Cryocooler Integration Options for Large Scale Space Systems

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The integration of the cryocooler to a load is an important detail in the use of any cryocooler or refrigeration system. Many system designs and tests have gone awry when attention to detail is not paid to the integration aspects. Unaccounted for thermal resistances or heat loads can leave a cooling system underpowered and significantly degrade system performance enough to impact the mission. Often for terrestrial applications, the simplest approach is to install the cold head directly into the top of the tank using it to induce natural convection and reliquefy any boil-off (see Figure 1). However, for in-space applications, the structural mass implications of such an attachment method, the lack of a tank at all, and the lack of natural convection to distribute the cooling within a tank lead to the need for other integration methods.

For many space cryocooler applications, the surface to be cooled is a small set of optics that are on the scale of a few square centimeters. These small area cooling devices can easily be cooled by point cooling devices typically seen on a Pulse Tube or Stirling type cryocooler or a thermal strap (see Figure 2). However, thermal straps or direct mounting require the warm and cold surfaces of a spacecraft to be in close proximity to each other, increasing the thermal challenges of the system. Many spacecraft in development continue to be these small systems where thermal strapping approaches work; however, several examples of large systems require different cooling integration approaches.

The James Webb Space Telescope (JWST), which is currently planned to launch in late 2021, uses several meters of small gold-plated tubing to distribute cooling from Joule-Thompson (JT) refrigeration system to the Mid Infrared Instrument (MIRI). [1, 10] This allows the cryocooler compressors to be packaged farther from the instrument. While the large sun-shades encompassing the telescope preclude the need for cooling large areas, the proposed Origins Space Telescope has wider distribution networks required for cooling than JWST. Origins is proposing cooling four instruments similarly to the way that MIRI was cooled with the JT refrigeration system as a cooling distribution loop that is precooled by Pulse Tube cryocoolers. [10]

While most of the other integration methods are passive (they are generally always on or always off), the gas-gap or mechanical heat switch can be used for either passive or active control or isolation of the cryocooler. [12] The gas-gap heat switch uses a conductive gas over a small gap and relatively large surface area to conduct heat between the two sides of the gap. If one side gets too cold, the gas is collected by a getter, greatly limiting the conduction. These can be used to help not only connect cryocoolers to instruments, but also behave as temperature control units, preventing the system from getting too cold.

For cooling of large propellant tanks, the cooling of large areas is required. To this effect, it was recently demonstrated that local cooling with large cooling loads can drive large unwanted temperature gradients in the system. [2] Multiple different approaches have been used to get around this challenge. Researchers from NASA's Marshall Spaceflight Center and Glenn Research Center demonstrated a forced pump cooling loop that interfaced with a thermodynamic vent system for cooling a tank. [3] While this does require the addition of heat to the system through running the pump, it does allow for integration of a more compact heat exchange area into a large volume system. Salerno and Feller developed the concept of broad area cooling, where a tubing network is attached to the exterior of the tank wall (see Figure 3), the refrigeration system working gas flown through it to provide direct cooling to the tank wall. [4] This approach was used for demonstration of both tank cooling and intermediate temperature cooling [13] and is currently being extended to higher heat removal cases such as liquefaction. [14] This system attempts to intercept most of the heat before it gets into the tank and uses the tank wall as an expanded heat exchanger area. This type of approach can work well with cooling cycles such as a Brayton cycle or Collins cycle where the working fluid of the refrigeration cycle goes directly through the tubing network on the tank wall. It can also work well with Pulse Tube and Stirling type cycles; however, a secondary circulation loop is required to move the heat from the tubing network on the tank wall to the cold heads. [5] Heat loads on any cold tubing that is not mounted in contact with the tank must be accounted for and carefully designed out. CERN has also recently explored this method for cooling resonating cavities in their cryo-modules. [6] Notardonato developed a system with the heat exchanger inside the tank for direct cooling of the fluid. [7] While this has the advantage of interacting directly with the fluid, for spaceflight applications, it must structurally be attached to the tank in a manner that allows it to survive launch and is less easily accessed if a problem occurs. This does however work very well for ground tanks and NASA recently installed a heat exchanger inside their new 4700 cubic meter sphere at the Kennedy Space Center. [11]

More recent developments such as pulsating heat pipes are showing promise for delivering cooling to distant locations with conductance values two orders of magnitude higher than that of traditional copper thermal straps. [8] Currently, efforts are underway to explore how long these pulsating heat pipes can be made without degradation in their performance. [9] With multiple cooling locations possible on a single cooling source, these may allow for even further simplification of cooling chains for large scale applications in space.

There is a wide array of methods of integrating cryocoolers into a system, with each method having its benefits and drawbacks. A careful assessment of options must be performed when assessing a new application to identify any additional thermal heat loads that serve as parasitic loads or temperature differences on the cryocooler or refrigeration system.

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Figure 1: Cryocooler mounted on top of a tank. Credit NASA.

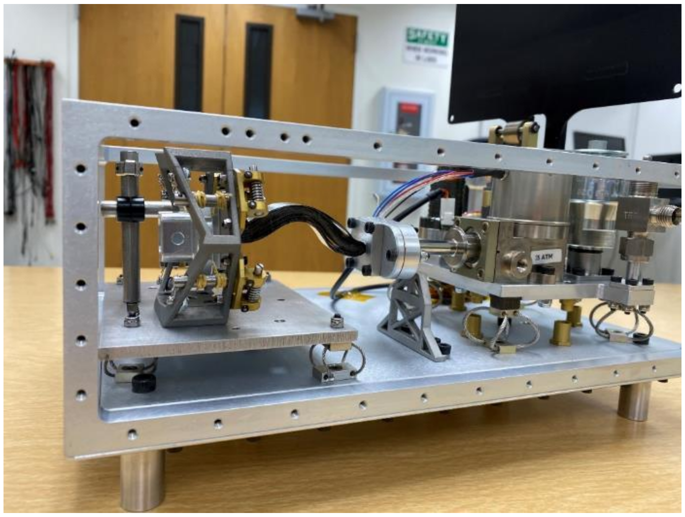

Figure 2: Optical plane mounted via flexible thermal strap to a cryocooler cold head. Credit NASA/JPL

Figure 3: Tank with tubes welded to the tank wall. Credit NASA.