

Space Exploration Applications for Development of High Capacity Cryocoolers

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ABSTRACT

Long-term storage of cryogenics is necessary to enable the National Aeronautics and Space Administration's (NASA) crewed missions to both the Moon and Mars. Such missions require in-space transport systems and descent/ascent vehicles for transportation to and from the lunar and Martian surfaces. Both in-space transport systems and Lunar/Martian landers utilize cryogenic fluids to minimize architectural volume and mass. In some cases, the propellants may be utilized further in primary or regenerative fuel cell systems to provide power in addition to propulsion. To enhance the capability of these cryogenic systems, the Agency is emphasizing reusability. This requires the in-space transport and ascent/descent elements to be replenished either on-orbit via tankers or propellant depots or on the lunar or Martian surface using liquefied in-situ produced propellants.

Nuclear Thermal Propulsion (NTP) is one of the leading propulsion options for crewed Mars missions and requires liquid hydrogen to be stored on-orbit for over four years. For extended duration missions of this magnitude, near "Zero Boil-Off" (ZBO) storage must be achieved to minimize the amount of excess propellant required at the time of launch. This requires an optimized suite of passive Cryogenic Fluid Management technologies and active cooling (cryocoolers). ZBO storage of propellants for long-duration crewed missions requires the use of cryocoolers at capacities that exceed the current State of the Art (SOA) by a significant margin. However, achieving ZBO storage is essential to the implementation of missions such as NTP as well as enabling reusable architectures for ascent/descent stages and surface systems. To support these programs, NASA is developing high capacity 20 K and 90 K reverse turbo-Brayton (RTB) cycle cryocoolers that offer a scalable, high efficiency, low vibration solution for cryogenic storage.

INTRODUCTION

Management of cryogenic propellants is a key technology to enable long-duration space exploration missions. Many of these missions require cryocoolers at capacities that exceed the current SOA by a significant margin. However, achieving ZBO storage is essential to the implementation of missions such as NTP as well as enabling reusable architectures for ascent/descent stages and surface systems.

NASA is currently investing in passive and active thermal control technologies that will enable both long-term in-space storage of cryogenic propellants at ZBO, as well as other unique technology opportunities such as primary or regenerative fuel cells.

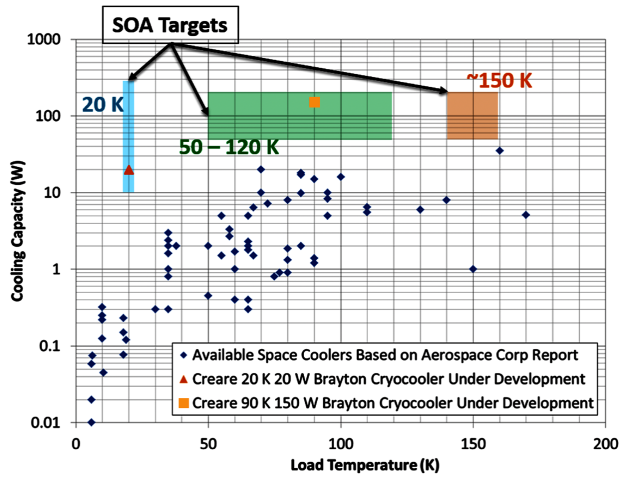


Figure 1. Currently available space cryocoolers as compared to targets for SOA [10].

CURRENT STATE OF THE ART

An update to the Space Cryocooler Flight Operating Experience Survey was published in Cold Facts Vol. 36 Issue 5 [1]. This survey documents the current and historical cryocoolers that have operated on spaceflight missions. These cryocoolers span a variety of technologies, including Pulse Tube, Stirling, Turbo-Brayton, and Sorption or Joule-Thompson (JT) coolers. NASA has targeted three temperature ranges of operation when evaluating cryocooler technologies for future human exploration mission use. These correspond to ranges of 20 K, 50-120 K, and 150 K. While currently available space cryocoolers can be found that operate in each of these ranges, the total heat lift capacity of these coolers falls short of mission needs.

As shown in Figure 1, the largest shortfall is in the 20 K temperature range, where projected heat lift capacities of 10-300 W are required to meet mission needs. The current SOA cryocoolers have a maximum heat lift of approximately 0.3 W. Even at the higher temperatures, the SOA falls short of the mission needs. In the 50-12 K range, current SOA cryocoolers reach a maximum heat lift around 20 W, while at 15 K the gap is narrowed as the maximum heat lift rises to around 40 W. This falls short of the projected need for 60-200 W of lift in the future. Further development is needed in all temperature ranges to improve the SOA.

SURVEY OF MISSIONS

Nuclear Thermal Propulsion

Nuclear thermal propulsion (NTP) is an in-space transport technology that enables long duration crewed exploration missions. NTP requires the storage of liquid hydrogen (LH2) exposed to several different external thermal environments for multiple years during transit to and from Mars. A key component to the mission’s success is the ability to eliminate hydrogen boil-off to reduce required propellant mass. Using thermal analysis of the heat transfer from the MLI, tank skirt, tubing, and 32 struts, Plachta et al. showed that a single-stage 20K cryocooler system would be required to remove 114 W from a 2.1 m diameter LH2 tank [2]. Over a 720-day period, this passive heat loss would equate to 16,500 kg of hydrogen boil-off. This single-stage system mass would be 1439 kg.

A parametric study showed the cooling system mass could be minimized by converting the single-stage to a two-stage system, utilizing a 90 K and 20 K cryocooler (Table 1). Plachta et al.

Table 1. Two-stage cooling system characteristics that meet the NTP mission requirements.

Cryocooler	Temperature, K	Lift, W	Cryocooler Mass, Kg
20K Class	24.2	16.5	99
90K Class	55	94	42

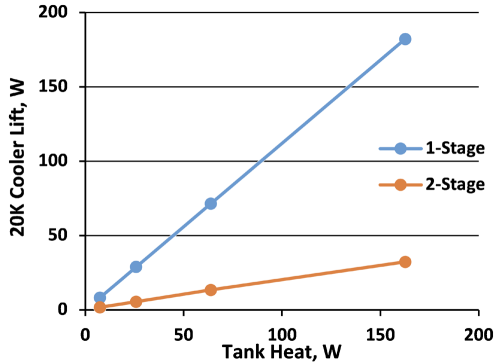


Figure 2. Tank heat load versus 20 K cryocooler lift requirements for 1-stage and 2-stage.

showed analytically that utilizing a 90 K cryocooler system in conjunction with the 20 K cryocooler reduces the overall system mass by 90%. This two-stage system also enables the 20 K cryocooler lift requirements to become more achievable when compared to the current technology SOA (Figure 2).

Reduced Boil-Off (RBO) testing by Plachta and Johnson provided similar relevant data, utilizing a 1.2 m diameter LH2 tank (1.4 m³, 95 kg of LH2), with a two-stage cryocooler system approach [3]. The 90 K class cryocooler reduced the warm boundary shield temperature to 80-100 K, and the lift of the 20 K class cryocooler was measured. Figure 3 shows the 20 K cryocooler required lift as a function of shield temperature for a 3.4 W passive heat load, and Figure 4 shows the reduction in required lift by the 20 K cryocooler as a function of shield temperature. These will be similar to the inputs driving the above missions as the general system design and architectures will be quite similar.

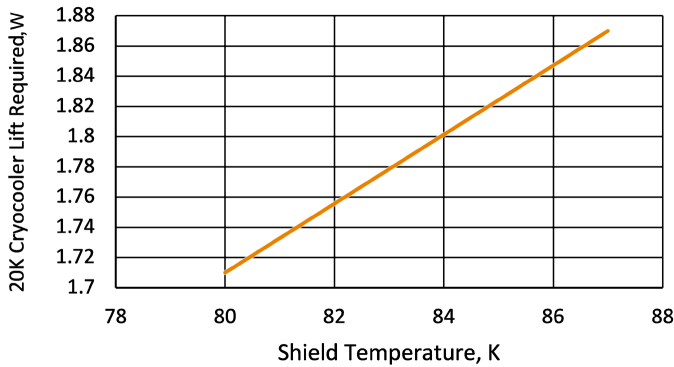


Figure 3. 20 K Cryocooler lift required for 3.4 W passive heat load in reduced boil-off.

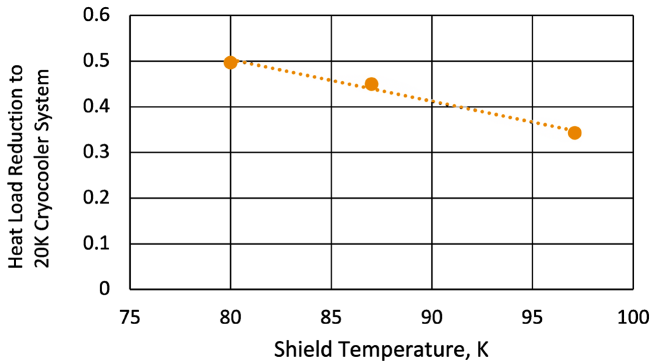


Figure 4. 20 K Cryocooler lift reduction by utilizing a second cryocooler stage, plotted as a function of shield temperature for the second stage.

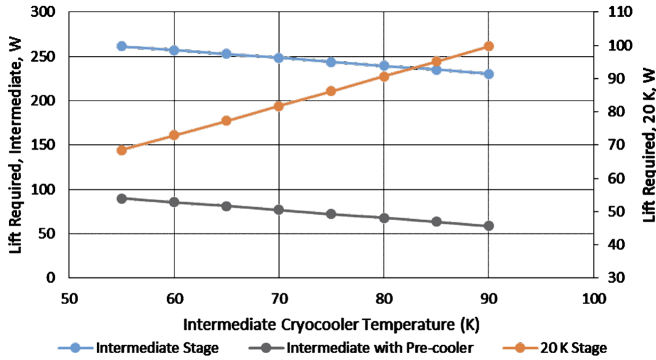


Figure 5. Cryocooler heat removal requirements at both 20 K and an intermediate stage for hydrogen liquefaction at a rate of 0.3 kg/hr assuming a 300 K entry temperature.

Ascent/Descent – Sustainable Lunar Architecture

In December 2017, NASA was tasked with returning astronauts to the lunar surface. Then in March 2019, it was announced that NASA will have “boots on the moon” by 2024 followed by a sustainable presence later in the decade. Under the Artemis program, NASA is engaging with industry partners to achieve these goals. In 2024, the Orion spacecraft will deliver astronauts to Near Rectilinear Halo Orbit where it will dock to a commercially developed lander to descend the crew to the lunar surface. The crew will explore the lunar surface for approximately six days before returning to the Orion spacecraft for the journey home. On subsequent missions, Orion will transport the crew to the orbiting outpost, Gateway, for extended durations to conduct research while making occasional descents to the lunar surface.

To achieve these goals, NASA and its industry partners are putting emphasis on cryogenic systems. The 2024 Artemis mission will require cryogenics to be available for durations greater than 100 days, while subsequent missions will require replenishing propellant tanks on-orbit and eventually making use of in-situ produced propellant on the lunar surface.

The current State of the Art for cryogenic storage in microgravity is 9 hours for liquid hydrogen in Low Earth Orbit. Although Near Rectilinear Halo Orbit is a more “thermally benign” environment, all descent/ascent vehicles under the Artemis program will need to determine how to mitigate propellant loss, whether it be a combination of passive storage and/or propellant replenishment, or active cooling (cryocoolers).

Active cooling via cryocoolers can enable zero boil-off conditions to extend propellant life, and will be required for the liquefaction of in-situ produced propellants on the lunar surface.

In-Situ Resource Utilization (ISRU)

In Cold Facts, Vol 36, Issue 3, several different lunar surface liquefaction architectures were discussed: liquefaction of oxygen/hydrogen using cryocoolers only at the phase change temperature, the addition of an intermediate cryocooler (with ortho to para conversion) between 55 K and 90 K for hydrogen, and the addition of pre-cooling radiators (again with ortho to para conversion for hydrogen) [4]. Analysis showed that architectures for Mars would use a similar approach, but the ability to achieve a temperature of 150 K on a pre-cooling radiator is highly improbable, as Martian surface temperatures are just slightly colder than Earth and Mars has an atmosphere of 5-7 Torr. Previous analysis by Hauser et al. suggested temperatures closer to 250K might be achievable [5]. Analysis was performed at 0.3 kg/hr hydrogen flow rate (which is typical for an ISRU system designed to liquefy approximately 10,000 kg per year of total propellant at a 6:1 ratio of oxygen to hydrogen) using a system inlet temperature of 300 K, intermediate radiator at 150 K, and including ortho to para conversion at each cooling location. The resulting lift requirements are shown in Figure 5. The results are directly proportional to flow rate and do not include the lift requirements to maintain the system at zero-boil-off or due to the parasitic losses associated with the integration of the cryocooler to

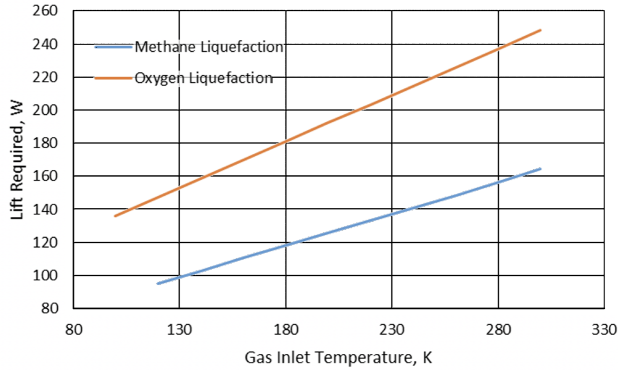


Figure 6. Cryocooler heat removal requirements for oxygen (2.2 kg/hr) and methane (0.65 kg/hr) as a function of gas inlet temperature.

the tank wall or other portions of the system. These will be similar to the inputs driving the above missions as the general system design and architectures will be comparable.

Recent studies by Polsgrove et al. suggested that for Martian applications, the oxygen liquefaction rate should be approximately 2.2 kg/hr, very similar to the rates required for lunar applications [6]. On the surface of Mars, methane can be produced using the in-situ resources to provide an alternate propellant to hydrogen. To keep the methane production in-line with the oxygen, a production rate of approximately 0.65 kg/hr is required. As the inlet temperature to a Martian system (or lunar system) can vary with time of day and any radiator pre-cooler, the cryocooler lift is shown as a function of inlet temperature of the gas in Figure 6. Significant reduction in lift requirements can be achieved by using some sort of pre-cooling system. Figure 7 shows the cryocooler lift requirements for the same flow rate of oxygen, inlet temperature of 300 K, as a function of storage pressure. Slight reductions in lift requirements can be achieved at elevated storage pressures, assuming the application can use the liquid at higher pressures.

While multiple heat removal systems exist that can be made to function in a gravity field significant enough to settle the fluid, recent effort within NASA has focused on tube-on-tank applications for liquefaction. In this method, the cryocooler working fluid is circulated through tubes that are fixed to the cryogenic storage tank walls to provide cooling of the tank and the contents inside. Testing on a Brassboard nitrogen liquefaction system showed that the tank could be filled to over 95% fill level with little reduction in liquefaction rate, due to the entirety of the tank wall acting as the heat exchanger. This means that the heat exchanger surface area is submerged almost fully at high fill levels. Additionally, due to the high Rayleigh numbers, even on the lunar surface, the natural convection will only be reduced by 25% on Mars and 40% on the Moon (proportional

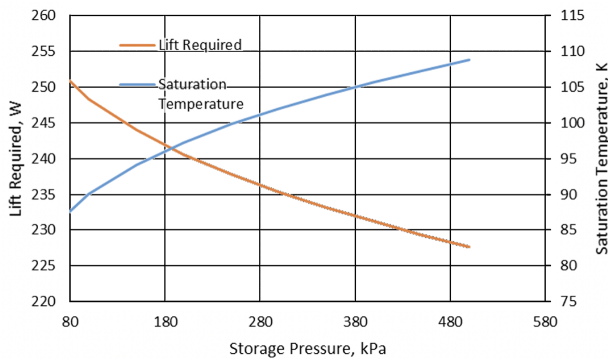


Figure 7. Cryocooler lift requirements as a function of oxygen storage pressure with 300 K inlet temperature.

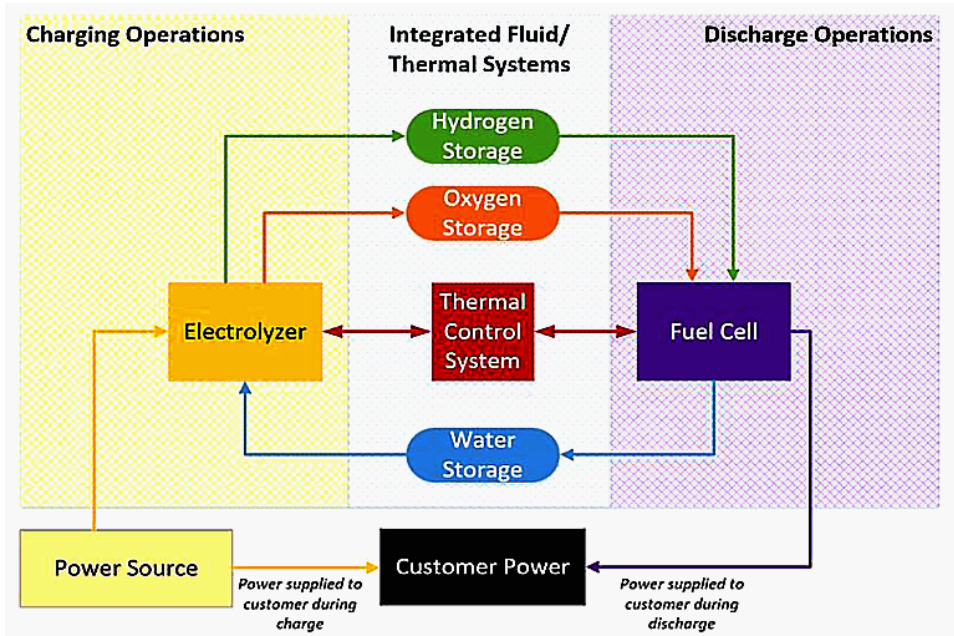


Figure 8. Basic principles of operation for a Regenerative Fuel Cell (RFC) [11].

to gravity to the 0.25 power). This means that integral mixing of a tank is not likely required to prevent stratification on the lunar or Martian surface.

REGENERATIVE AND PRIMARY FUEL CELL

A unique potential application for cryogenic storage lies in utilizing hydrogen, oxygen, and even methane for power, rather than propellant. Fuel cells operate by reacting hydrogen and oxygen to create water, simultaneously producing electricity during the course of the electrochemical reaction. Unlike a battery, which provides power by utilizing its own stored energy, fuel cells convert energy from the reactants (“fuels”), allowing them to provide power as long as the reactant is available. Because an energy storage device needs to store enough energy to last the duration of a mission, its mass can become prohibitively high for extended mission durations such as those found in lunar and Martian applications. Fuel cells, however, are sized primarily on the power output requirement, independent of the mission duration. This is appealing in applications such as cryogenic vehicle stages, where boil-off propellant can be used to power the vehicle instead of being vented overboard. This can be advantageous for reduced boil-off systems, where the overall mission mass is reduced through the incorporation of both power conversion and propellant storage technologies. However, if the reactants are not already present as part of the mission architecture, the mass and volume penalty added by the reactant storage must be included in the total primary fuel cell system architecture.

Fuel cells can be paired with an electrolyzer, which breaks water down into hydrogen and oxygen gases when provided with electricity, to create a Regenerative Fuel Cell (RFC). The RFC is a continuous energy storage plant that utilizes solar or another source of energy as well as water to generate and store hydrogen and oxygen during a charge cycle. Then, that hydrogen and oxygen can be used to create electrical power and water during a discharge cycle. This functionality is further described in Figure 8. This is an attractive energy storage solution for surface operations with extended eclipse durations, such as those found on the Moon, as well as exploration of shadowed craters where refueling may occur in a non-shadowed location [7].

For both primary and regenerative fuel cells, reactant storage is by far the driving component in both mass and volume trades, as illustrated in Figure 9 [7, 8]. By decreasing the reactant storage impacts to total system mass and volume, additional mission applications and opportunities

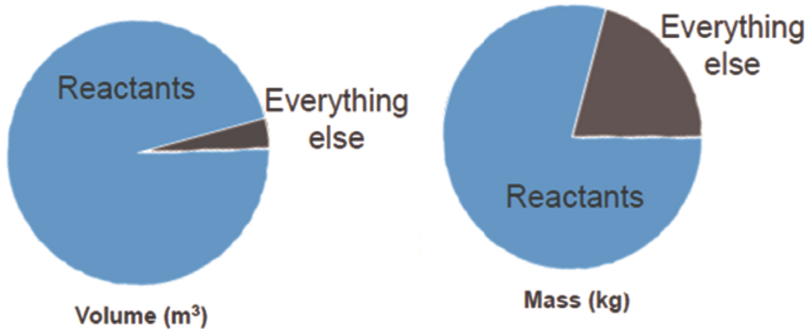


Figure 9. Typical mass breakdown of RFC systems, highlighting the large impact of reactant storage on the total system [12].

emerge. Taking advantage of cryogenic storage of the reactants is one method that may reduce the overall system mass and volume of the primary fuel cell or RFC. The additional power required for liquefaction of the reactant gases may remove cryogenic storage from consideration for many missions where the burden of liquefaction operations is entirely on the RFC or primary fuel cell subsystem. However, in applications in which liquefaction and cryogenic storage is already present, such as ISRU, dual-use of the stored reactants for power as well as the eventual propellant end-use may be beneficial.

IMPACT ON OTHER OPERATIONS

Cryocoolers can be used to simplify or improve performance in a number of other areas, including propellant depots and fluid transfer operations. Propellant depots, which necessitate essentially indefinite extended storage durations, tend to drive the requirements to prioritize thermal efficiency over mass reduction. The heat removal rate for the depot will change with orbital location (the farther away from the Earth and the Sun, the better), size, and functionality. For the size of the depot in a microgravity environment, integration of the cryocoolers will probably be via tube-on-tank and tube-on-shield broad area cooling. Similar to the NTP and liquefaction operations, multi-stage cooling should reduce system mass, power, and heat rejection requirements. There has been discussion about including liquefaction in an orbital depot [9], but this may require a more complicated integration mechanism.

There are several ways that cryocoolers can simplify fluid transfer systems. One such method is using the cryocooler to chill down the receiver tank prior to start of a transfer, and then maintain the tank in a cold state by absorbing heat as the transfer continues. This application drives the cryocooler to be operational over a wider range of temperatures than usually designed, causing the compressor design to change as compared to traditional applications. Similarly, using the cryocooler to cool down a transfer line prior to and throughout transfer operations can reduce overall operational complexity. Another application for cryocoolers is to aid in the acquisition of liquid in a supply tank prior to transferring it to the receiver tank. In a microgravity condition, pressure or pumps alone are not enough to drive a transfer because there is an absence of gravity to separate the phases. To address this, special devices called Liquid Acquisition Devices (LADs), driven by capillary flow, are generally used to separate the phases. While these are often used for room temperature fluids on orbit, the general design philosophy makes them excellent nucleation sites for boiling to occur. This makes the design of such devices that much more complicated for cryogenic fluids. By cooling them directly with a cryocooler or force circulation loop that is fed by a cryocooler, that complication is removed.

When considering possible applications for a cryocooler in a spaceflight system, the main driving parameters are generally not the cryocooler mechanical hardware itself. Typically, cryocoolers are driven by the input power requirements and heat rejection requirements. These two requirements are often at odds with each other. For instance, the cryocooler becomes more efficient and needs

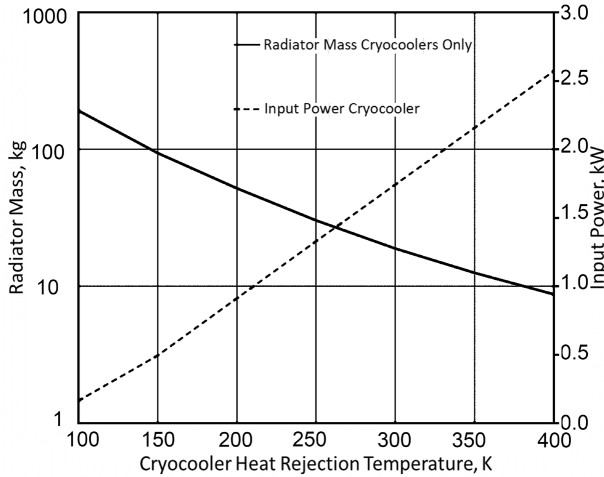


Figure 10. Radiator mass and input power for a 112 W at 90 K cryocooler system.

less power at colder heat rejection temperatures. However, since the only method for spacecraft to dump heat over long durations of constant flow is radiation (which is T^4 dependent), that decrease in power at a lower temperature will still increase the radiator area. Figure 10 shows the trade for an 112 W at 90 K cryocooler system, where the Carnot efficiency is assumed to be 15% and the radiator is assumed have an areal density of 3.86 kg/m². Since the radiator mass is plotted on a log scale, it is much more sensitive to the temperature than the input power and thus tends to drive heat rejection temperatures higher.

CURRENT NASA DEVELOPMENTS

20W/20K Reverse Turbo-Brayton Cycle

NASA has awarded an SBIR Phase III contract to develop a 20 W at 20 K cryocooler, which is anticipated to complete acceptance and characterization testing in 2021. This cryocooler is a critical element (integrated with a 150 W 90 K cryocooler) to the development of a two-stage cooling system for liquid hydrogen storage required for the NTP program, as well as allowing for potential other applications, such as ISRU liquefaction of hydrogen.

A 20 W/20 K class cryocooler would represent a large advance in the current SOA. Table 2 shows the projects goals and current projected values in comparison with the current SOA.

150W/90K Reverse Turbo-Brayton Cycles

High capacity cryocoolers have long been identified as a technology development “long pole” by the Cryogenic Fluid Management community. In 2016, Creare, LLC began working the development of a High Efficiency, High Capacity 90 K Reverse turbo-Brayton cycle cryocooler for NASA. With a targeted threshold value of 120 W of lift capacity, this cryocooler is a significant improvement over current state of the art. It will have the lift needed for applicability to lunar and Mars missions, in-space stages, propellant depots, and liquefaction and storage systems for in-situ produced propellants. The cryocooler will operate over a range of temperatures allowing for commonality for liquid oxygen, liquid methane, and liquid natural gas systems. It may also be used for liquid hydrogen applications if two-stage cooling is implemented.

Table 2. Key performance parameters for the 20W/20K RTB cryocooler project.

Parameter	State of the Art	Project Goal	Current Value
1) Lift Capacity (W)	1	20	19.1
2) Specific Mass (kg/W)	18.7	4.4	5.3
3) Specific Power (W/W)	370	60	95

Table 3. Key performance parameters for the 150W/90 K RTB cryocooler project.

Parameter	State of the Art	Project Goal	Current Value
1) Lift Capacity (W)	20	120	150
2) Specific Mass (kg/W)	1	0.8	0.4
3) Specific Power (W/W)	15	15	8

The cryocooler will be designed with the key performance parameters described in Table 3. Creare, LLC will demonstrate the performance of the cryocooler via characterization and vibration testing advancing the Technology Readiness Level to TRL 6. NASA will then take delivery of the engineering model cryocooler and further risk reduction testing will be conducted.

Electronics for Reverse Turbo-Brayton Cycle Cryocoolers

Since the start of the High Efficiency, High Capacity 90 K reverse turbo-Brayton cycle cryocooler development, all efforts have focused on the cryocooler mechanical components. Current development plans will advance the cryocooler “mechanical side” to TRL 6 while the overall system will remain at TRL 4 due to development efforts needed for the cryocooler electronics and software, the “electrical side”. To close this gap, NASA plans to award a contract for the design, build, and demonstration of an engineering model cryocooler electronics package. The demonstration will include thermal-vacuum and vibration testing to advance the electronics to TRL 6.

Pulse Tubes

In February 2019, NASA awarded two contracts to begin the study of scaling existing cryocoolers with extensive flight heritage towards the 150 W at 90 K target. Both Lockheed Martin [10] and Northrop Grumman [11] developed concepts that closed by using multiples of their existing flight pulse tube cryocooler line with a circulation system in place that could be used to cool a large cryogenic tank similar to how a reverse turbo-Brayton might be used. Based on the assessment provided by both companies, these systems could be developed faster than a reverse Brayton cryocooler, but have lower performance characteristics than the reverse Brayton systems.

REMAINING GAPS

In comparing the Lunar and Martian mission requirements to the current developments in progress, including those funded by NASA and other government agencies, many of the requirements are covered by a single development path currently within the Space Technology Mission Directorate (STMD) plan, at least for developing to the Engineering Unit level. However, as in the case with the 150 W at 90 K developments, alternative or parallel development paths are often sought to mitigate the risk moving forward. Maintaining parallel development paths is within the interest of both NASA and the emerging space industry to keep costs low as well as to provide options with different benefits.

Within the current development paths, most end at the Engineer Unit level, while the flight qualification of the unit is left to the flight user to perform. In the same vein, cryocooler electronics are just as important for the cryocooler system as the thermal-mechanical portions of the system. A concerted effort has begun to push the development of the electronics towards flight status to match the mechanical units.

Finally, in reviewing the thermal analysis of the liquefaction systems, there may be a niche opportunity for 150 K class cryocoolers as an alternative to the development of low temperature radiators. The ISRU community has also been looking for 150 K class cryocoolers for the solidification of CO₂ out of the Martian atmosphere [12].

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