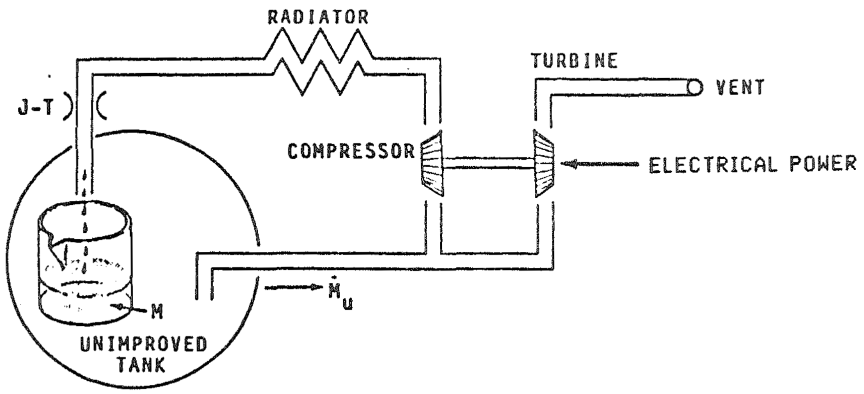
Two thermal control systems were evaluated in this analysis. These systems showed the greatest promise for improving storage life and include:

- An open cycle thermodynamic vent system with:
  - a refrigeration system for partial hydrogen reliquefaction located at the LH_2 tank
  - refrigeration at the LH_2 tank - vapor cooled shield for integrated and non-integrated tank designs to reduce boiloff
- A closed system with direct refrigeration at the LH_2 tank vapor-cooled shield to eliminate boiloff

For storage tank designs utilizing active coolers, careful design of the passive thermal control system is necessary to achieve the optimal refrigeration system performance and minimal overall thermal control system mass.

Individual subsystems must be integrated functionally and structurally to form an operable propellant reliquefier. The liquefaction equipment in this schematic includes the refrigerators (ex., reversed Brayton), their drive motors, and large space radiators. Boiloff from the liquid hydrogen and liquid oxygen storage vessels is recycled through the refrigeration equipment where reliquefaction occurs. However, the boiloff reliquefaction process requires refrigerator operation at cryogenic temperatures.

OPEN CYCLE-RELIQUEFACTION



- LIQUID HYDROGEN REQUIRES LOW TEMPERATURE REFRIGERATOR OPERATION

Figure 1

In the present study, a reversed Brayton cycle unit was baselined for the propellant processor. The Brayton cycle refrigerator was selected over Sterling, Vuilleumier and other cycles because it has the lowest weight and volume at the higher power refrigeration requirements. It uses gas bearing turbomachinery, resulting in high cycle efficiency, long life and high reliability. Two refrigeration stages are required for hydrogen liquefaction.

A summary of the estimated liquefaction performance capability used for final processor sizing is shown. Current refrigeration systems could practially reliquefy only a percentage of the total boiloff from an OTV propellant storage depot tank.

Unless modifications are made to the tank design (with addition of refrigerated or non-refrigerated vapor cooled shields) it would appear that reliquefaction systems may not be as attractive for minimizing propellant boiloff, as alternative thermal control system designs.

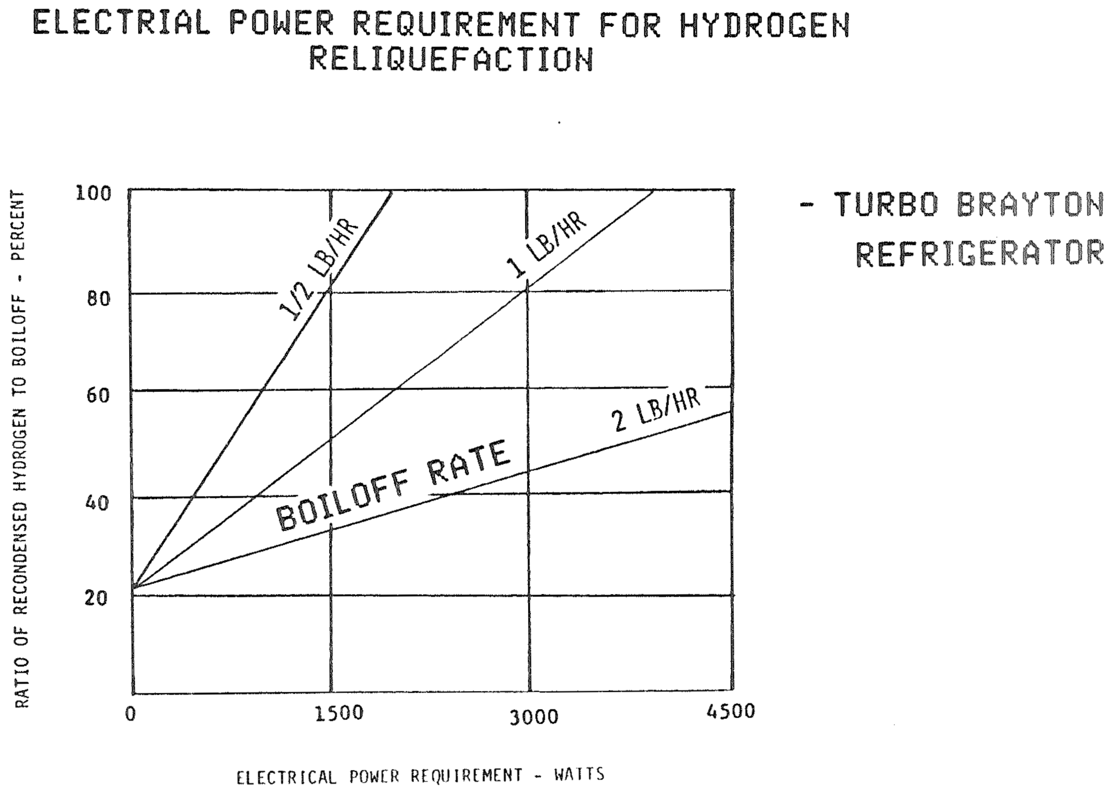

ELECTRIAL POWER REQUIREMENT FOR HYDROGEN RELIQUEFACTION

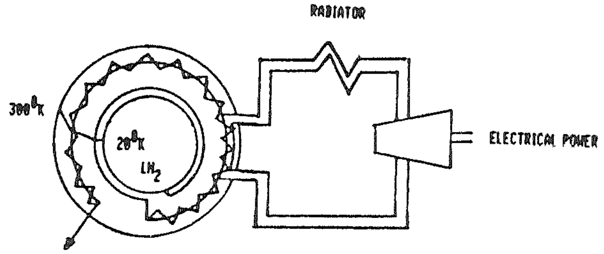
Figure 2

The cryogenic storage system, described in the present study, is for orbital long-term storage of subcritical liquid cryogens. The system consists of a pressure vessel containing the saturated liquid cryogen, a structural support system, multilayer insulation (MLI), and a vapor-cooled shield (VCS) with a heat exchanger.

Use of a vapor-cooled shield integrated with a refrigerator permits operation of the refrigerator at temperatures higher than 20°K, thereby obtaining a marked improvement in cooler efficiency.

Two thermal control open cycle systems were analyzed. These systems were evaluated for their ability to reduce boiloff losses while minimizing their environmental impact. The systems include integrated and independent LO_2/LH_2 thermal control systems.

OPEN CYCLE - COOLED SHIELD



- PERMITS REFRIGERATOR OPERATION AT HIGHER TEMPERATURE
- TWO APPROACHES
  - INTEGRATED LO_2-LH_2 THERMAL CONTROL
  - INDEPENDENT LO_2-LH_2 THERMAL CONTROL

Figure 3

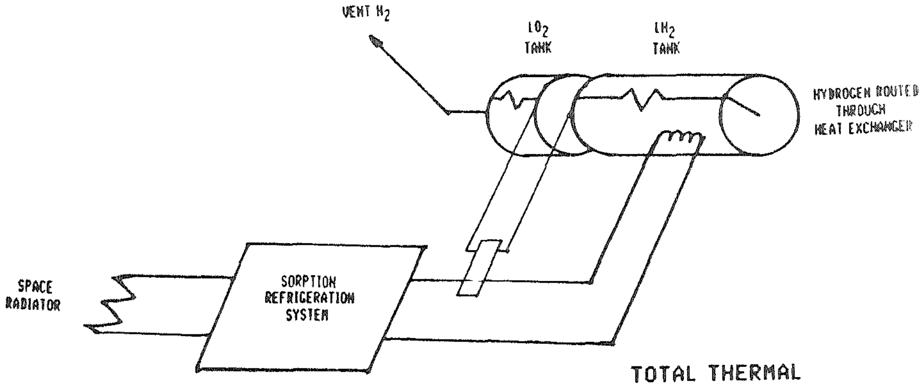
For a given location, the shield temperature can be optimized to:

- minimize the combination of thermal control system, total propellant and tankage mass.

In the accompanying figure, a sorption refrigeration system which has been coupled to the LH_2 and LO_2 propellant tanks is shown and is representative of an integrated thermal control system design for the LH_2/LO_2 tanks. The vented liquid hydrogen is passed over the surface of the fuel tank where it evaporates and maintains the tank temperature at 20°K, before entering an intermediate heat exchanger. Here, the refrigerator working fluid is precooled to 28°K, thereby increasing the cooler performance. The hydrogen leaving the intermediate heat exchanger would then be routed through the heat exchanger placed around the oxygen tank, before being vented to space. The amount of boiloff is governed by a requirement to remove all of the liquid oxygen tank heat load, with no LO_2 venting.

The table gives a comparison of the thermal control system mass and LH_2 boiloff for three thermal control options for a 15700 Kg (7800 ft^3) LH_2 OTV storage tank. The amount of boiloff which directly evolves from the LH_2 tank, when

OPEN CYCLE-INTEGRATED LO_2-LH_2 TANK THERMAL CONTROL



COOLING METHOD	TOTAL THERMAL CONTROL SYSTEM MASS (kg)	LH_2 BOILOFF (kg/hr)
MLI only	less than 20	.728
TVS+VCS	1436.3	.314
TVS+ REFRIGERATOR	111.0	.292

*SORPTION COOLER WITH 28°K PRECOOLING

Figure 4

configured for passive cooling, will serve as a baseline. Using a TVS attached to a 55°K hydrogen tank shield, all of the excess heat from the LH_2 and LO_2 tank can be removed without the need for any additional refrigeration or oxygen venting. With this design, the boiloff is reduced to 53 percent of its original value. Because the system is constrained by the requirement that the boiloff be large enough to intercept all of the heat leak into the LO_2 tank, the amount of LH_2 boiloff is not reduced substantially by lowering the shield temperature to 20°K and coupling a refrigerator to it. However, by letting the tank wall serve as a 20°K vapor cooled shield (VCS), the mass of the VCS can be eliminated. Thus, the total thermal control system mass is greatly reduced. In spite of the above efforts to reduce structural weight, the amount of fluid vented during a long mission can be large. Vent losses can be greatly reduced by providing an independent LH_2 tank thermal control system design.

In order to properly design a propellant tank thermal control system, it is important to assess the impact of various parameters upon the vapor generation of the cryogenic propellants stored within the tank. The accompanying figure illustrates the effect of varying from its nominal value the magnitude of a given parameter (i.e., MLI thickness, environment temperature, strut heat leak, pipes and penetrations and para/orthos conversion efficiency) upon the calculated tank heat input relative to the tank's heat input using the parameter's nominal value. The nominal values represented in this figure were obtained from data representing the SOA technology as defined by Martin Marietta for an OMV.* The tank heat inputs appear to be most sensitive to changes from nominal values in the MLI thickness and environment temperature. Consequently, atten-

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* J. Robinson, Point Design and Technology Assessment, Long Term Cryo Storage Study, Final Program Review, Sept. 20, 1983.

tion was focused on the effects of these two parameters in developing a tank thermal design which minimized boiloff within the system constraints.

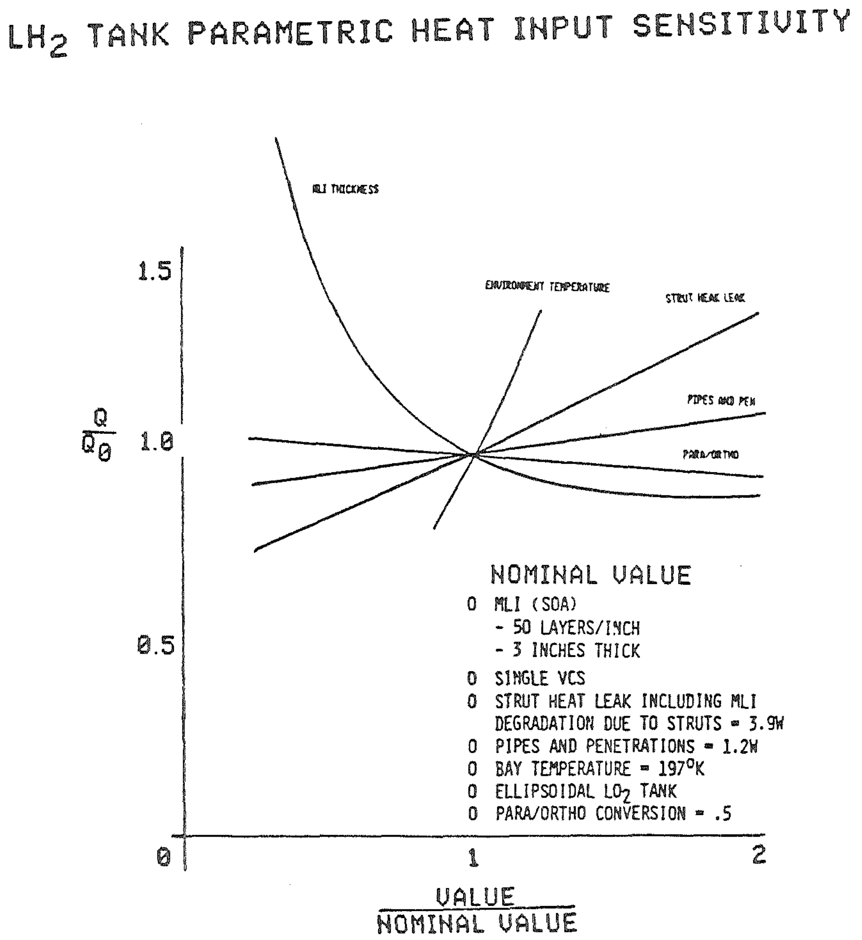
LH$_2$ TANK PARAMETRIC HEAT INPUT SENSITIVITY

Figure 5

Mass and energy conservation equations have been applied to the system in order to minimize the propellant boiloff. The accompanying figure shows the reduction in boiloff for refrigerated and non-refrigerated tank designs versus the boundary temperature ratio T_H/T_C. The optimization study was performed for an OMV3, LH$_2$ tank designed for a ten year mission duration. The boiloff from this tank, configured for passive cooling (utilizing 2 inches of MLI and no shield), served as a reference against which the boiloff from improved tank designs were judged. The curves are represented successively from the top as:

i) a non-refrigerated single shield tank which is temperature and position optimized at T = 87°K nd x/t^* = 0.44

ii) a multiple shielded tank (i.e., an infinite number of cooling shields)

iii) a refrigerated single shield tank which is optimized at T = 45°K and x/t = 0.5.

Here, x/t represents the non-dimensional distance from the tank for a given shield thickness, t. An optimized single shield refrigerated tank design substantially reduces the boiloff as compared to that generated from single and multi-shielded nonrefrigerated tank systems.

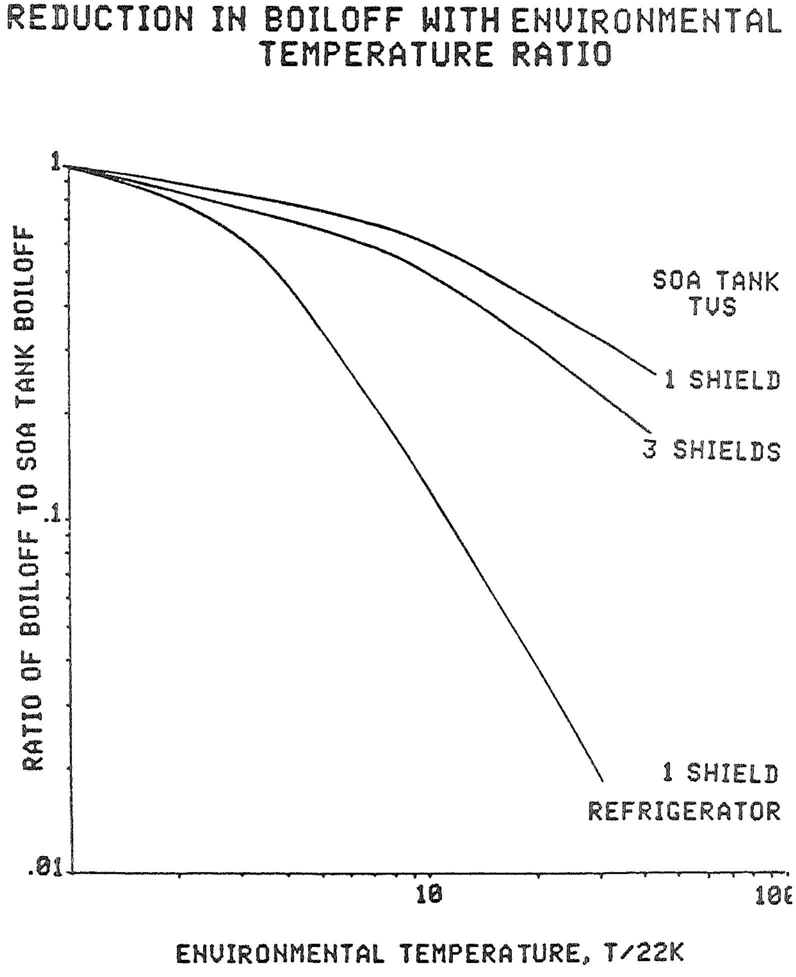

Figure 6

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* x/t represents the non-dimensional distance from the tank wall for a given insulation thickness, t.

Material technology advances and vessel design ingenuity can reduce propellant boiloff and overall system structural weight. In spite of these efforts, the weight of fluid vented during a long mission can be large. Consequently, a comparison of the relative performance of open and closed cycle thermal control schemes for a typical propulsion vehicle (OMV 3) is presented. It was assumed that the mass of propellant required at the end of any given mission was held constant. In addition, the shield temperature and position were optimized as a function of mission duration.

The launch weight of a tank configured for open cycle passive cooling utilizing two inches of MLI is shown to exceed the launch weight of the closed cycle system with active cooling at the 20°K tank wall (reference system) for mission durations greater than 1/2 year. Furthermore, an open cycle thermal control system with an actively cooled shield is shown to be preferable to the reference system for missions less than 1.6 years. Beyond this time, there

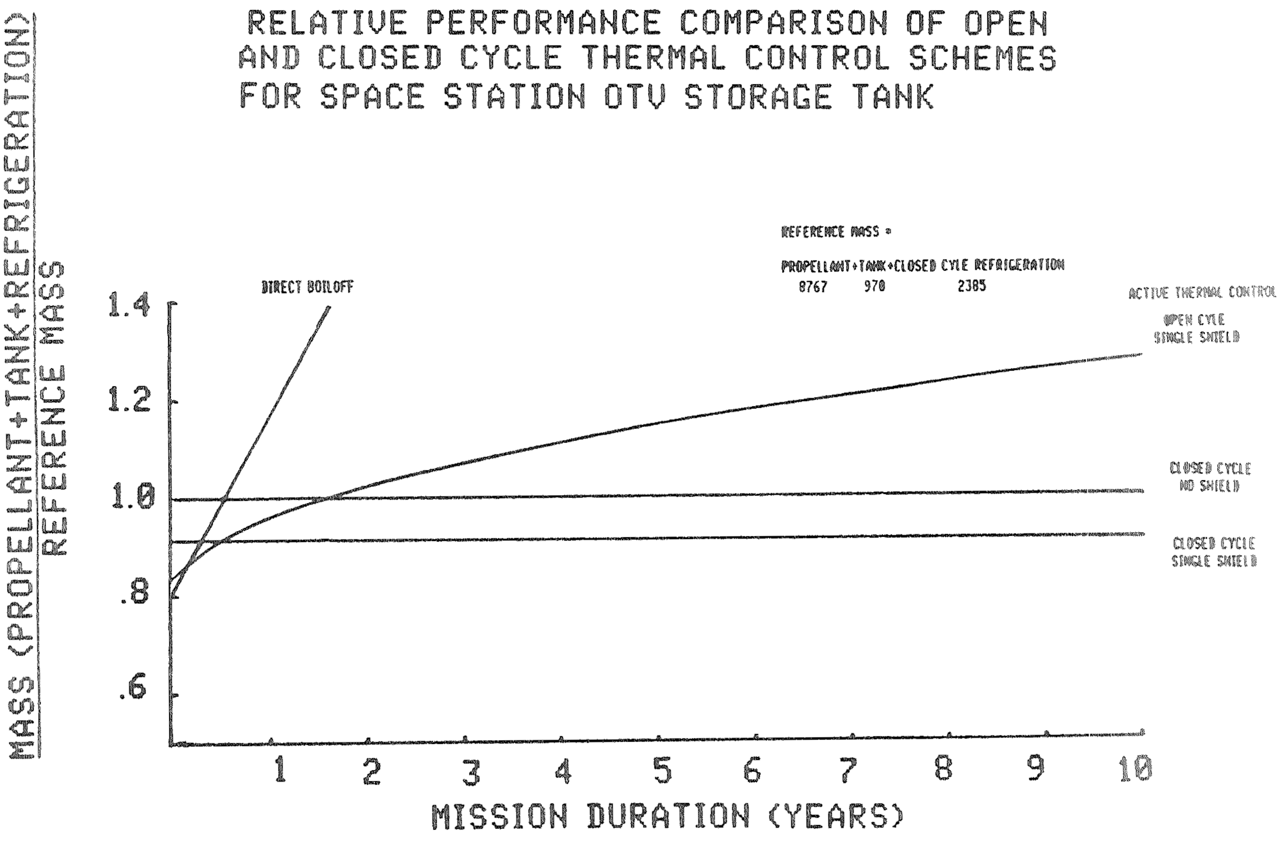

Figure 7

is a substantial mass savings to be gained by employing a closed cycle system with direct refrigeration at the tank wall. Finally, the use of actively cooled shields will enhance the overall thermal control system performance.

As an alternative to actively cooled, open cycle systems, a refrigeration system can be employed that provides direct cooling of both cryogenic tanks. Figure 1 shows a hybrid $LaNi_2$ charcoal nitrogen (C/N_2) propellant tank direct cooling refrigeration scheme. Alternative designs could utilize Stirling, Brayton and Veuillemier refrigeration systems.

CLOSED CYCLE THERMAL CONTROL

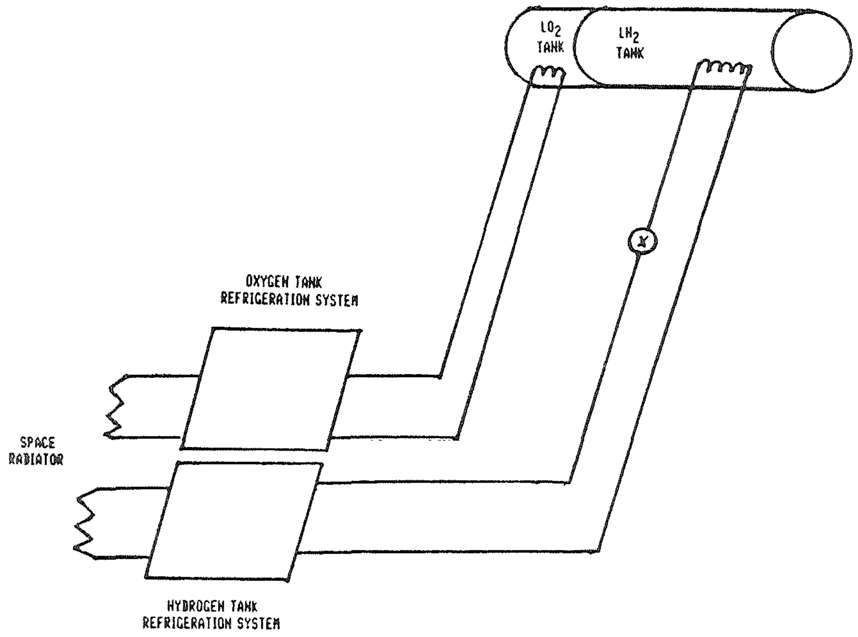

Figure 8

A preliminary investigation was made of the above refrigeration system design to determine the overall closed cycle refrigeration system mass. An optimized shield temperature and location were found which minimized the overall refrigeration system mass. For mechanical coolers, the optimized shield temperature and position is 94°K and x/t = 0.5.* By adding a refrigerated shield to an insulated tank (which utilizes a 20°K cooler to intercept heat at the tank wall), the overall refrigeration mass was reduced by approximately 55% for the mechanical coolers.

An assessment of the space station propellant thermal control system mass and heat loads has been made, corresponding to the minimum and maximum size propellant tanks which could be maintained on space station. The Turbo Brayton system was used to represent a typical mechanical refrigeration system, which was attached to a vapor-cooled shield. The refrigeration system mass included power supply, energy storage and radiator. The mass of the vapor-cooled shield was not included in the analysis and the shield weight could become quite substantial, particularly if the mass of the tubing and supports are accounted

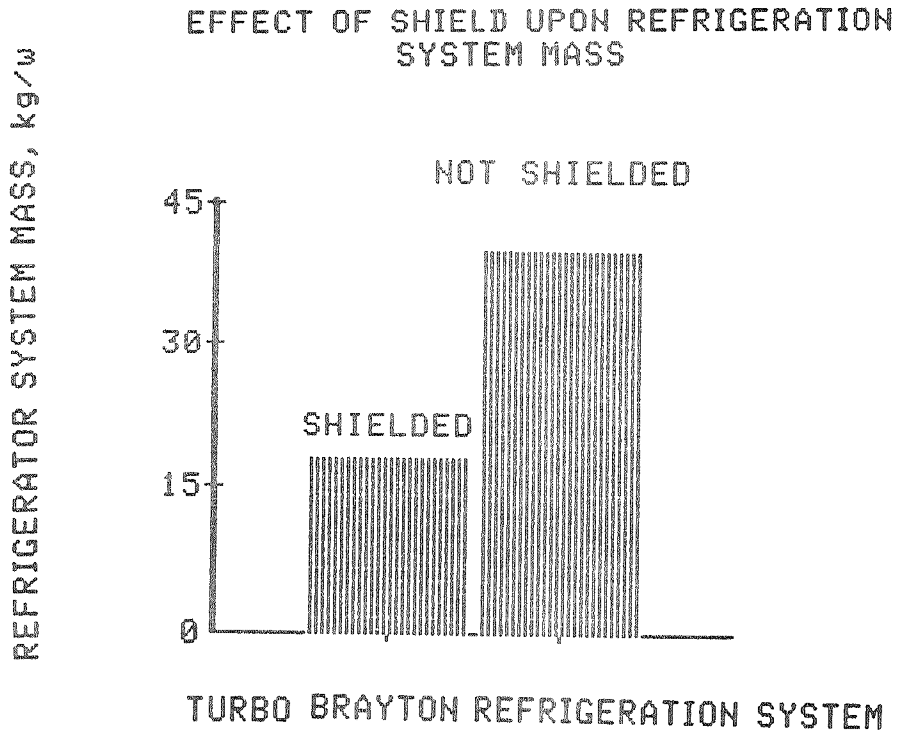

Figure 9

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* x/t represents the non-dimensional distance from the tank wall for a given insulation thickness, t.

for. The shield masses for the onboard propulsion and OTV tank farm storage tanks could conservatively reach a maximum of 24.5 kg and 1340 kg, respectively.

Although these refrigeration systems represent a non-trivial mass penalty, their employment can substantially reduce the mass of accumulated boiloff expended over the life of a long duration mission. This translates into a substantial savings in initial wet system mass transportation costs.

SPACE STATION PROPELLANT THERMAL
CONTROL SYSTEM MASS AND HEAT LOADS

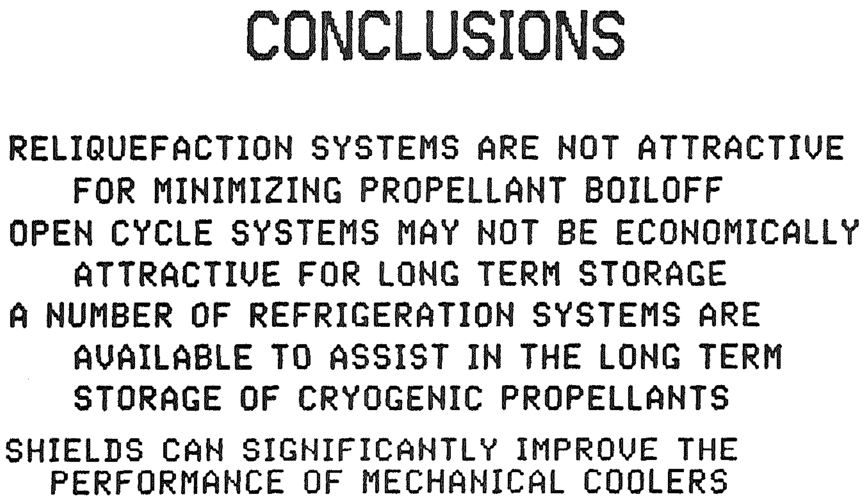
System	Propellant	Volume (ft^3)	Propellant Mass (Kg)	Heat Input (watts)	Refrigeration System Mass	
					Shielded (Kg)*	Unshielded (Kg)
On Board Propulsion System	H_2	32	61	2.22	40.0	89.9
OTV Tank Farm	H_2	7800	15,700	116.5	2097.0	4718.0

* Assumptions

- Shield mass not inlcluded
- Sized for Turbo Brayton System

Figure 10

Increasing the storage life of state of the art, passive vented and non-vented propellant tanks is essential in order to satisfy the requirements of long duration missions within economic constraints. For a vented propellant storage tank design, active coolers may be employed for propellant reliquefaction, or for intercepting heat along a vapor-cooled shield in order to reduce the heat load to the tank. Reliquefaction systems are shown to not be attractive for minimizing propellant boiloff in an unshielded tank design. Careful thermal design is necessary to achieve the minimum possible boiloff within the system constraints. Independent storage tank thermal control, utilizing actively refrigerated vapor-cooled shields for vented propellant storage, results in a significant reduction in boiloff loss over alternative vented storage tank system designs. However, open cycle systems may not be economically attractive for long-term storage. The maximum fluid and vessel weight savings occurs if the refrigeration capacity is chosen to match the vessel heat leak, thereby allowing storage without venting. Use of refrigerated shields has been shown to significantly improve the performance of mechanical coolers in non-vented, as well as vented, storage tank designs. This type of storage tank, thermal control system design, results in a significant reduction in refrigeration system mass.



CONCLUSIONS

RELIQUEFACTION SYSTEMS ARE NOT ATTRACTIVE FOR MINIMIZING PROPELLANT BOILOFF

OPEN CYCLE SYSTEMS MAY NOT BE ECONOMICALLY ATTRACTIVE FOR LONG TERM STORAGE

A NUMBER OF REFRIGERATION SYSTEMS ARE AVAILABLE TO ASSIST IN THE LONG TERM STORAGE OF CRYOGENIC PROPELLANTS

SHIELDS CAN SIGNIFICANTLY IMPROVE THE PERFORMANCE OF MECHANICAL COOLERS

Figure 11