An Overview of NASA Efforts on Zero Boiloff Storage of Cryogenic Propellants
2001 Space Cryogenics Workshop
July 12–13, 2001

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Abstract

Future mission planning within NASA has increasingly motivated consideration of cryogenic propellant storage durations on the order of years as opposed to a few weeks or months. Furthermore, the advancement of cryocooler and passive insulation technologies in recent years has substantially improved the prospects for zero boiloff storage of cryogenics. Accordingly, a cooperative effort by NASA's Ames Research Center (ARC), Glenn Research Center (GRC), and Marshall Space Flight Center (MSFC) has been implemented to develop and demonstrate "zero boiloff" concepts for in-space storage of cryogenic propellants, particularly liquid hydrogen and oxygen.

ARC is leading the development of flight-type cryocoolers, GRC the subsystem development and small scale testing, and MSFC the large scale and integrated system level testing. Thermal and fluid modeling involves a combined effort by the three Centers. Recent accomplishments include: 1) development of "zero boiloff" analytical modeling techniques for sizing the storage tankage, passive insulation, cryocooler, power source mass, and radiators; 2) an early subscale demonstration with liquid hydrogen 3) procurement of a flight-type 10 watt, 95 K pulse tube cryocooler for liquid oxygen storage and 4) assembly of a large-scale test article for an early demonstration of the integrated operation of passive insulation, destratification/pressure control, and cryocooler (commercial unit) subsystems to achieve zero boiloff storage of liquid hydrogen. Near term plans include the large-scale integrated system demonstration testing this summer, subsystem testing of the flight-type pulse-tube cryocooler with liquid nitrogen (oxygen simulant), and continued development of a flight-type liquid hydrogen pulse tube cryocooler.

Keywords: Orbital Cyrogen Storage

Introduction/Background

Future mission planning within NASA has increasingly motivated consideration of cryogenic propellant storage durations on the order of years as opposed to a few weeks or months. Manned and unmanned Mars missions, long-term geosynchronous missions, deep space missions, and space depots are a few examples. Furthermore, the advancement of cryocooler, passive insulation, and electrical technologies in recent years has substantially improved the prospects for zero boiloff (ZBO) storage of cryogenics. The ZBO weight benefits for long-term missions are substantial, particularly since the tank size and insulation weight grow with mission duration in a passive storage concept but not with ZBO. Additionally, mission flexibility is significantly enhanced since delays in rendezvous and docking or other operations can be accommodated without jeopardizing propellant mass margins; i.e, the cryogens can be treated like storable propellants. Transient environmental heating effects can also be more easily accommodated. Accordingly, as depicted in Figure 1, a cooperative effort by NASA Ames Research Center (ARC), Glenn Research Center (GRC), and Marshall Space Flight Center (MSFC) has been implemented to develop and demonstrate ZBO concepts for in-space cryogenic storage of cryogenic propellants, particularly liquid hydrogen (LH$_2$) and liquid oxygen (LO$_2$). ARC is leading the development of flight-type cryocoolers, GRC the subsystem development and small-scale testing, and MSFC the large-scale and integrated system level testing. The development of analytical modeling was initiated by GRC and ARC and becomes a joint effort among the three Centers as testing and experience progress. Basically, the early concept demonstrations are performed with low-cost available hardware and are followed by increasingly flightlike hardware with the schedule largely dependent on the availability of technology funding.
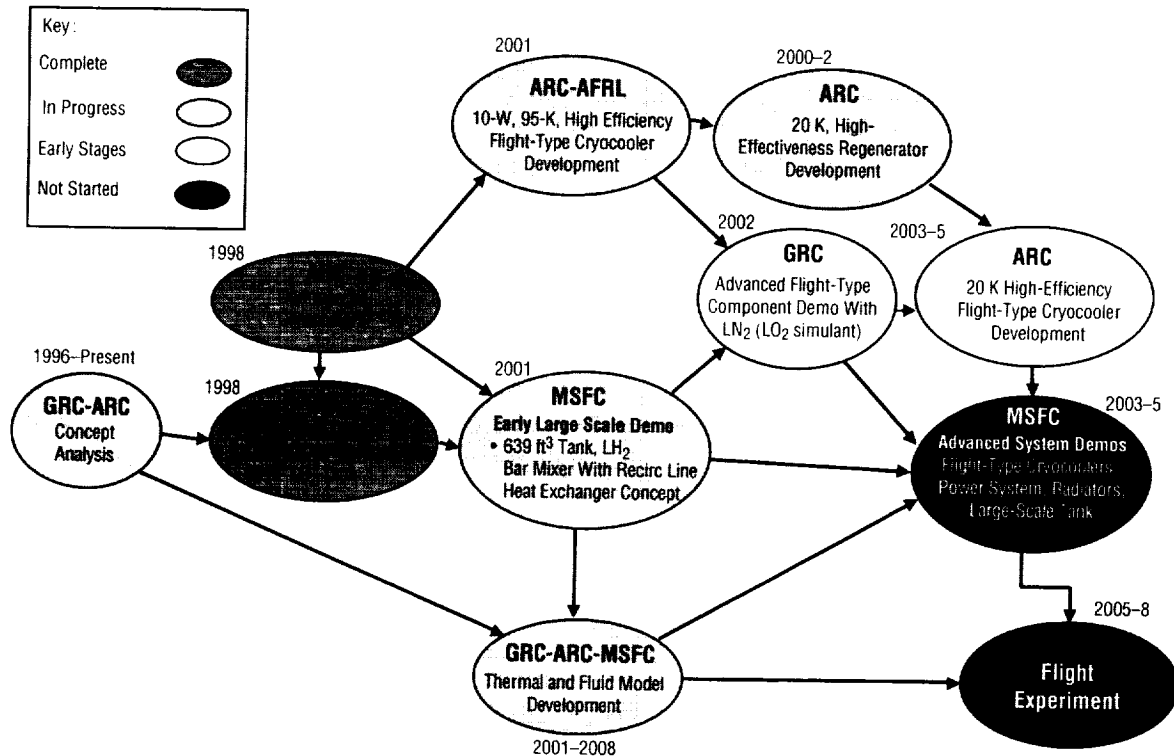

Figure 1. NASA's ZBO Concept Development Roadmap.

The ZBO concept and associated hardware can be applied to a wide range of other missions including in situ consumable production (ISCP) and storage for human and robotic missions [1,2]. Dewars for on-orbit experiments represent another application possibility. For example, a ZBO system for storing liquid nitrogen (LN_2) for the Space Shuttle and Space Station astrobiology experiments could alleviate prelaunch support complications. One such experiment required storage of samples in a 12-liter LN_2 dewar for periods of up to 12 days. Sample preparations several weeks in advance necessitated replenishment with LN_2 until loading on the Shuttle for launch [3]. A ZBO system would extend sample storage time periods and simplify prelaunch support.

Concept Description

ZBO involves the use of a cryocooler/radiator system to intercept and reject cryogenic storage system heat leak such that boiloff and the necessity for venting are precluded. As depicted in Figure 2, a cryocooler (with a power supply, radiator, and controls) is integrated into a traditional orbital cryogenic storage subsystem that includes passive thermal insulation, a destratification mixer, instrumentation, and controls. The insulation maintains the heat leak within the thermal capability of the cooler and the destratification mixer, combined with the instrumentation and controls, ensures pressure control independent of the ullage and liquid positions within the tank (during zero gravity or parking orbit coast periods) [4]. If the concept application is limited to gravity environments where the ullage is known to always be in the upper portion of the tank, then the cryocooler coldhead can be positioned in the ullage and adequate pressure control can be achieved without a mixer.
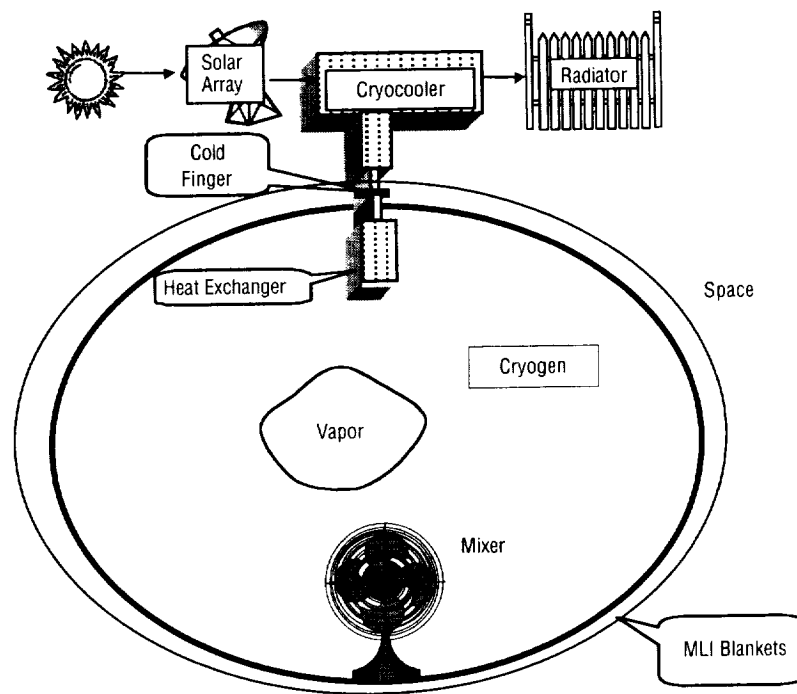

Figure 2. In-Space ZBO Concept.

Analytical Modeling

An analytical model has been developed to support ZBO trade studies. The model is described in more detail in Kittel et. al [5]. Included are relationships for estimating cryogenic tank size and weight, multilayer insulation (MLI) weight and performance, vapor-cooled shielding, and cryocooler subsystem performance with associated weights of the power source and radiators. For comparison purposes, inputs associated with cryocoolers or the ZBO concept can be omitted and a similar set of performance numbers can be generated for passive storage techniques. Empirical relationships based on a study of tank supports for flight systems for LO_2, liquid methane (LCH_4), and LH_2 tanks are used to model the penetration heat leak as a function of tank weight, resonant frequency, and external temperature. Optional vapor-cooled shielding, which are applicable to H_2 storage only, have weights of 2 kg/m^2 and 2.5 kg/m^2 incorporated for passively and actively cooled shields, respectively. Additionally, a para-to-ortho converter is incorporated in the shield modeling. The MLI is modeled based on insulation weights in [6], where a substantial increase in performance (~50% improvement) was achieved with a variable density MLI. The solar cell mass of 0.026 kg/W includes a supporting structure and a 30% contingency. The radiator mass is based on masses estimated by Glaister and Curran with a 30% contingency added. Cooler efficiency and weight are based on those defined by Strobridge [7] with efficiency increases added to account for advances in the last 25 yr. However, the Stobridge data do not address two-stage coolers where some of the heat leak is intercepted by the first stage. Such coolers are applicable to the LH_2 storage. A conservative approach was selected, which assumes that each of the two stages are independent stages. The mass of the tank structure for a particular cryogen is modeled assuming a 203.9 kg/cm^2 (29 psia) operating pressure and tank weights per unit area based on aluminum material with a 25% reduction to account for composite tank technology improvements.

As an example, model results for the storage of 670 kg of LH_2 and 4,000 kg of O_2 in low-Earth orbit (LEO) are presented in Figures 3 and 4, respectively. With passive storage, the storage tank size and insulation weight increase with days in orbit (to accommodate and control boiloff), whereas the ZBO storage system mass remains constant. The ZBO system mass advantage, compared with passive storage, begins at 60 days and 10 days for the H_2 and O_2 storage, respectively. Also, it is important to note that ZBO would substantially add operational flexibility since mission timelines can be extended in real time with no propellant losses. Additionally, the adaptability of a given storage system to other mission applications is greatly enhanced. Of course, individual mission requirements and environment can make a difference in whether a passive or active storage system is optimal. Model results for other mission application examples are presented in Kittel et al. [2,5].

The model has subsequently been upgraded to include power and weight associated with a mixer for zero gravity destratification and pressure control (required in both passive and ZBO concepts). In fact, the model is continually updated as technology products and inputs become available.
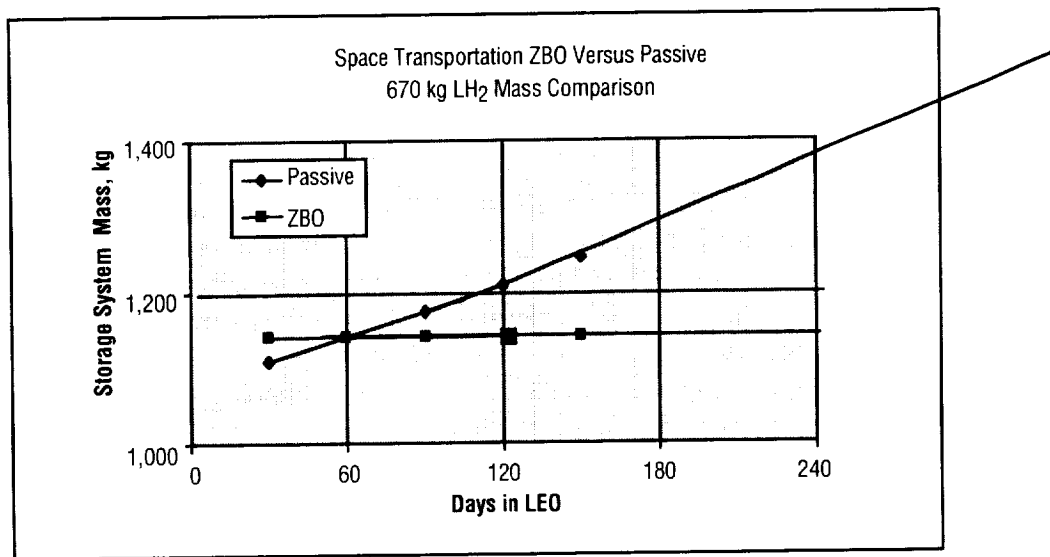
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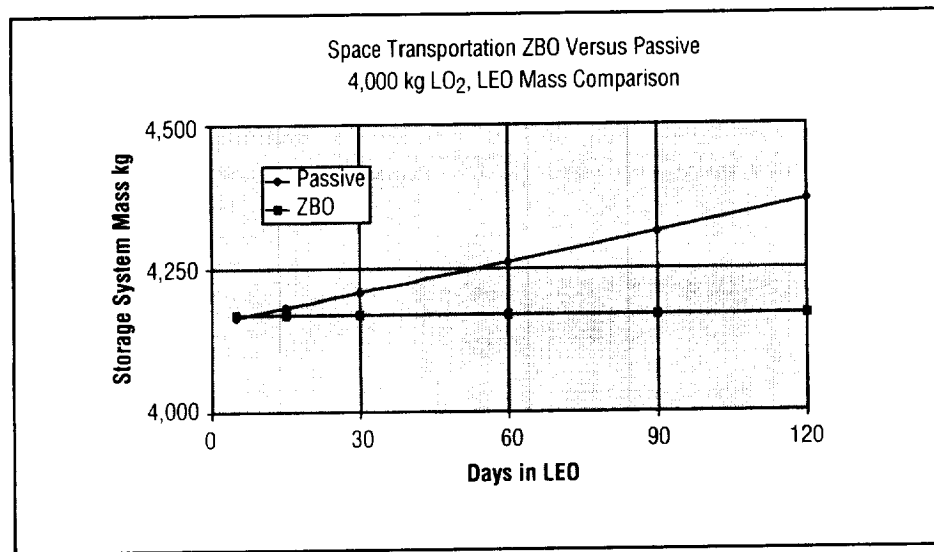Figure 3. LH$_2$ Storage system Mass Versus Time in LEO, Passive, and ZBO Concepts.

Figure 4. LO$_2$ Storage System Mass Versus Time in LEO, Passive, and ZBO Concepts.

Cryocooler Development

Space applications of ZBO will necessitate the development of lightweight high-efficiency (LWHE) cooler systems, including the associated flight electronics, with cooling capacities in the 1–20 W range. The major challenge is represented by the LH$_2$ application since a two-stage unit is required to operate at 20 K, the nominal H$_2$ saturation temperature. For space applications requiring cooling capacities of ≥10 W, pulse tube coolers offer the advantage of reduced complexity since there are no moving parts at the coldhead. For cooling requirements in excess of 10 W, reverse

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turbo-Brayton coolers are the clear choice at present. In combination with advances in regenerator development, improvements in cooler efficiency, reduction in mass, and extension of operating lifetime will make two-stage LH_2 coolers economically feasible for ZBO space transportation systems.

As part of a joint effort with the U.S. Air Force, NASA, and TRW, Inc., a flight-type 10-W, 95-K pulse tube cryocooler for LO_2 and LCH_4 storage has been developed (Fig. 5). This TRW cooler delivers 1 W of cooling per 12 W of input power, that is, has an efficiency of 18% of Carnot at 95 K, and weighs >4 kg. This efficiency is nearly a third better than previous designs, while the mass has been reduced by roughly a factor of three. The operating lifetime goal of this cooler is 10 yr. Besides the LO_2 application, coolers such as this provide technology for the development of 20 K two-stage LH_2 pulse tube coolers. A key technology component for LH_2 pulse tube coolers is the regenerator. Recent advances in materials technology have shown that rare Earth materials, particularly alloys of erbium and nickel, offer order-of-magnitude improvements over lead and similar materials in heat capacities at temperatures below 60 K. These new materials, in combination with advances in regenerator geometry optimization, can offer a significant improvement in pulse tube efficiency at the lower temperatures required for LH_2 coolers. Figure 6 shows heat capacity as a function of temperature for selected regenerator candidate materials [8]. The technology goals for an initial LH_2 pulse tube cooler are an efficiency of 3–5% of Carnot, cooling capacity of 2 W at 20 K, and a cooler mass of 15 kg. Larger capacity pulse tube coolers and reverse turbo-Brayton cycle coolers will be pursued as technology funding permits. As mentioned in the introduction, as the prototype coolers are developed, the units will be utilized in technology test beds at GRC and MSFC to acquire experience and data regarding performance and system design sensitivities.
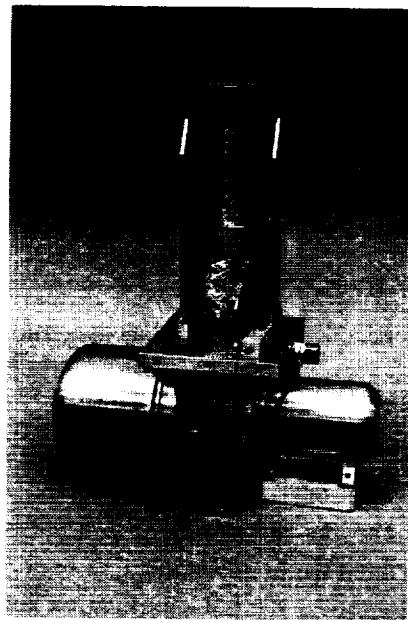
• 10-W Coding at 95 K
• Weight = 3.6 Kg
• 10-yr Life

Figure 5. State-of-the-Art TRW Flight-Type Pulse Tube Cryocooler.

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Volumetric Heat Capacity
Versus
Temperature

Heat Capacity (Jcm^{-3}K^{-1})

2
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2

Temperature [K]

4   10   100

—o— He @ 2MPa
— SS
—+— Pb
---/- CuBrnz
----- AL-272-1
—A- AL-272-1K
-•- AL-272-1F
—■- AL-272-1F-0.27
--•- ErNi
--A-- Er3Ni
—▼- Er6Ni2Sn
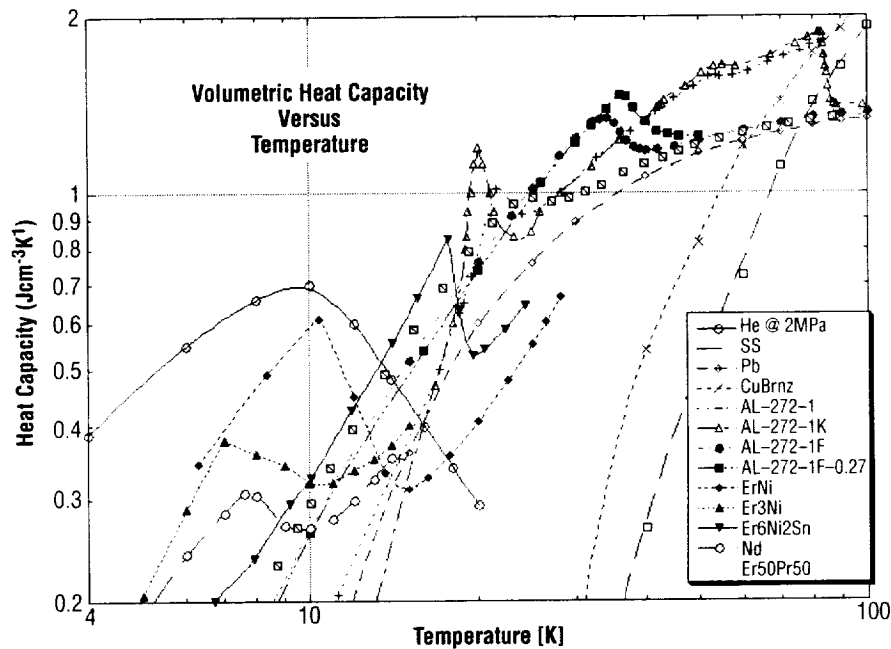—o- Nd
     Er50Pr50

Figure 6. Volumetric Heat Capacity Versus Temperature of Candidate
           Regenerator Materials.

To date, flight coolers in the range of 20 K are limited to cooling capacities of >2 W [9]. Included are a multistage Stirling cooler providing 120 mW at 20 K, a continuous sorption cooler expected to provide 1.6 W at 20 K, and a split Stirling two-stage cooler providing 0.45 W at 30 K.

Concept Demonstrations

The development of flight-type LH$_2$ coolers is expensive and the schedule is largely dependent on the availability of technology funding. Commercial coolers are affordable and in many respects thermodynamically representative in terms of integration into a H$_2$ storage system. Therefore, early concept demonstrations with LH$_2$ have been pursued by the ARC, GRC, and MSFC team using commercial coolers. GRC first performed testing in 1998 [10] with a two-stage Gifford/McMahon cycle cooler (borrowed from National Institute of Standards Technology) and an existing, multilayer, insulated 1.42-m^3 (50-ft^3) tank (Fig. 7). The cooler second stage had a cooling capacity of 17.5 W at 18 K, while the first stage provided 20 W at 35 K. The second stage was attached to a 248 cm^2 copper condenser, which was suspended in the ullage. Testing determined that the tank baseline heat leak without the cooler installed was 14.5 W. With the second stage only (first stage had zero heat load) the tank pressure gradually dropped over a 61-hr test period, demonstrating that a ZBO condition could be achieved. Additional cooler integration thermodynamic and heat transfer data were obtained by evaluating the effects of attaching copper shielding to the first stage and shutting down the cooler operation. This low-cost testing provided early experience and data to guide subsequent system level testing.

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Figure 7. ZBO Concept Evaluation With 50-ft^3 Tank, GRC.

A system level demonstration with a large-scale 18 m^3 (639 ft^3) LH$_2$ tank is being conducted at MSFC during the summer of 2001. A commercial Cryomech GB37 unit was selected and procured by ARC for testing with MSFC's Multipurpose Hydrogen Test Bed (MHTB). The unit, capable of extracting 30 W at 20 K, was then delivered to GRC for bench testing and design of a heat exchanger and structure for integrating the cooler into the MHTB. The concept, depicted in Figure 8, involves connecting the second stage cooling finger with a heat exchanger inserted into an existing recirculation line (Fig. 9) that in turn, interfaces with a pump and spray bar mixer system. The spray bar recirculation system, used in previous testing [4], is designed to provide destratification independent of ullage and liquid positions in a zero gravity environment. The recirculating H$_2$ is pumped past the coldhead heat exchanger. The cooled liquid then flows into the spray bar and is sprayed into the tank. Since the cooler thermal extraction rate cannot be directly controlled, the MHTB environmental shroud will establish an environment such that the tank heat leak is below the thermal extraction capability of the cooler. Then, based on the measured tank pressure decrease rate, internal heaters will be adjusted to achieve steady-state pressure conditions with ZBO. A control system logic based on ullage pressure response has been designed to automatically provide a constant average tank pressure condition. Testing at tank fill levels of 95%, 50%, and 25% is planned. With a variable output flight-type cooler and controls, tank heaters would not have to be implemented; however, experience with the MHTB will provide valuable experience to guide the design and development of future systems.
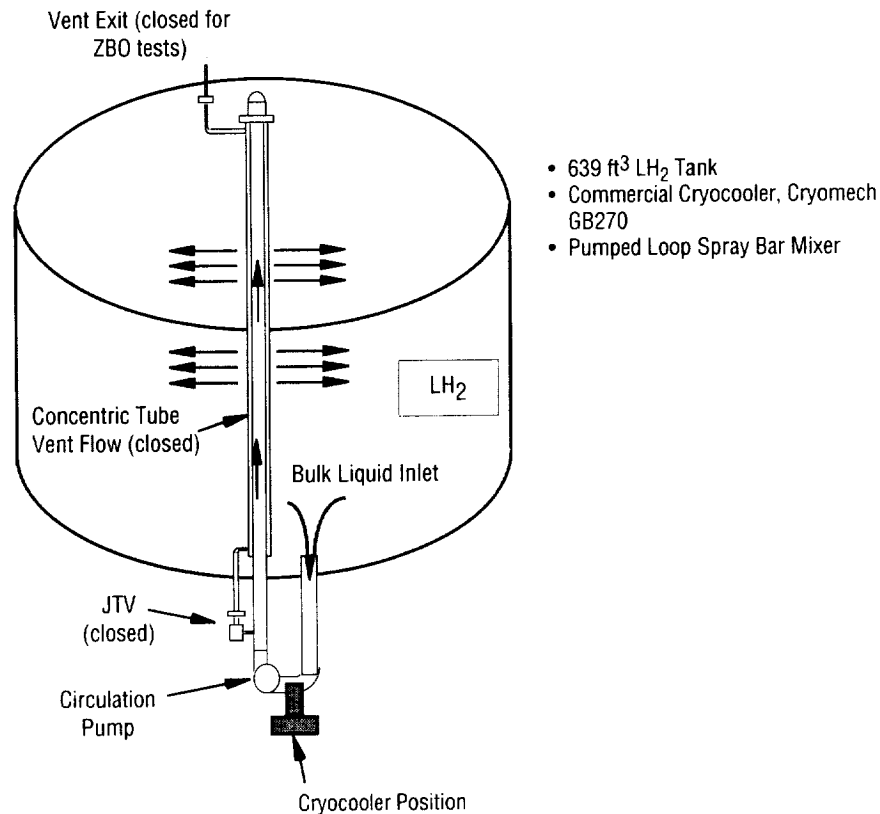
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Figure 8. MHTB ZBO Demonstration Test Setup Schematic.

Additional demonstration testing is planned with the TRW flight-type pulse tube cooler (Fig. 10) and LN_2. GRC is currently assembling hardware for component/subsystem testing in 2002. The cooler is being installed on top of the 1.4 m^3 tank used in earlier testing at GRC (Fig. 7). In this instance, however, the coldhead will interface with a heat pipe/mixer arrangement such that the ullage is not directly cooled. The coldhead is attached to a heat pipe that passes through the ullage and interfaces with a mixer submerged in the tank bottom. This configuration prevents a natural convection thermal exchange with the ullage and forces the thermal exchange or liquid cooling to occur at the cold end of the heat pipe near the tank bottom. This enables a closer simulation of a flight application and more realistic characterization of cooler performance than if the coldhead were simply extended into the ullage. Characterization testing will include measuring the effects of varying input power, radiator heat rejection and sink temperatures, destratification or mixing rates, and pressurant gas (He and H_2). Additionally, the cooler control panel integration and performance will be evaluated. The GRC testing will "pave the way" for system level testing with the same cooler in a large tank demonstration at MSFC in 2003.

Future ZBO demonstrations at the three NASA centers, for both LH_2 and O_2, will involve progressively more sophisticated and flightlike equipment as the supporting technologies progress. Industrial involvement in concept development would be very beneficial and is expected to be factored into the ZBO effort as soon as possible.
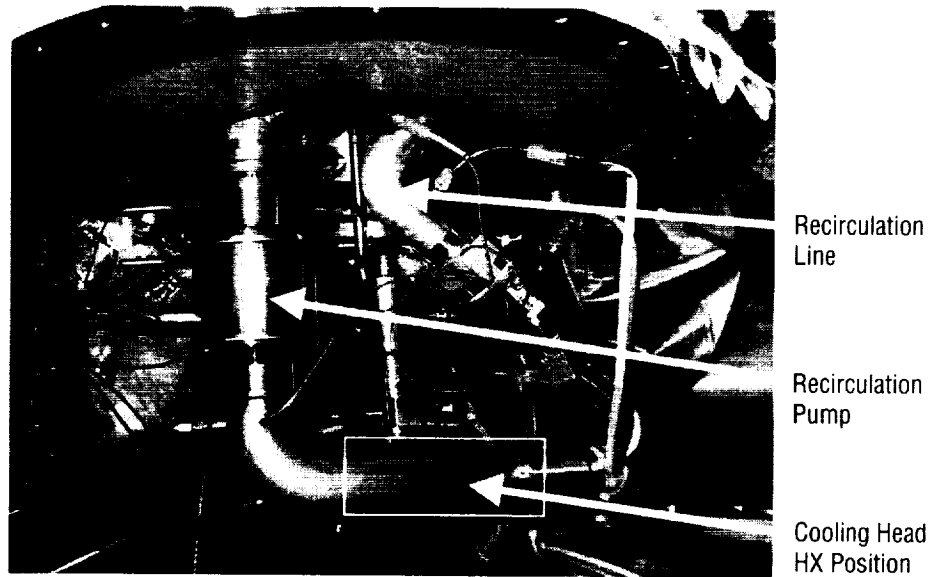
Recirculation Line

Recirculation Pump

Cooling Head HX Position

Figure 9. Cryocooler Cooling Head Installation Location on MHTB.

Summary

ZBO involves using a cryocooler/radiator system to intercept and reject cryogenic storage system heat leak such that boiloff and the necessity for venting is precluded. A cooperative effort by ARC, GRC, and MSFC has been implemented to develop and demonstrate "ZBO" hardware and concepts for in-space storage of cryogenic propellants, particularly LH_2 and O_2. An analytical modeling technique for sizing the storage tankage, passive insulation, cryocooler, power source mass, and radiators has been developed. Current model results for the storage of 670 kg of LH_2 and 4,000 kg of O_2 in LEO indicate that the ZBO system weight mass advantage, compared with passive storage, begins at 60 days and 10 days for the H_2 and O_2 storage, respectively. Early testing has been pursued with commercial cryocooler units and LH_2 to demonstrate the concept and to acquire data and experience to guide future development activities. GRC testing in 1998 with a 17.5-W, 18-K cryocooler in a 1.4-m^3 tank demonstrated that ZBO conditions could be achieved. A large-scale LH_2 test article (18-m^3 tank) has been modified at MSFC for testing and demonstration of the integrated operation of passive insulation, destratification-mixing, pressure control, and cryocooler subsystems. Testing is scheduled for the summer of 2001. ARC led the procurement of a flight-type 10-W, 95-K pulse tube cryocooler for LO_2 storage through a cooperative effort with the Air Force. Hardware for subsystem testing of this flight-type pulse tube cryocooler with LN_2 (O_2 simulant) is currently being assembled for testing at GRC in 2002. The GRC testing will pave the way for system level testing with the same cooler in a large tank, system level demonstration at MSFC in 2003. The development of progressively more flightlike LH_2 cryocoolers is being pursued at ARC. Future concept testing will therefore involve increasingly sophisticated and flightlike equipment as the supporting technologies progress. Industrial involvement in concept development is expected to be factored into the ZBO effort as soon as funding levels permit.
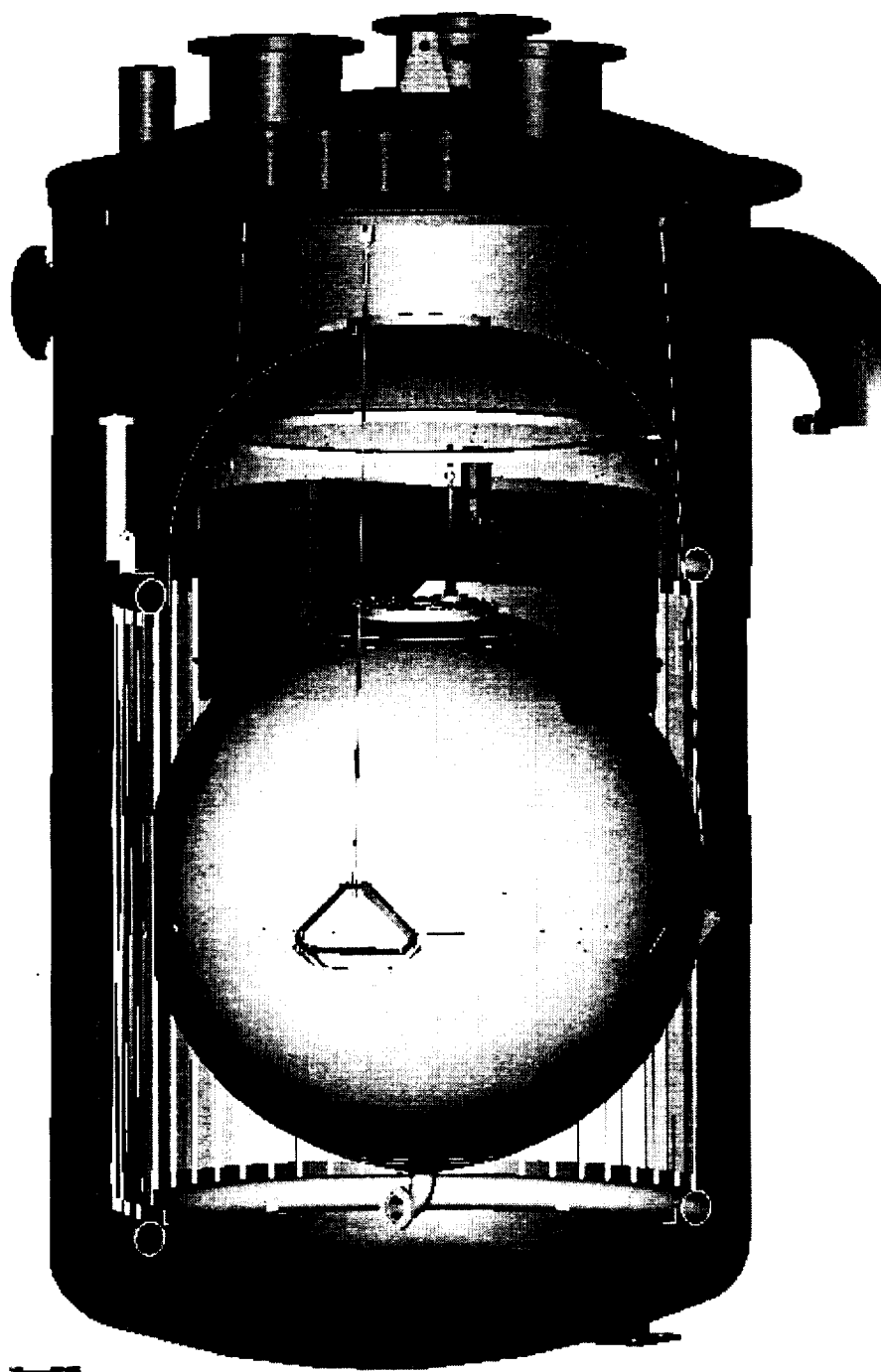
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Figure 10. LN$_2$ ZBO Test Article Installation in Vacuum Chamber, GRC.

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