Engineers help space chamber reach cold target at unprecedented efficiency

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A compressor being installed for the new 20 Kelvin helium refrigerator at NASA Johnson Space Center's Space Environment Simulation Lab Chamber A. The new system will allow testing of components of the James Webb Space Telescope.

As the U.S. sweated through its warmest year on record outside, a testing chamber at NASA Johnson Space Center in Houston reached its coldest temperatures yet on the inside, cooled by one of the world's most efficient cryogenic refrigeration systems.

Designed by members of the Cryogenics group at the Department of Energy's Jefferson Lab, the system reached its target temperature of 20 Kelvin, about -424 degrees F, for the first time in May 2012 and again during commissioning tests in late August. It reached its target temperature in just over a day and maintains a steady temperature with less than a tenth of a degree in variation over a load temperature range of 16 to 330 Kelvin, all with no loss of helium and using half the liquid nitrogen than comparable systems. But what is even more remarkable is its ability to maintain design efficiency down to a third of its maximum load.

"The range of load temperature and capacity while maintaining peak efficiency and temperature stability is unprecedented," said Venkatarao (Rao) Ganni, deputy Cryogenics Department head, and a key member of the system design team.

The successful cool down is great news for NASA, who will be using the Space Environment Simulation Lab Chamber A to subject components of the James Webb Space Telescope to the rugged conditions it will encounter in space when it is launched in 2018. Jonathan Homan, a senior engineer in the Systems Test Branch of the Thermal Systems Division at Johnson Space Center, is in charge of the cryogenics operations of Chamber A.

"The satellite is going to orbit the sun away from the Earth at a point called L2, it's about a million miles away from the Earth, about four times the distance of the moon," Homan explained. "All flight hardware needs to go through a very rigorous test and integration program. The satellite has to be exposed to the environment it's going to be living in for the next decade or so. The only way to verify its proper operation is to get the optics to the on orbit temperatures and test their functionality. This way, the program can verify that the scientists get the data that they are looking for."

Chamber A

Chamber A was chosen to test the integrated primary optics of the James

Webb Space Telescope. The chamber was built in the 1960s to test the Apollo Service and Command module to simulate the space conditions in a near-Earth orbit, and its trip to and from the moon. Chamber A already had its own cryogenics systems to create this environment. A liquid nitrogen system was capable of cooling the chamber to 80-90 Kelvin to re-create the bleak cold of space. The chamber also had a liquid helium system, which was used to create a space-like vacuum by 'cryopumping', or condensing, air from the chamber.

"Chamber A was designed originally to test the Apollo Service and Command module back in the Apollo program era, and of course, it's been used for the space station and Sky Lab, and many other NASA and non-NASA space projects that need a large, thermal vacuum facility," Homan said.

One big problem faced by NASA, however, was upgrading the separate cryogenics systems to meet the new demands that would be placed on the testing chamber by the ambitious James Webb Space Telescope. As it stood, the chamber's cryogenics systems were not capable of meeting the basic requirements of the tests. First, the range of refrigeration had to be extended from 80 Kelvin down to at least 20 K. Next, the tests needed to be conducted over long durations, 90-120 days, which was not possible due to system components (pumps) that required maintenance every two weeks, and a great number of valves, with each one a potential point of failure during a test. And finally, the system was inefficient, gobbling up 48,000 gallons of liquid nitrogen every day to maintain consistent operations.

Adding to the difficulties, large-scale cryogenics systems are usually designed for a specific function, with no two exactly alike. Making an upgrade even more of a challenge, the NASA team wanted very much to re-use components that they already had onsite to reduce the cost and installation time. To meet these goals, the decision was made to approach cryogenics experts in industry and at national labs to find the best solution.

"We haven't been able to find in industry that link between people who own and operate equipment and people who design and build equipment, and that's really what I was able to find with the cryogenics group at Jefferson Lab. You've got a group there that not only understands the operations, but also the detailed design on the equipment that they are operating and maintaining," Homan said.

Ganni agreed and explained that the members of the laboratory's cryogenics group has that knowledge through their own experience in industry, as well as through involvement in the building, operating and/or improving the cryogenics plants at Jefferson Lab, Brookhaven National Lab, Oak Ridge National Lab and others.

"At the beginning of my career, I worked for industry, and I was involved in the design of cryo plants. In industry, people would give us their specifications, and we really don't have a complete picture of its end use, except for these few descriptions. We would have a really short duration to understand what the customers really needed," Ganni explained. "As a user, I have a much more clear understanding of the experiment's cryogenic needs. So, when I came to JLab, I realized that we know more about what we want and can write these in the specifications to the vendor. So we should separate what they are good at and we should do our own work, because we are competent enough to do that work ourselves."

It was this experience and willingness to pioneer new technologies that led the group to improve the efficiencies of the laboratories' cryogenics systems, applying the concepts of the patented Floating Pressure - Ganni Cycle and other improvements to reduce the cost and improve the efficiency and stability of cryogenics operations. In the early stages of the Chamber A project, the group applied the Floating Pressure - Ganni Cycle to an existing industry-supplied refrigerator, dramatically improving its reliability and its efficiency and temperature stability by an order of magnitude.

A new system

Initially, the JLab Cryo Group was requested by NASA to provide the process design and from that develop the specification for the helium refrigeration system that will allow the chamber to reach 20 Kelvin. This new helium system is similar to an air conditioning system that circulates its working fluid (i.e., the refrigerant), absorbing heat from one location (the place being cooled) and rejecting it to another (usually the ambient environment). However, that is where the similarity ends. It operates on a different thermo-dynamic cycle and uses much larger and a different type of compressor and heat exchanger. Also, unlike an air conditioner, it uses a turbine expander that operates at thousands of revolutions per second. This new helium system was designed to operate using the Floating Pressure – Ganni Cycle.

A few years into the project, NASA also requested the Cryogenics Group's help in the design modifications of the chamber's liquid nitrogen system that is needed to provide a thermal intercept temperature between the 20 Kelvin helium and ambient temperature. The system previously used by NASA circulated the 80-90 Kelvin liquid nitrogen using pumps and many valves and components. This type of system is known in the field as a forced-flow design. The Cryogenics Group's proposal was to convert the liquid nitrogen system to a gravity-fed design, also called a thermo-siphon, which works in roughly the same way as a percolator in a coffee maker.

A smaller scale thermo-siphon design had been installed and successfully used for Jefferson Lab's 2 Kelvin cold box located at the CHL. However, one had never before been incorporated into an upgrade of such a large facility. Chamber A is mammoth, having a hinged door over 12 meters in diameter, a height of over 36 meters, and a diameter of almost 20 meters. After thermal and process modeling of the proposed thermo-siphon proved favorable, NASA chose to include it in the final design, ultimately reducing the system installation cost, improving reliability, reducing operation and maintenance costs, and consuming less liquid nitrogen.

Other improvements included far fewer valves, better-insulated piping and a drain that allows the return of the remaining liquid nitrogen (not used during testing) to the storage tanks for future use.

"Everything in the plant was designed and specified by JLab: the process, the components and everything being built." Ganni said. The group has found that this greatly assists the vendors seeking to provide the equipment and provides the most effective trade-off between equipment performance and cost.

All contracts were competitively bid by NASA. The helium cold box was awarded to Linde Kryotechnik AG, the helium compressor skids to Salof Refrigeration and the gas management and oil removal equipment to Riggins Company, a company located near Jefferson Lab.

Tests a success

The process to upgrade these systems began in 2007. As the pieces were installed, they were tested individually and leak-checked. In March 2012, the compressor was commissioned. The cold box was commissioned in May. Finally, the entire system was put through its paces in a cooldown and functional test of the chamber in late August 2012.

The cooldown was expected to take about 48 hours. Instead, it was complete in the first attempt in just 30 hours. As the system was pushed to its limits, it demonstrated its ability to provide 11.2 kW at 15 K, all the way to 118 kW at 100 K, holding the temperature steady to within plus or minus 0.1 K. So, it not only exceeded its design load, but it exceeded its design temperature range and temperature stability.

In fact, the system is far more flexible than any ever built. It is capable of maintaining a steady temperature at any figure between 15 and 330 K, a hugely impressive range.

"Space simulation testing definitely requires extreme temperature swings, both at cryogenic and hot temperatures," Ganni said.

In addition, thanks to the Floating Pressure - Ganni cycle, it was able maintain its peak efficiency down to one-third of its maximum capacity.

"Our system automatically matches to the need of the load." said Ganni. "The key is automatic. No one else needs to take it there; the system says okay, this is the load it needs, and I am going to figure out how to satisfy that, and at the most efficient way. That's what the whole floating pressure theory is all about."

In addition to the success of the helium refrigerator, the liquid nitrogen thermo-siphon cooling system was also successful. It only requires a mere 18,000 gallons to cool the chamber, compared to the old figure of 58,000 gallons. What's more, due to the efficiencies introduced by the thermo siphon, the system used just 24,000 gallons of nitrogen each day in operations, compared to the 48,000 that would have been used without it. It also drained the unused liquid to the storage tanks at the end of the test, allowing the door and scavenger panel to operate independently, cooled by the liquid (while the other panels were warmed-up), allowing the chamber to achieve a bake-out temperature of 70 ^{0}C.

Now, as other upgrades to the chamber continue, plans are being made to use the chamber to conduct operational tests of components of the James Webb Space Telescope.

Beyond NASA

Of course, the Cryogenics group still has its hands full. They are committed to assisting NASA by ensuring the refrigeration system runs smoothly throughout the telescope's testing phase. While the NASA work has required a commitment of fewer than two full-time-equivalent staffers, the group has also been busy with the design, procurement and building of an additional main cryoplant to double the JLab cryogenics capacity and the Hall D cryogenic system here at Jefferson Lab.

The Central Helium Liquefier-2 is being built to support the cryogenics requirements of the CEBAF accelerator operating at 12 GeV. Ganni said that the project benefitted from the NASA work, in that it provided a template for the group's procurements for CHL-2.

"How are the specifications going to be, how is it going to be procured, how is it going to be installed, it's already been worked through the system. So we don't have to fight these battles again for JLab," Ganni added.

Once that upgrade is complete, there's more work to do. The Facility for Rare Isotope Beams will need a cryo plant. And they know just who has the expertise to design it.

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