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Broad Area Cooler Concepts for Cryogenic Propellant Tanks[1]

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ABSTRACT

Numerous studies and ground tests have shown that broad area cooling (also known as distributed cooling) can reduce or eliminate cryogenic propellant boil-off and enable long duration storage in space. Various combinations of cryocoolers, circulators, heat exchangers and other hardware could be used to build the system. In this study, several configurations of broad area cooling systems were compared by weighing hardware combinations, input power requirements, component availability, and Technical Readiness Level (TRL). The preferred system has a high TRL and can be scaled up to provide cooling capacities on the order of 150W at 90K.

INTRODUCTION

Space missions to the Moon, near earth objects, and Mars will benefit from the reduction of cryogenic propellant boil-off because of the significant mass savings. NASA's Chief Technologist, Robert Braun, elaborates on this in the article "Investment in the Future: Overview of NASA's Space Technology" [1]. Investing in technologies that yield improvements in cryogenic boil-off loss suggest a 40% mass savings is possible over a reference Mars mission as shown in Figure 1.

Clearly, the boil-off can be reduced through passive techniques. Specifically, high efficiency multi-layer insulation (MLI) combined with low thermal conductivity support structures reduce heat loads by at least an order of magnitude.

Zero-boil off, on the other hand, requires a combination of passive insulation and active refrigeration. Consequently, advanced passive insulation, when coupled to an active refrigeration system designed to reduce the heat leak, allows tank operation for long periods without venting. Using these techniques, zero boil-Off (ZBO) is attainable.

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[1] Thermal & Fluids Analysis Workshop (TFAWS), NASA Langley Research Center (2011)

This study examines various hardware configurations and different working fluids for developing broad area cooling (BAC) systems for accomplishing zero boil-off of cryogenic propellants.

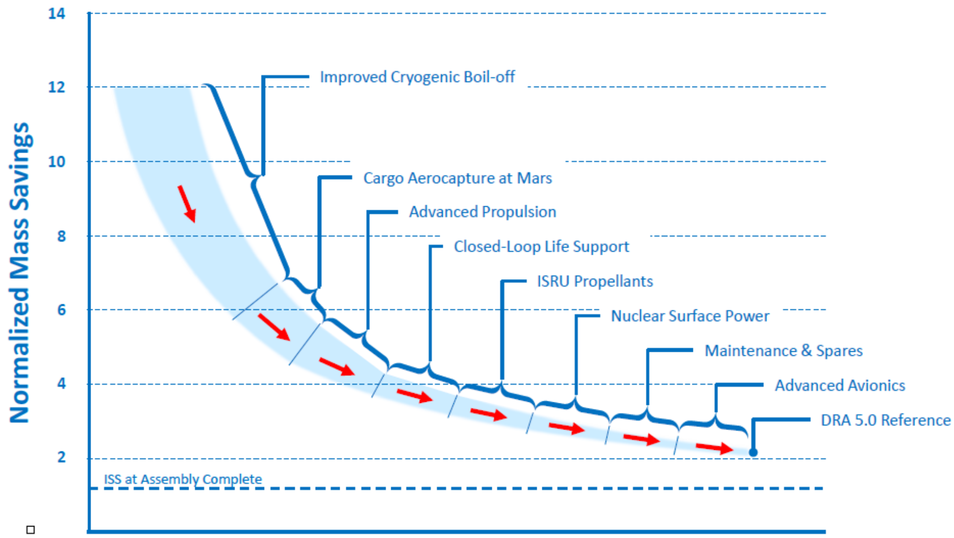


Figure 1, The Value of Technology Investments: Mars Mission Example [1]

Broad Area Cooling

Studies at the NASA Glenn Research Center in 2005 [2-4] found that boil-off from a liquid hydrogen (LH_2) propellant tank could be greatly reduced by incorporating a gas cooled shield in the tanks multilayer insulation (MLI). These shield designs were derived from vapor cooled shields (VCS) used with thermodynamic vent systems (TVS). The gas was circulated at 90K through widely spaced cooling tubes attached to a foil shield embedded within the MLI, as shown in Figure 2. Not only does broad area cooling system provide distributed cooling both over large surface areas, it can also provide cooling at localized penetrations. Although this arrangement intercepts a large proportion of the heat leak from the environment, it does not provide zero boil-off for a liquid hydrogen (LH_2) propellant tank.

For a liquid oxygen (LOX) propellant tank, instead of attaching the tubes to a shield, the cooling tubes would be attached directly to the outside of the tank wall, a.k.a. "tube-on-tank". Although a cooled shield could be placed on the outside surface of the tank, that would increase the temperature drop between the tank and the coolant. This would require the cryocooler to operate at a lower temperature, which would reduce its efficiency. The cooling tubes could also be located inside of the tank. Since the normal boiling point for LOX is 90K, cooling at 90K can intercept all of the environmental heating and provide zero boil-off for a LOX propellant tank.

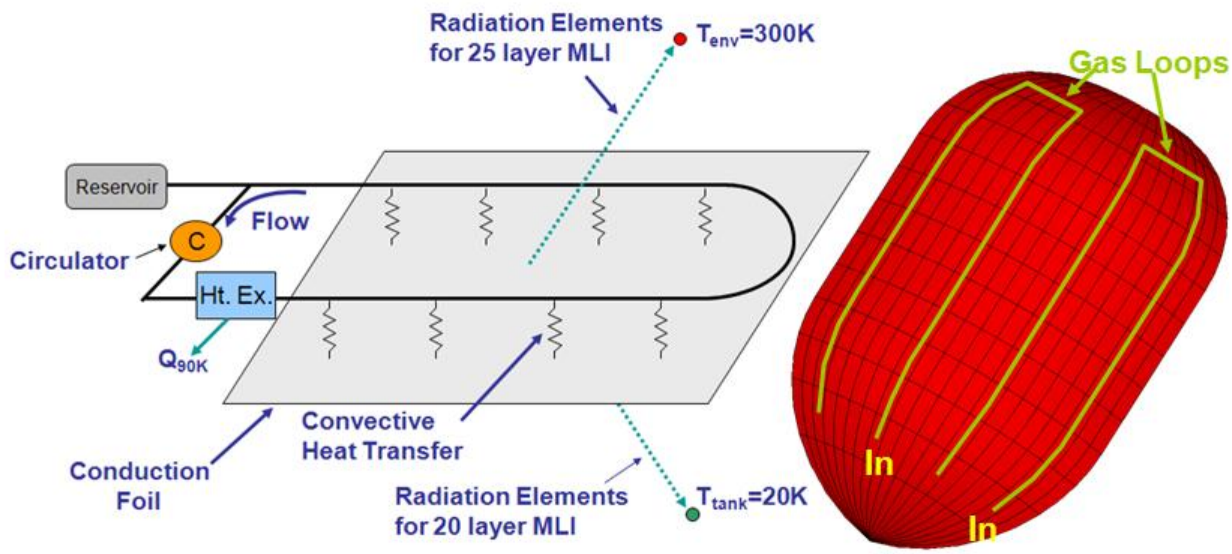


Figure 2, BAC Concept c. 2005

A broad area cooling system typically consists of a cryocooler, a circulator, a cooling tube network, and a heat rejection system. Various types of cryocoolers can be used, such as pulse tube, Stirling cycle, or Reverse Turbo Brayton cycle, but the preferred type would be one that can be scaled to handle the large heat loads expected in future spacecraft applications. The circulator provides the capability to locate the cooler and radiator far from the propellant tank and these circulators can be fans, pumps or compressors. The heat rejection system typically consists of a radiator and a fluid loop, such as a loop heat pipe (LHP), that transports the heat from the cryocooler to the radiator.

One method for cooling both LOX and LH_2 propellant tanks is shown in Figure 3. This concept uses the same coolant flow to cool the walls of a LOX tank and then cools the shield within the MLI of the LH_2 tank. This method provides zero boil-off for the LOX and reduced boil-off for the LH_2.

One way to attain zero boil-off for LH_2 is by using a 20K cryocooler with broad area cooling tubes attached to directly to the tank. A technology demonstrator, shown in Figure 4, has been designed and built by Sierra Lobo Inc. and was designed to store liquid hydrogen with zero boil-off for an arbitrary length of time [7].

Combining the two concepts above, zero boil-off could be provided for both propellants by considering a staged cycle. Cooling at both 90K and 20K could be provided by single two-stage cryocooler. An example of a two stage cryocooler that has been built and demonstrated for space applications is shown in Figure 5. The first and second stages provide cooling at 100K and 65K, respectively [8]. A similar device proposed by Boeing [9] and shown in Figure 6, accommodates 80W at 95K and 10W at 22K.

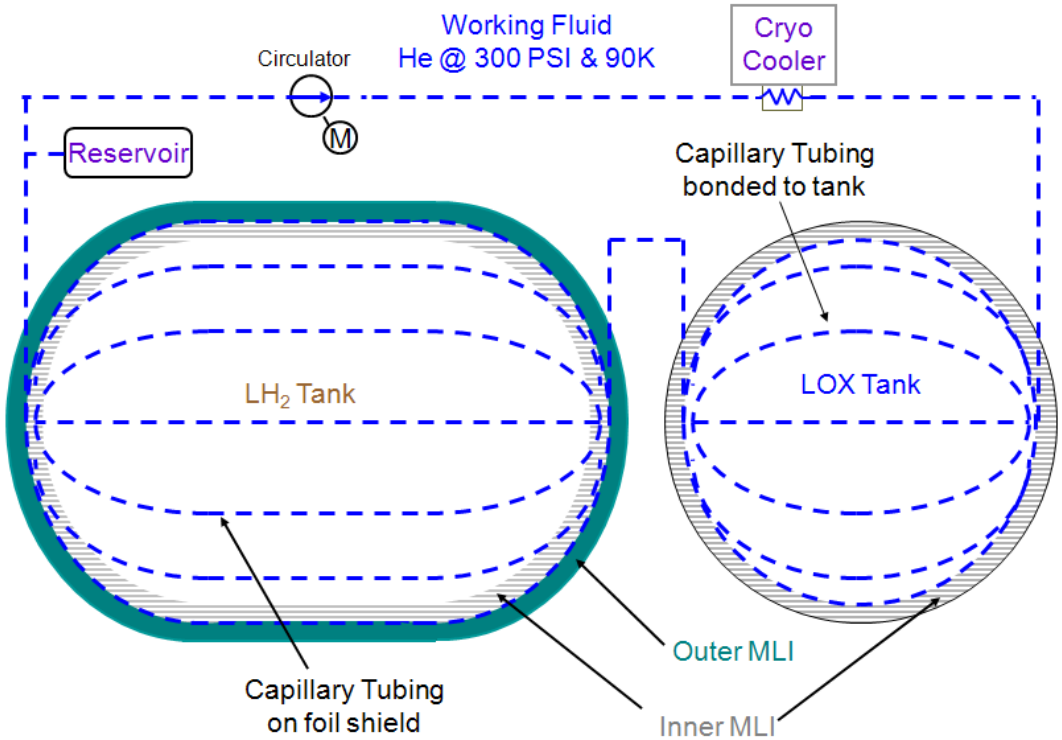


Figure 3, Broad Area Cooling of LOX Tank and a Shield on a LH_2 Tank

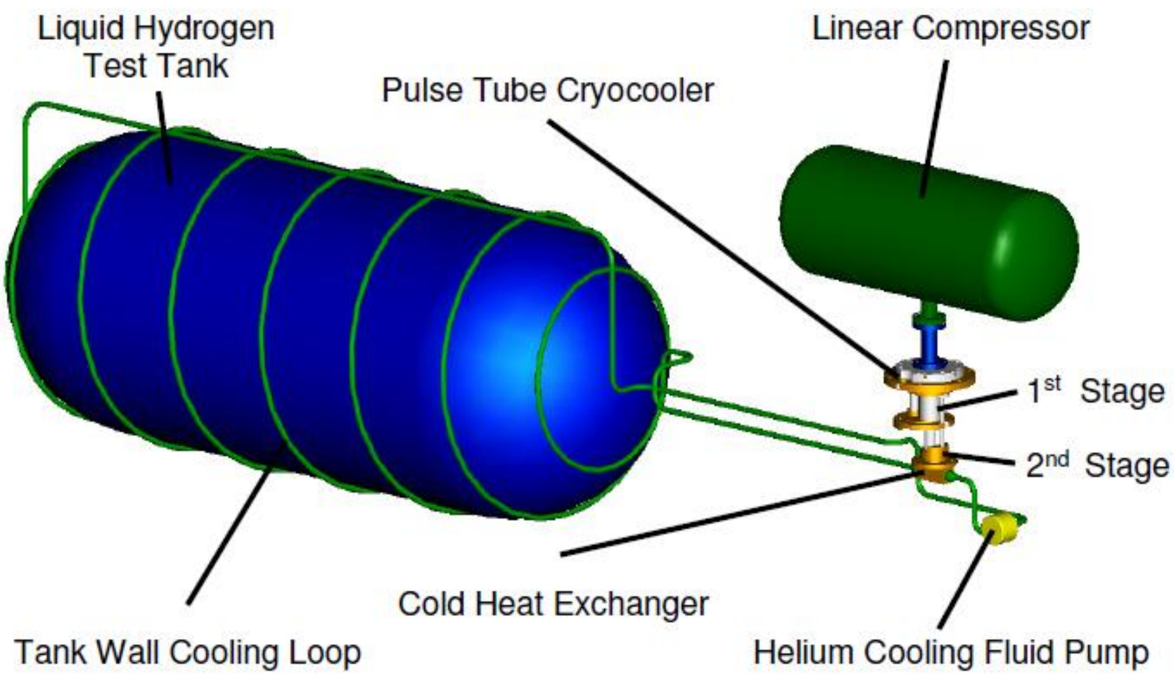


Figure 4, Sierra Lobo Inc., Zero Boil-Off Liquid Hydrogen Technology Demonstrator [7]

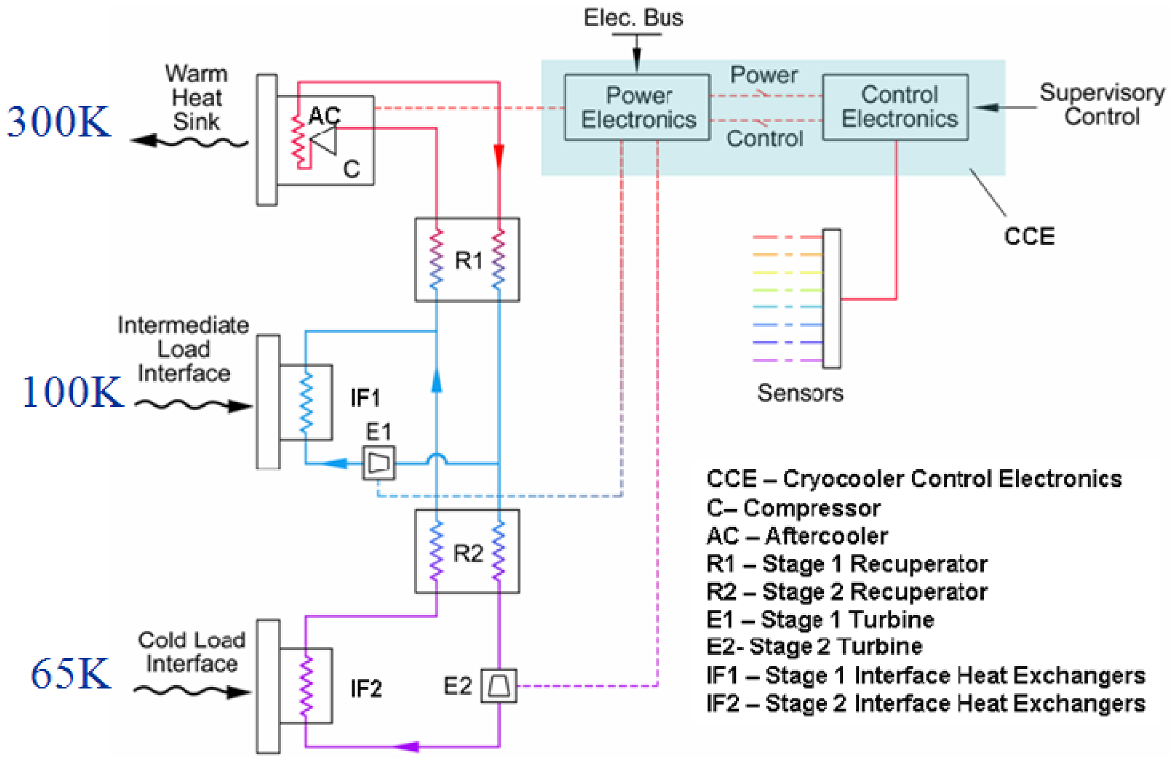


Figure 5, Creare Inc., Two Stage Turbo Brayton Cryocooler [8]

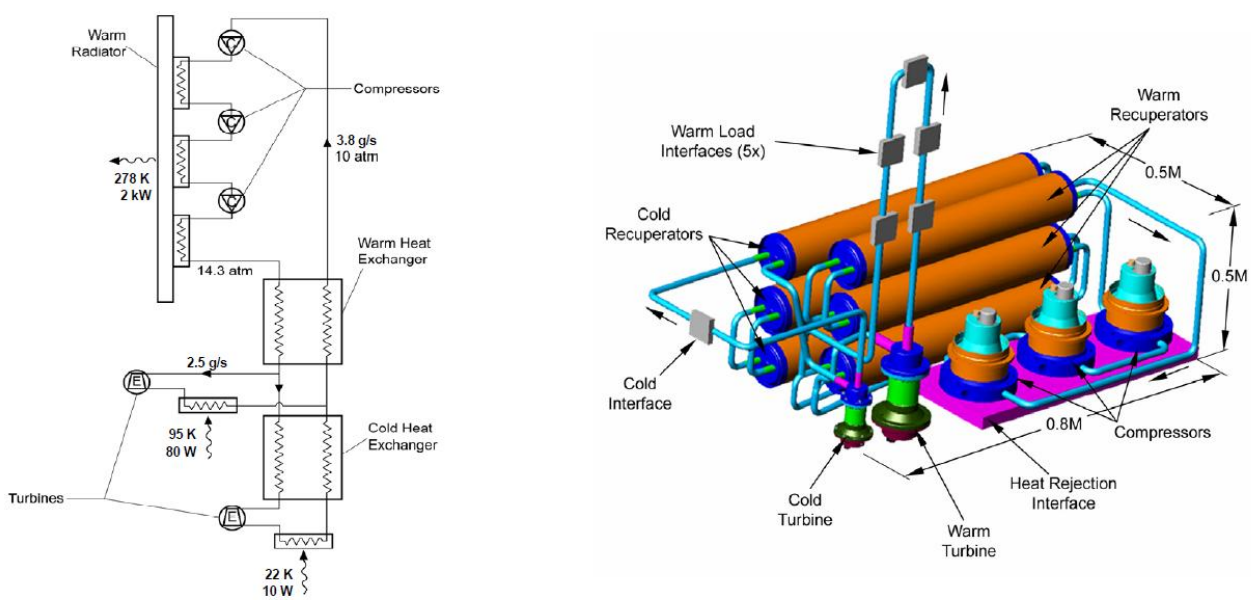


Figure 6, ACES Cryocooler [9]

The original task of this study was to select a circulator to be used for a LOX tank zero boil-off demonstration at NASA Glenn Research Center. The initial system schematic is shown in Figure 7. This concept consisted of a generic circulator and a generic cryocooler. The coolant was helium at 300PSIA and cooling was performed at 5K below the normal boiling point of LOX. It had not been decided whether to bond the BAC tubes directly to the tank or attach them to a shield that surrounded the tank.

This particular design required the use of a circulator operating at the cold temperature of the coolant. There are very few commercially available circulators that operate at these temperatures, so another concept was conceived by Feller et. al [5,6]. Here, a recuperator allowed the circulator to be thermally isolated from the cryogenic temperatures and the circulator was located at the warm temperature of the working fluid (Figure 8).

Since the circulator function could be integrated with the cryocooler, it was realized that choosing a circulator independently of the cryocooler and other components was not feasible and that a cooling "sub-system" needed to be selected, which had to include the functions of the cryocooler, circulator, interface heat exchanger, and recuperator.

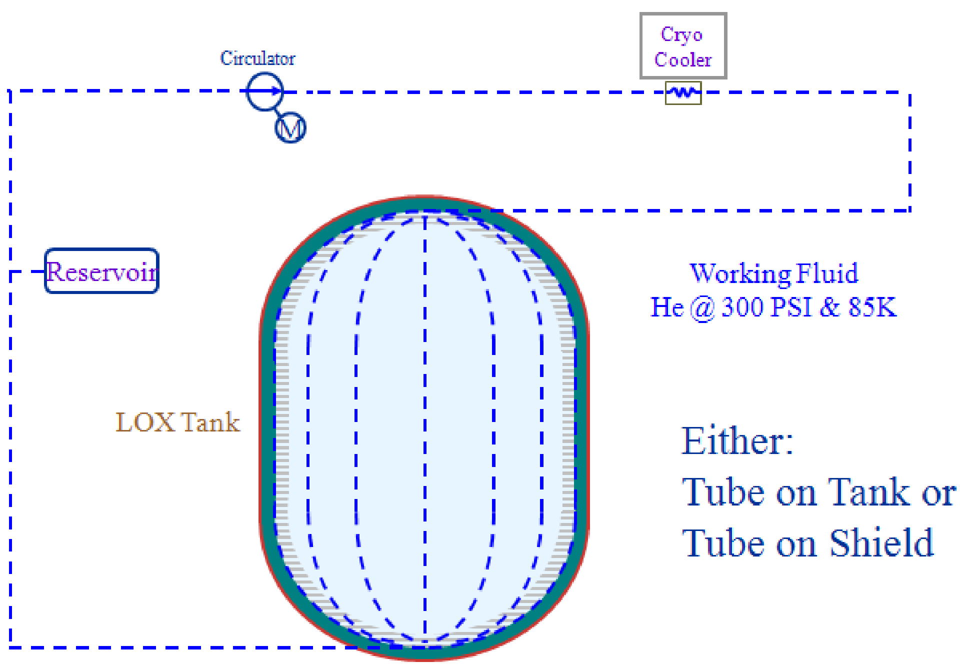


Figure 7, Initial Broad Area Cooler Concept for LOX Zero Boil-Off Demonstration

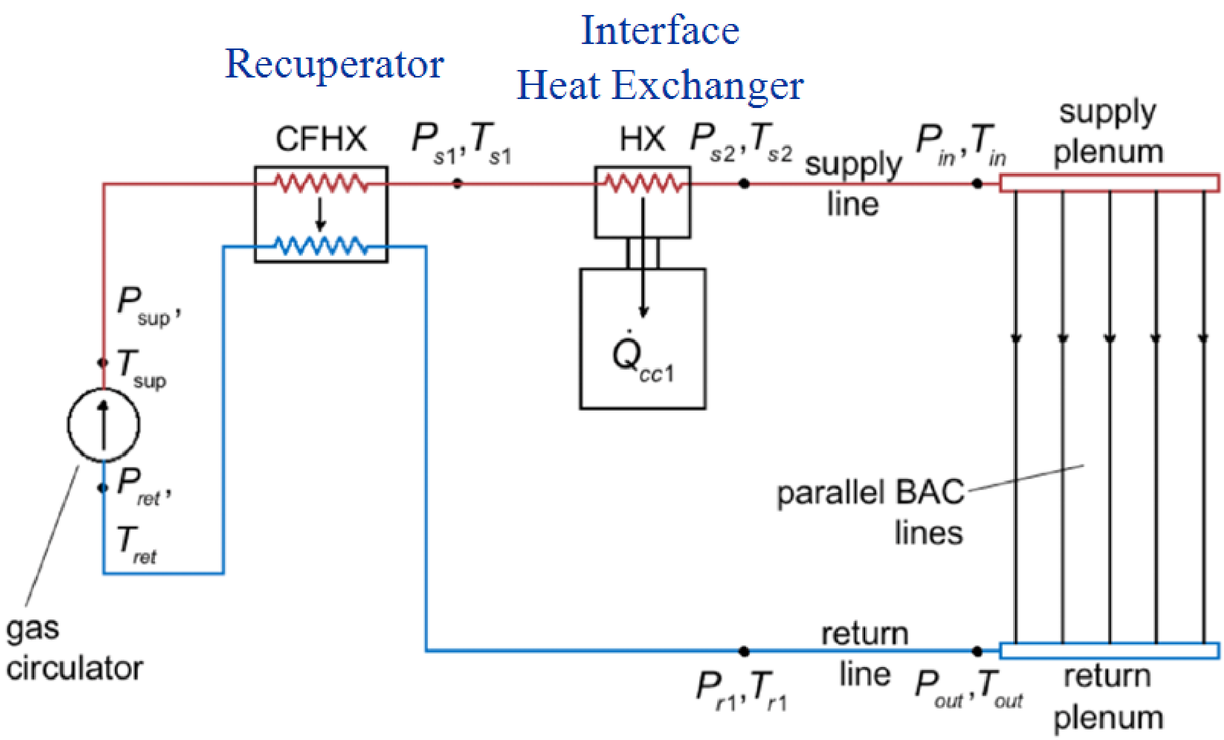


Figure 8, BAC Network with Warm Gas Circulator [5,6]

Circulators

There were many circulator and fluid options as shown in Table 1. The circulator fluid could be warm or cold, the circulator could be a separate device or integrated with the cryocooler compressor, and the circulation fluid could be a gas, liquid, or two phase substance. The circulator design is also a function of the coolant type, which can be helium, neon, argon or nitrogen.

For safety reasons, prior to testing with LOX, cryogenic propellant systems are typically first tested with liquid nitrogen (LN_2). This facilitates identification of leaks and other problems prior to using a non-inert fluid. Since LN_2 is colder than LOX, this cooling system is being designed to operate at a temperature slightly below the normal boiling point for nitrogen.

Since LN_2 has a normal boiling point of 77K and the coolant will be 5K to 10K lower, argon and nitrogen cannot be used for a single phase gas system. Therefore, a typical pumped gas system must use either helium or neon.

Table 1, Circulator and fluid options for BAC designs

- Circulation Options
    - Pumped gas loop
        - Cold fan or linear compressor
        - Warm fan or linear compressor
    - Pumped liquid loop
        - Cold circulator (pump)
        - Warm circulator
    - Pumped two-phase loop
        - Gas fan or linear compressor
            - Warm
            - Cold
        - Cold Liquid pump
            - Superconducting rotary or linear pump
    - Circulation provided by cryocooler compressor
- Fluids
    - He, Ne, Ar, N_2

For the cold circulator, two existing pumps were found: the Superconducting Blower (Sierra Lobo, Inc.) and the Near Infrared Camera and Multi-Object Spectrometer Circulator (Creare, Inc.), pictured in Figure 9 and Figure 10, respectively.

The Sierra Lobo blower operates at 20K and flows 0.57g/s of helium. The motor is made with superconducting windings and, therefore, has low power consumption when operated well below the superconducting transition temperature of 90K. The Creare NICMOS circulator operates at 80K and flows 0.75g/s of neon. This circulator is currently operating on the Hubble Space Telescope and therefore has a TRL of 9.

CryoZone makes several sizes of CryoFans that can also be used as a cold circulator. Of interest for this application were the Noordenwind with a 31mm diameter and the Ciezo with a 25mm diameter impeller. In this design, the motor must remain at room temperature. Therefore, to reduce the heat leak by conduction to the working fluid, a long drive shaft attaches the compressor blades. This has a disadvantage because it adds to the heat the cryocooler is required to remove of approximately 4W. In another configuration, these fans could be used with a recuperator as warm circulators but, in this case, the recuperator adds a similar heat penalty.

Figure 9, Sierra Lobo Inc. Superconducting Blower [7]

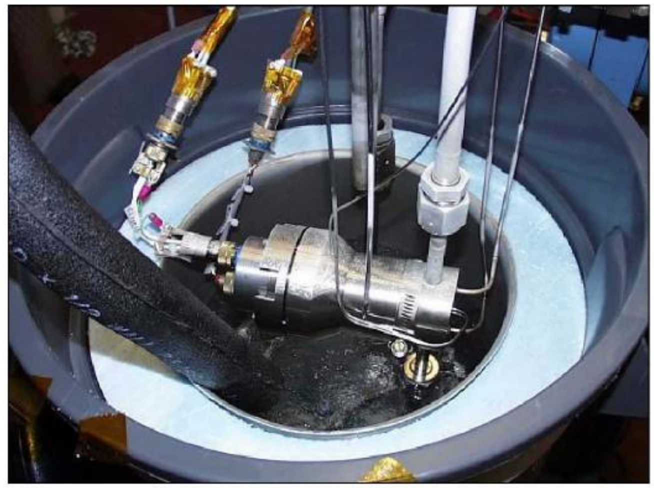
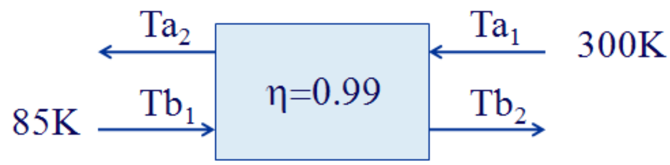


Figure 10, Creare Inc. NICMOS Circulator [10]

Figure 11, CryoZone CryoFan [11]

Specifically, the calculation of a typical recuperator penalty is shown in Figure 12. Using a recuperator with a 99% effectiveness and flow conditions for a typical design, an equivalent penalty of 6.9W was incurred (in fact, this was more than the expected heat conducted through the CryoFan shaft and housing). Thus, the recuperator is not beneficial here.



$\eta=(Ta_1-Ta_2)/(Ta_1-Tb_1)$

if
- $\eta=0.99$
- $Ta_1=300K$
- $Tb_1=85K$

then
- $Ta_2=87.2K$
- $\Delta T=Ta_2-Tb_1$
- $\Delta T=2.2K$

if
- mdot=0.6gm/sec
- $c_p=5.2J/gmK$

then
- Effective heat added
- $Q=mdot\,c_p\,\Delta T$
- Q=6.9W

Figure 12, Recuperator Penalty

With cryocooler compressors, the compressor usually must be warm, necessitating a recuperator. Examples of advanced recuperator designs are shown in Figure 13 and Figure 14. The size of the recuperator is related to the flow rates and fluid pressures involved. The Reverse Turbo-Brayton cycle has relatively high flow rates at low pressures; therefore, their recuperators are relatively large. On the other hand, a Stirling cycle cryocooler might use a linear compressor for a circulator that has lower flow rates and higher pressures, allowing for a smaller recuperator.

Figure 13, Creare Inc., Recuperator [12,24]

Figure 14, Ball Aerospace, Recuperator [13]

Linear Compressors

The linear compressors used for Stirling cycle cryocoolers can also be used as circulators. Their flow is rectified by reed-valves. These linear compressors produce relatively low flow rates and relatively high pressures when compared to centrifugal compressors. These higher pressures are useful when Joule-Thompson (J-T) cooling is added as an additional cooling stage. An example of J-T cooling by Ball Aerospace is shown in Figure 15. For this application, the James Webb Space Telescope (JWST) Mid-Infrared Instrument (MIRI), a Stirling cycle cryocooler provides three stages of cooling to 15K. A linear compressor is used as a circulator using helium (He) as a working fluid and a series of four recuperators. A J-T valve provides a fourth stage of cooling to 6K using ^{4}He, even lower tempertures can be achieved with ^{3}He.

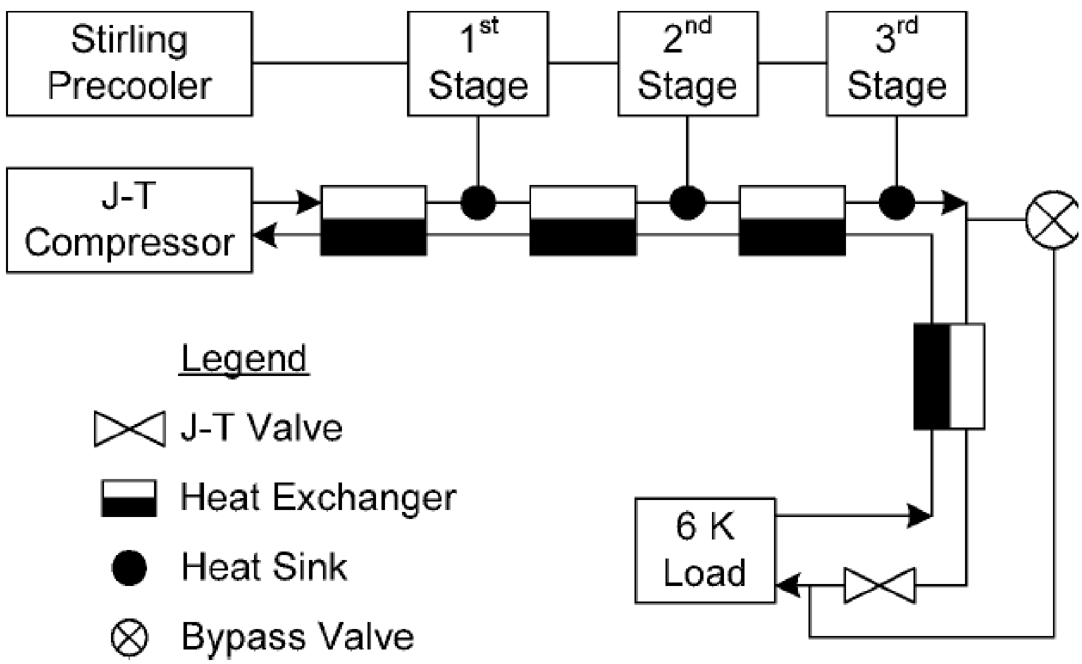


Figure 15, Ball Aerospace 4-6K Space Cryocooler [14]

Pulse tube cryocoolers result in similar arrangements. Three configurations are shown in Figure 16. The first configuration contains two linear compressors (one for the pulse tube and the other for the circulator). The flow from the circulator compressor is rectified with reed valves located on the warm side of the recuperator. The second configuration differs in that one linear compressor drives both the pulse tube and provides circulation by drawing flow from the compressor. As a drawback, induced flow from the compressor that drives the pulse tube reduces the performance of the pulse tube. In the third configuration, flow is drawn from the cold end of the pulse tube and rectified. Since the flow is cold, recuperators are not needed, but, similar to the previous configuration, drawing flow from the pulse tube results in a performance reduction. In fact, by drawing flow, configurations 2 & 3 can only provide low circulation flow rates.

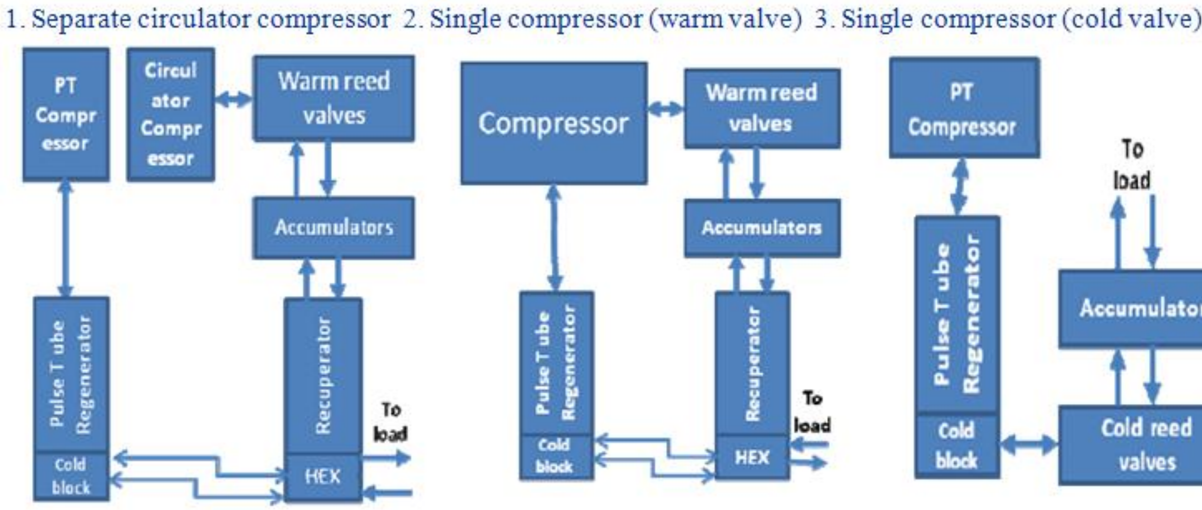


Figure 16, Northrop Grumman, Hybrid Cryocoolers [15]

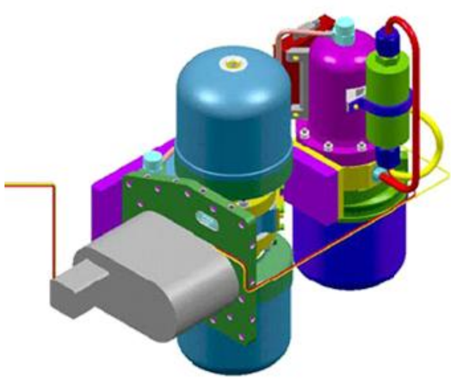


Figure 17, TRW, Pulse Tube Cooler with circulator linear compressor [16]

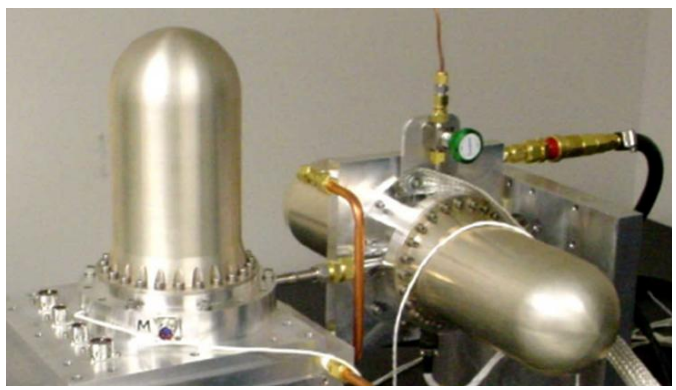


Figure 18, Ball Aerospace, Stirling Cycle Cryocooler with circulator linear compressor [17]

Two-Phase

The coolant in the BAC can either be a single phase gas, a single phase liquid, or two-phase fluid. In a two-phase system, cooling is done by evaporation rather than by convection. This has a few advantages. First, the required mass flow for cooling by evaporation is much lower than what is needed for cooling by convection. Therefore, less power is needed for pumping and tubing can be smaller. Second, the working fluid would operate at constant temperature. In a convection cooling system, there is a change in coolant temperature; therefore, the coolant inlet needs to be at lower temperatures, which reduces the Carnot cycle efficiency of the cryocooler. Third, the return and supply can flow through coaxial tubing; thus, the returning vapor can insulate the supply liquid from the environment. The advantages associated with employing a two-phase cooling system are shown in Table 2.

Table 2, Two-phase cooling system attributes.

- Heat removed by evaporation
  - Heat changes quality not temperature
  - Return vapor is same temperature as supply liquid
- High heat transfer coefficients
  - Boiling and condensation
- Lower mass flow
  - Can pump liquid instead of gas
  - Very low pumping power required
  - Little heat added by pump
  - Low mass flow rate is compatible with the low flow rate of linear compressors
- Smaller tubing
- Coaxial tubing insulates supply
- Superconducting motors might be applicable

An example of a two-phase Argon system is shown in Figure 19. The cold end of the cryocooler is attached to the coolant condenser and also to the fluid pump. This assures that vapor does not form in the pump. Liquid flows through the inner channel of the coaxial tubing to the load and the returning vapor flows through the outer channel. Pumping is provided by a micro annular gear pump developed by Mikrosysteme. "Positional and shape tolerances are within a few microns, which is needed to generate sufficient pressure head . . . ."[18] This type of pump would not work in microgravity without modification because fluid would travel up the shaft housing and be evaporated by the heat from the motor.

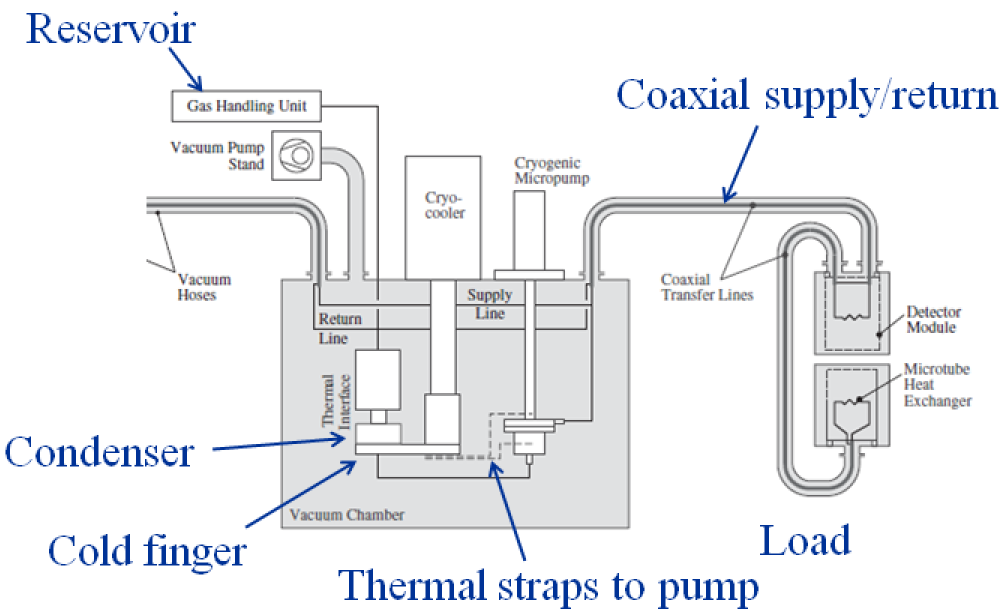


Figure 19, Two-Phase Argon System [18]

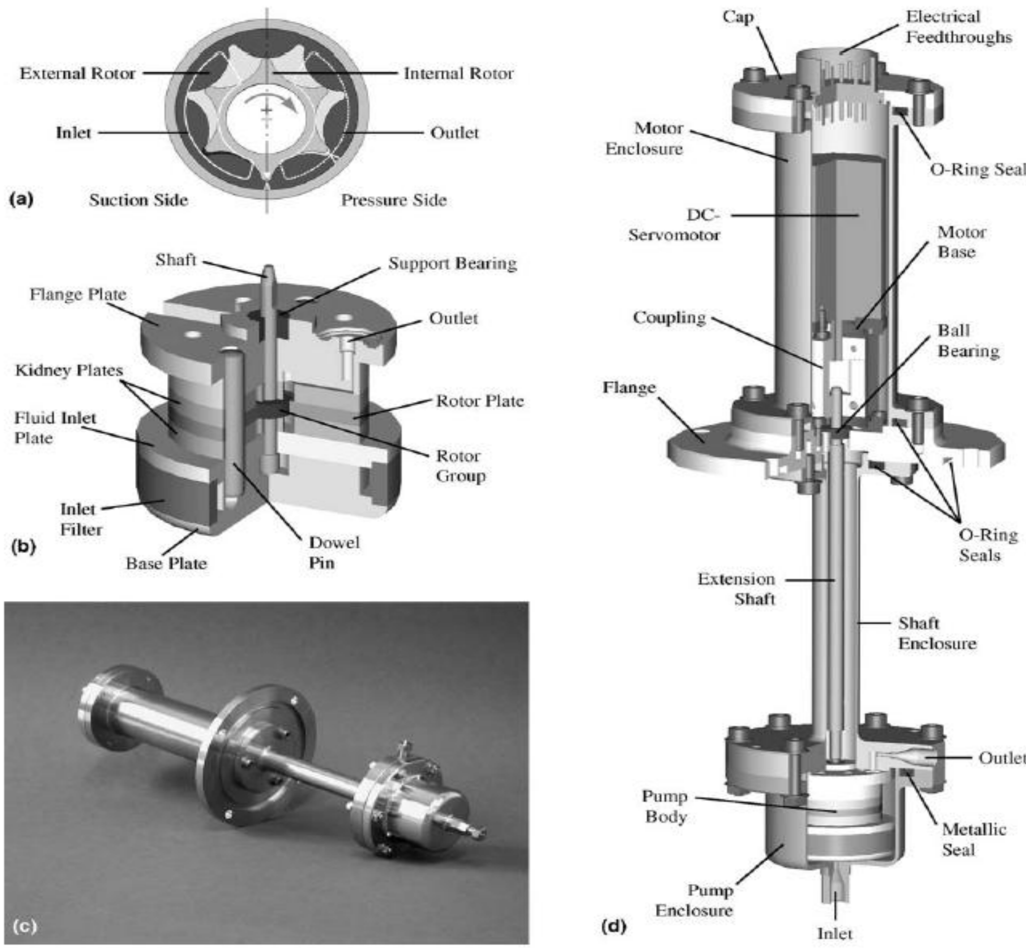


Figure 20, Mikrosysteme, Liquid Argon Pump [18]

A two phase BAC could look like the system shown in Figure 21. This system incorporates a cold circulator and a zero-gravity condenser at the cryocooler cold head. The reservoir provides sufficient volume for the system to be about 50% liquid when the system is cold, but also prevents excessive pressure when the system is warm. Another version of a two-phase BAC is shown in Figure 22. In this version, a liquid pump would be located downstream of the cryocooler and is thermally linked to the cold finger. If the windings could be cooled to be below the superconductivity transition temperature, a very low power superconducting motor can be used.

Another option for a two-phase system is to insert a restriction just upstream of the load as is done in Figure 23 and Figure 24. This creates an isenthalpic expansion and stimulates evaporation at the load. Although the device is called a Joule-Thomson device, no J-T cooling occurs.

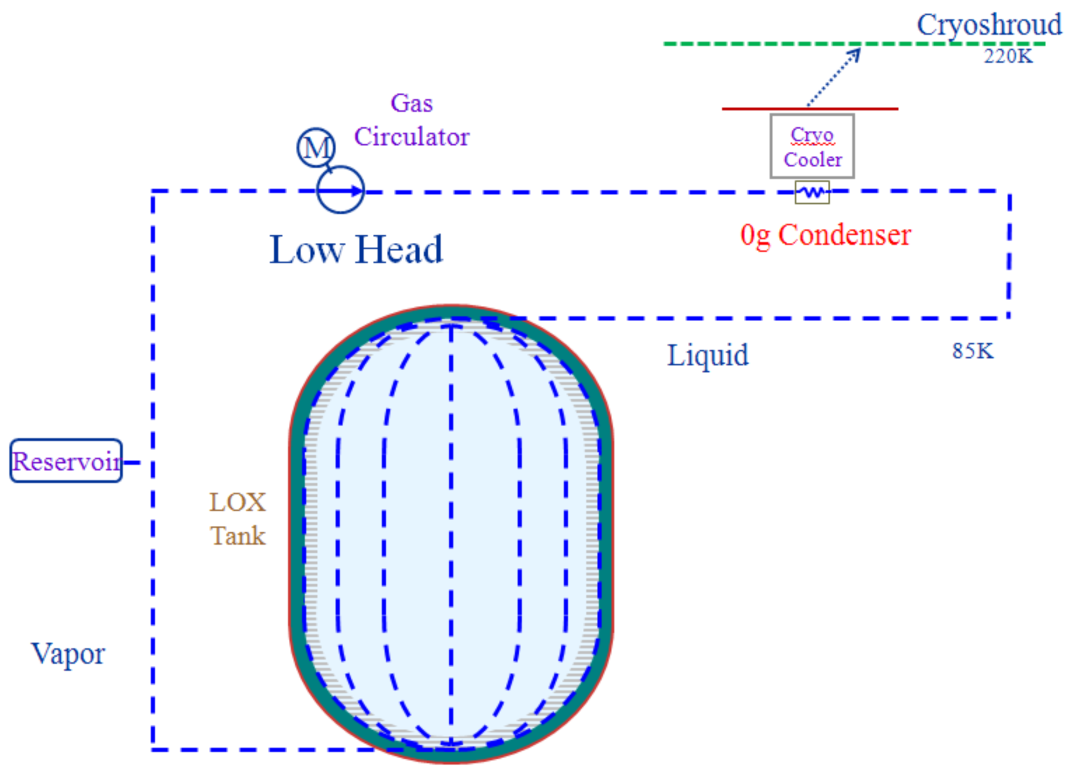


Figure 21, Two-Phase Broad Area Cooler

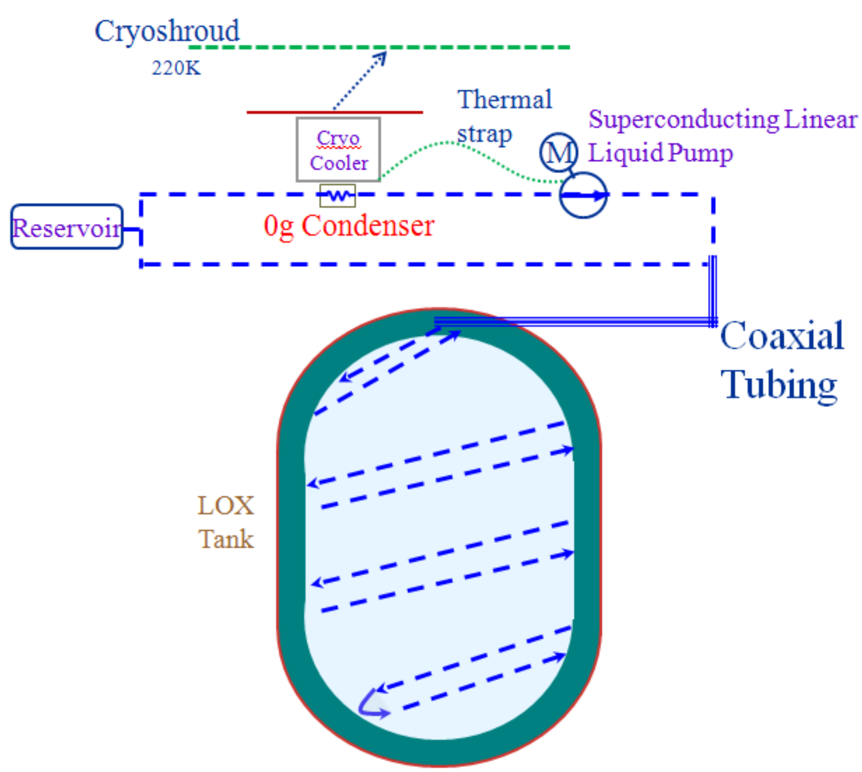


Figure 22, Two-Phase BAC with Superconducting Pump

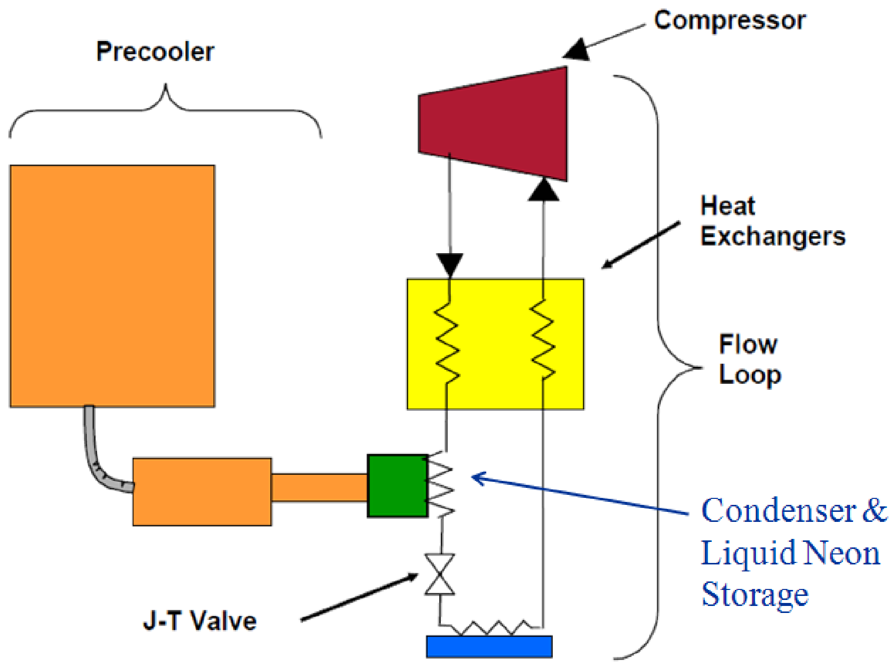


Figure 23, Ball Aerospace 35K Cooler [19]

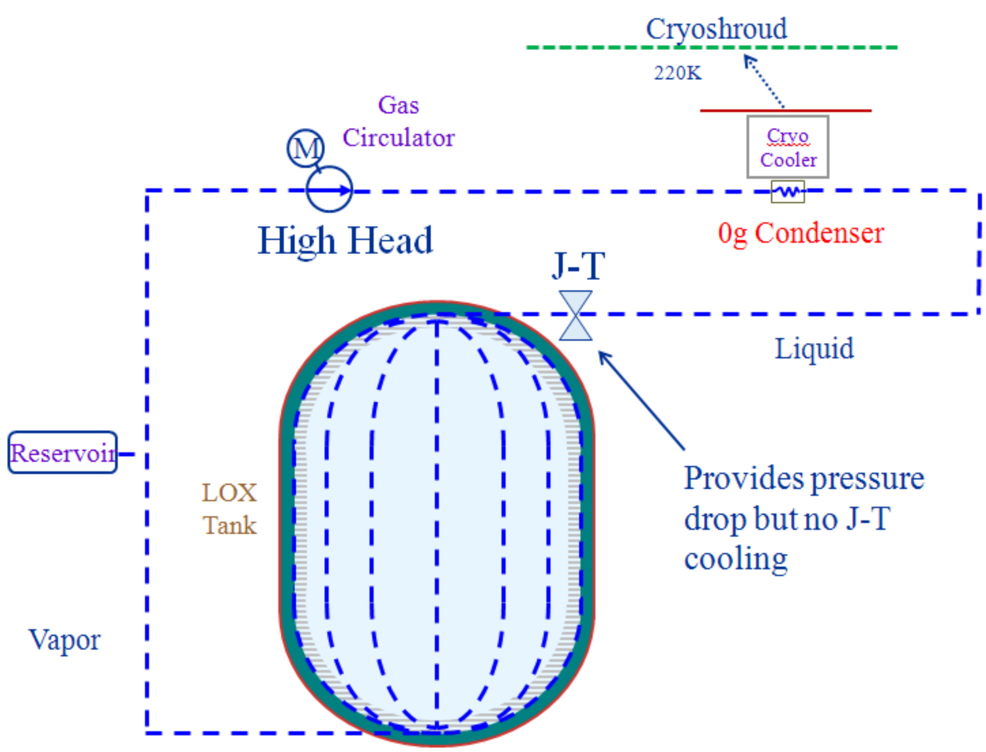


Figure 24, Two-Phase BAC
with isenthalpic pressure drop

Interface Heat Exchangers for Cryocoolers

The major source of thermal resistance in a broad area cooling system is the thermal interface between the coolant and the cryocooler cold finger. The cold finger typically has a small interface area; thus, the interface heat exchanger needs to be designed to provide minimal amount of thermal resistance using a small amount of area while not adding a significant amount of pressure drop to the system. Two examples of interface heat exchanger are shown in Figure 25 and Figure 26.

Figure 25, CryoFan Interface Heat Exchanger [11]

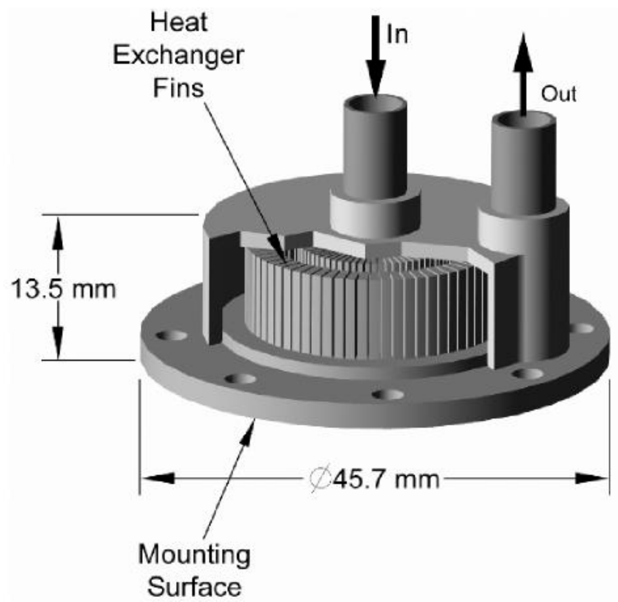


Figure 26, Creare Interface Heat Exchanger [10]

Cryocoolers

Several companies have built cryocoolers that have been used for in-space applications. These companies include Northrop Grumman Space Technology (NGST), Ball Aerospace & Technologies Corp., Sunpower®[2], and Creare Inc. Other sources of cryocoolers include QDrive of Clever Fellow Innovation Consortium, Sierra Lobo, and others. NGST cryocoolers are pulse tubes and Ball uses the Stirling cycle. Examples of pulse tube and Stirling cycle cryocoolers are shown in Figure 27 through Figure 30. Creare uses a Reverse Turbo Brayton Cycle (RTBC), an example of which is shown in Figure 31. In the case of the pulse tube and Stirling cycle cryocoolers, a separate compressor is needed to provide the circulation function and another system is required for heat rejection to the radiator. This 'hot' heat rejection system could be a heat pipe or another pumped loop.

[2] Sunpower & CryoTel are registered trademarks of Sunpower, Inc.

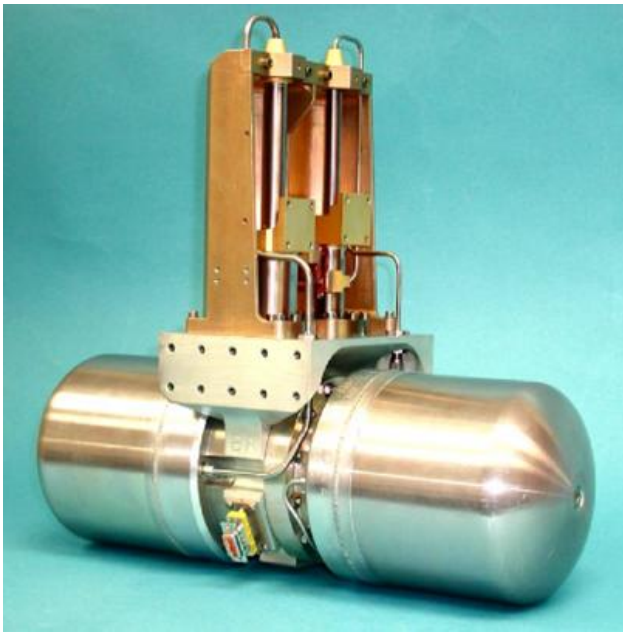


**Figure 27, Northrop Grumman,
High Capacity Cryocooler(HCC) [21]**

**Figure 29, Northrop Grumman,
High Efficiency Cooler(HEC) [21]**

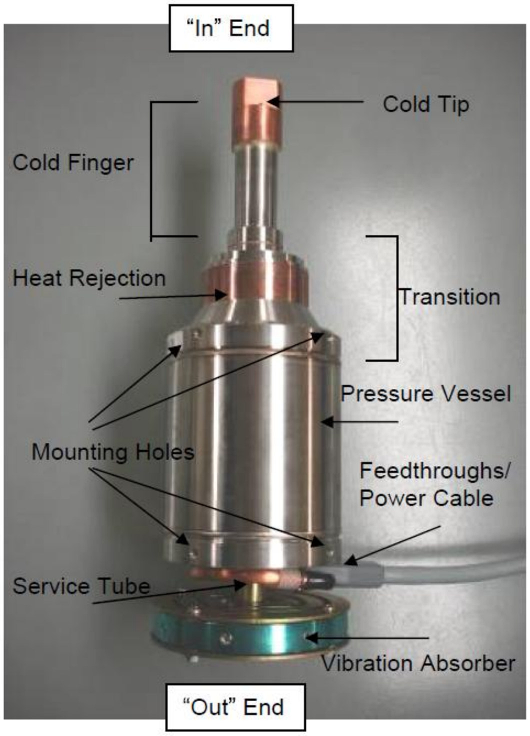


**Figure 28, Sunpower CryoTel®[2] GT
Cryocooler [22]**

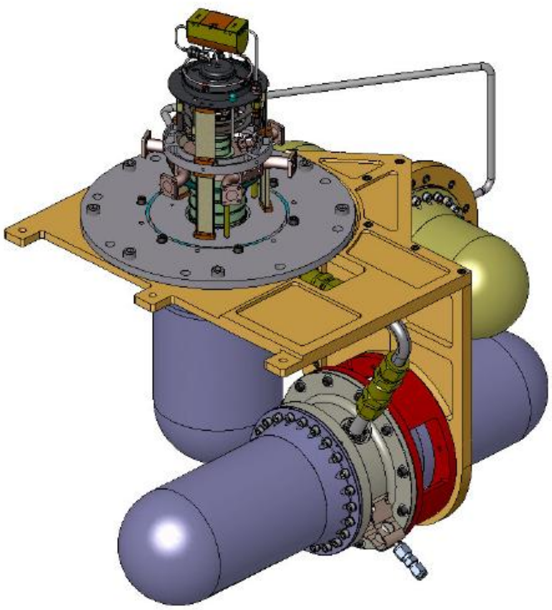


Figure 30, Ball, 35K Cryocooler [19]

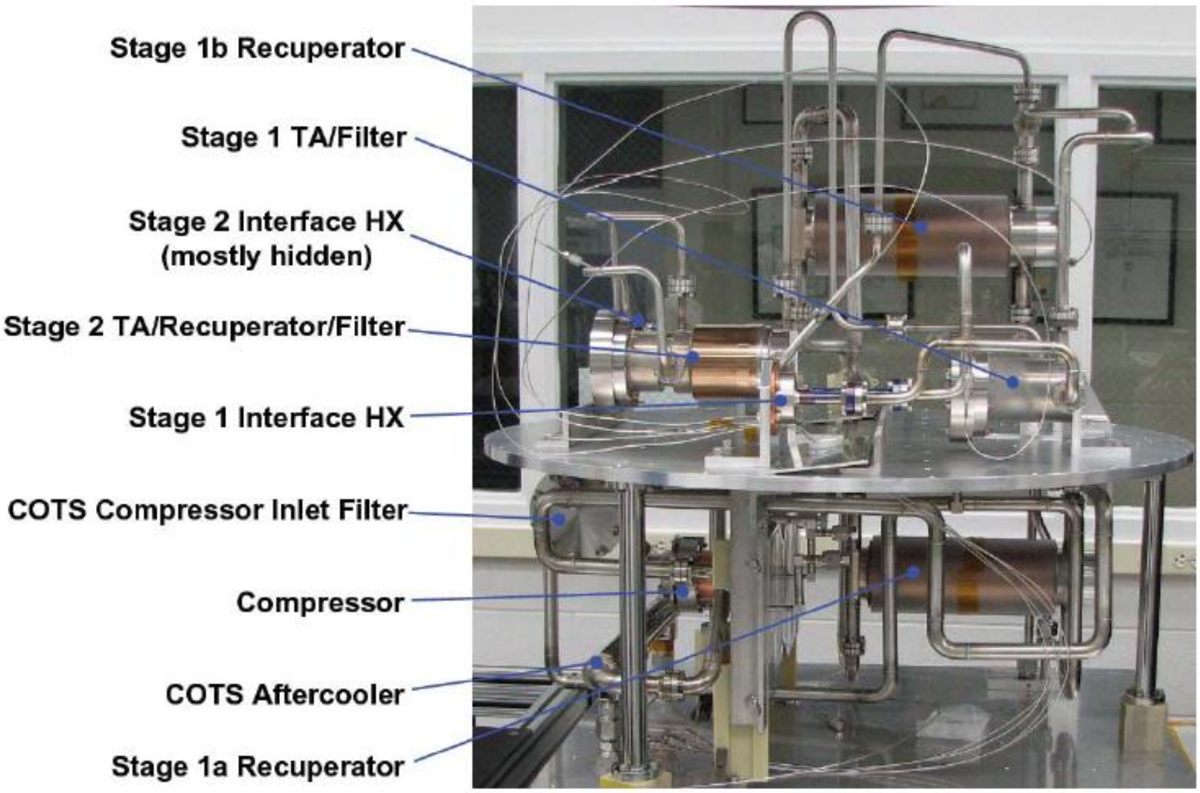


Figure 31, Creare, Two-Stage Reverse-Brayton Cryocooler [8]

It is also typcial for a RTBC to also have a circulator for the coolant network and a heat pipe for the radiator. This is the method used for NICMOS cryocooler on Hubble. A schematic of the NICMOS sytem is shown in Figure 32 But in the case of the RTBC cryocooler, the cooler's compressor can be used to circulate the coolant through the BAC network and also through the radiator, as shown in Figure 33. Doing this eliminates the need for a separate circulator, an interface heat exchanger, or a heat pipe. Thus one fluid system can transport the heat from the propellant tank to the radiator.

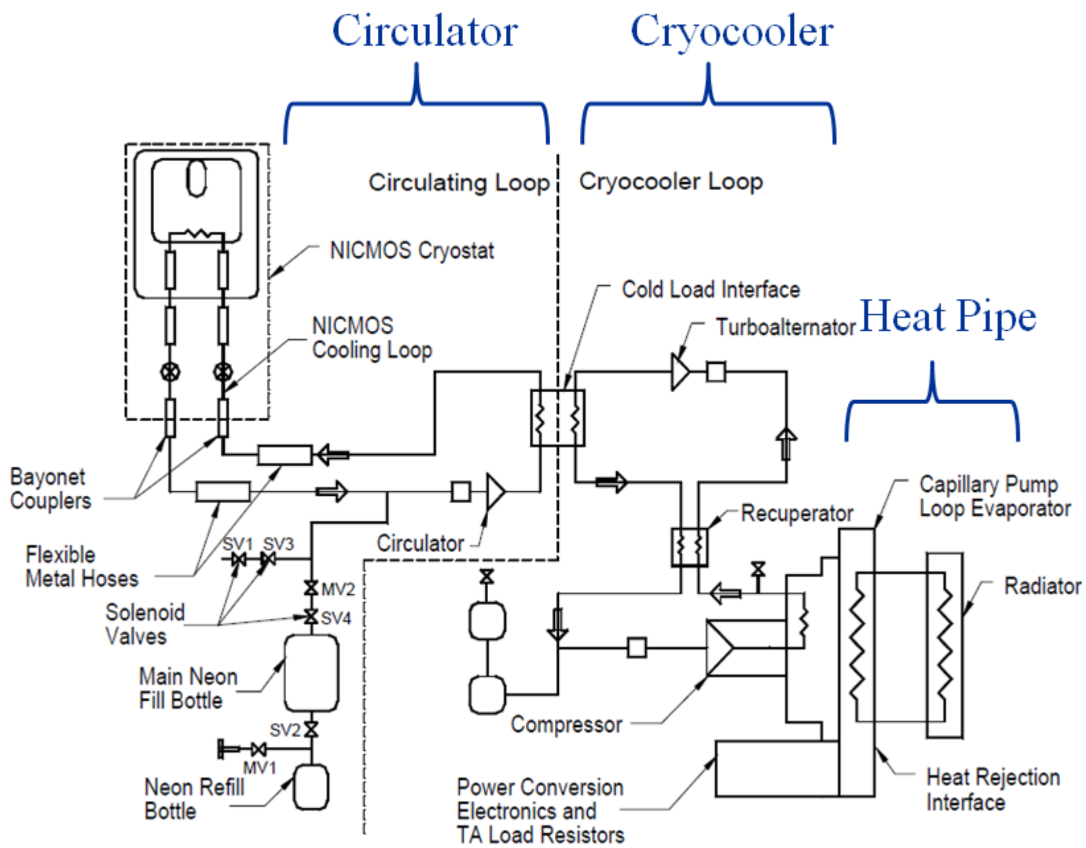


Figure 32, NICMOS Cryocooler System [23]

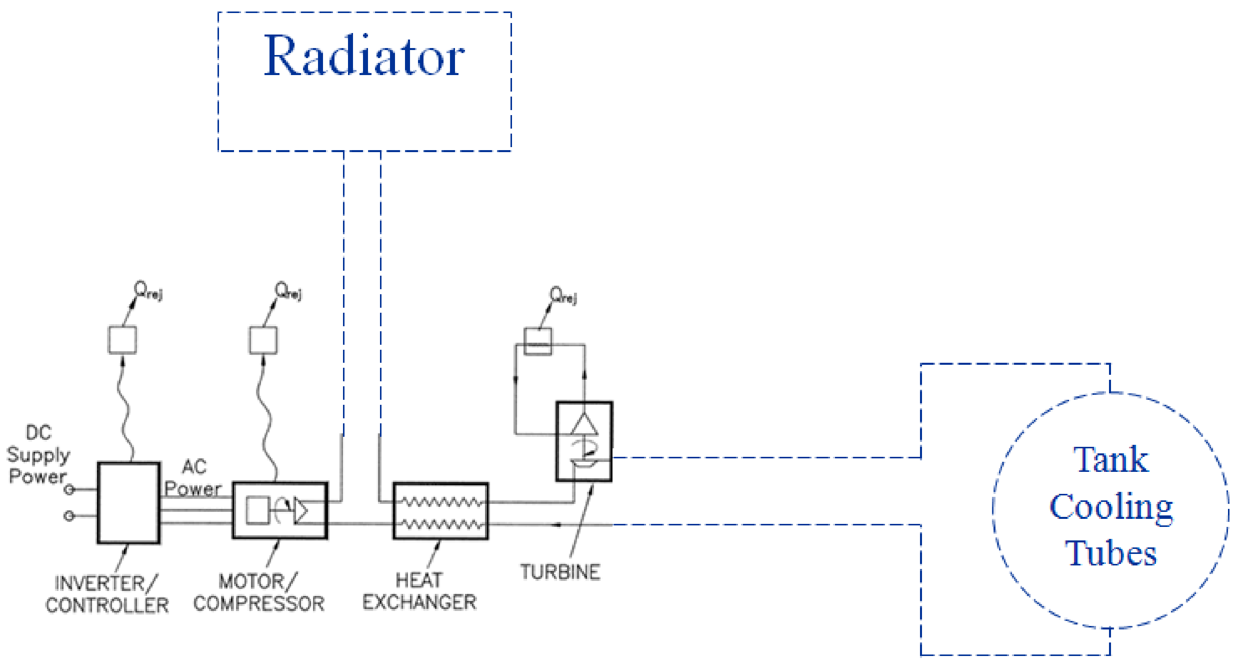


Figure 33, Reverse Turbo-Brayton Cycle Cryocooler [20]
adapted to a Broad Area Cooler

Scaling

This study has shown that numerous combinations of existing components can be used to build a BAC with a cooling capacity of 15W at 90K, but actual flight tanks could have cooling needs that are an order of magnitude greater. Therefore it is important that the type of system chosen be scalable to accommodate much greater cooling loads. Zagarola and McCormick [24] have analytically scaled the NICMOS cryocooler from its existing capacity of 6.3W to 40W, and have shown that "as cooling loads increase, the system efficiency is predicted to significantly increase and the specific mass is predicted to dramatically decrease". A RTBC concept proposed by Boeing [9] provides 80W of cooling at 95K and simultaneously provides 10W at 22K. In this case the RTBC "uses helium as the working fluid and this cooled gas can be easily distributed to the loads (i.e. the 22K and 95K shields)". The RTBC "is inherently well suited for high cooling loads due to the compact nature and high efficiency of turbomachinery".[24]

The current state-of-the-art for high-capacity flight-ready cryocoolers are Ball's SB235E, Figure 18, which has a cooling capacity of 10W at 85K [17] and Northrop Grumman's HCC, Figure 27, which can lift 16.5W at 85K [25]. Although not flight ready, high capacity cryocoolers are also available through QDrive and Sunpower. These can be scaled to higher capacities by using multiple units.

Conclusions

This study examined and analyzed various hardware configurations and different working fluids for developing a BAC system for accomplishing ZBO of cryogenic propellant storage. For demonstrations which require less than 15W of cooling at 90K, numerous circulators and cryocoolers can be used to build a Broad Area Cooler system. Each type has inherent advantages and disadvantages but the preferred system would be one that has a 'clear path to flight'; that is, it has a high Technical Readiness Level and is scalable to very high cooling capacities.

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