

# A 4 K tactical cryocooler using reverse-Brayton machines

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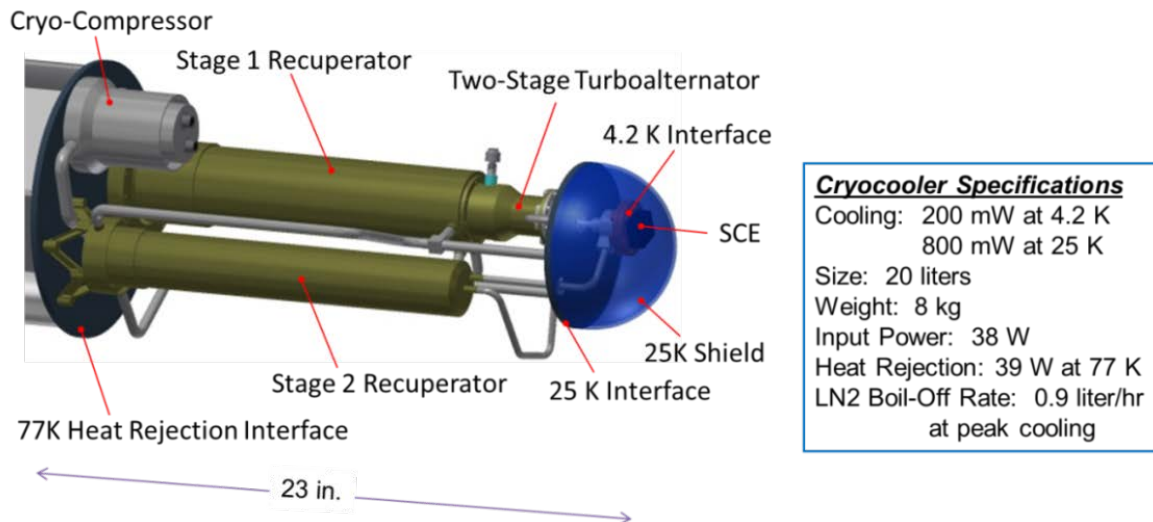
**Abstract.** Superconducting electronics and spectral-spatial holography have the potential to revolutionize digital communications, but must operate at cryogenic temperatures, near 4 K. Liquid helium is undesirable for military missions due to logistics and scarcity, and commercial low temperature cryocoolers are unable to meet size, weight, power, and environmental requirements for many missions. To address this need, Creare is developing a reverse turbo-Brayton cryocooler that provides refrigeration at 4.2 K and rejects heat at 77 K to an upper-stage cryocooler or through boil-off of liquid nitrogen. The cooling system is predicted to reduce size, weight, and input power by at least an order of magnitude as compared to the current state-of-the-art 4.2 K cryocooler. For systems utilizing nitrogen boil-off, the boil-off rate is reasonable. This paper reviews the design of the cryocooler, the key components, and component test results.

## 1. Background

Superconducting Electronics (SCEs) and spectral-spatial holography have the potential to revolutionize digital communications for multiple tactical applications. Digital receivers, transmitters, transceivers, and processors have been demonstrated utilizing these technologies with extremely high bandwidth, but must operate at cryogenic temperatures. The most challenging application in terms of size, weight, and power (SWaP) involves small airborne platforms. Passive refrigeration using liquid helium provides the required thermal environment, but is not practical in the field. Commercial mechanical refrigerators, also known as cryocoolers, are large and inefficient and are unable to meet SWaP requirements for small platforms. Space cryocoolers are smaller and lighter, but inefficient at low temperatures and expensive. A new type of tactical refrigeration system is required that has high thermodynamic efficiency, is able to meet SWaP requirements for small platforms, and is optimized for operation with cryogenic electronics.

The technical approach we are developing is a two-stage Reverse Turbo-Brayton (RTB) cryocooler that provides refrigeration at 4.2 K and 25 K, and rejects heat at 77 K through boil-off of liquid nitrogen. The cryocooler concept and projected performance are shown in Figure 1. The cryocooler is predicted to reduce each SWaP parameter by an order of magnitude as compared to the current state-of-the-art 4.2 K cryocooler. In addition, liquid nitrogen is relatively safe, non-toxic, easy to handle, and unlike liquid helium, readily available and transportable. The nitrogen boil-off rate is reasonable. This paper reviews the design of the cryocooler, the key components, and component test results.





**Figure 1.** Compact and efficient cryocooler for cooling low-temperature electronics and instruments.

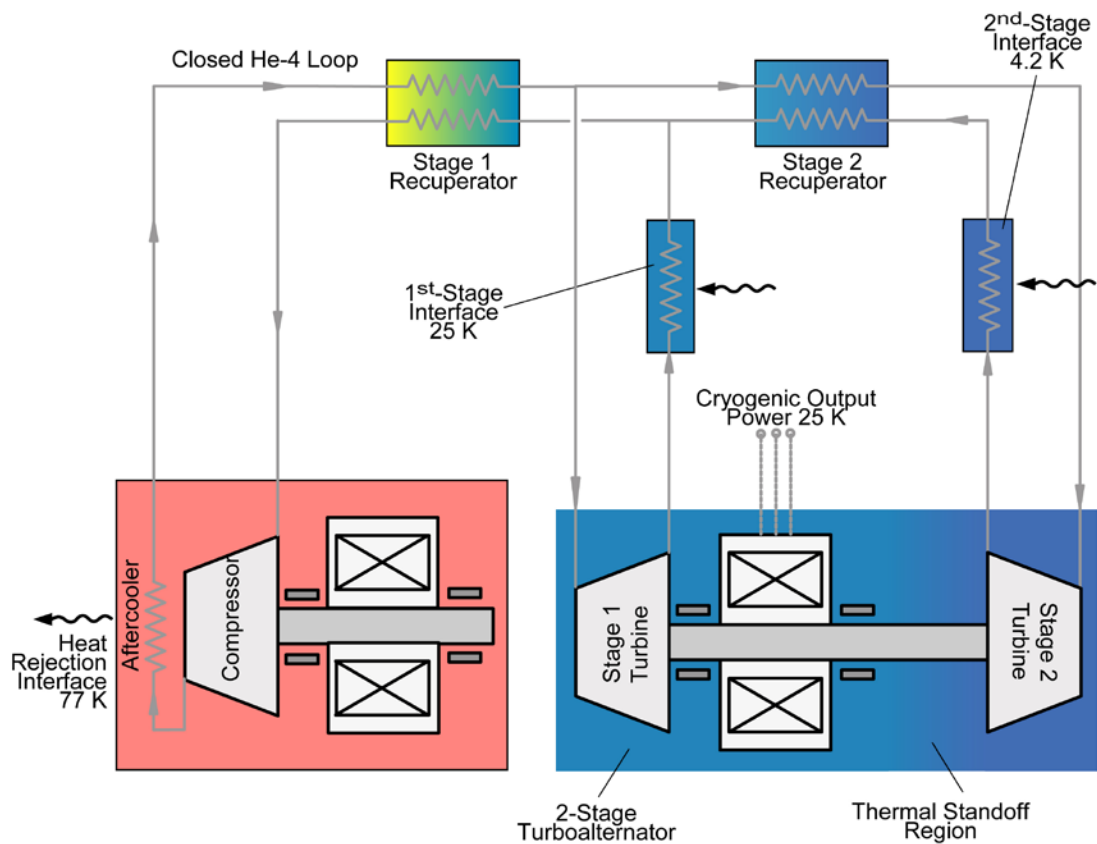
## 2. Cryocooler Description

A schematic of the RTB cycle is shown in Figure 2. The cycle gas is helium operating between pressures of nominally 0.8 atm and 1.2 atm. The key components within the cycle are the cryo-compressor, two-stage turboalternator, and recuperators. The compressor and turbine utilize high-speed, miniature rotors that are supported on self-acting gas bearings and brushless permanent magnet motors and alternators. The expected operating speeds are 6000 rev/s (360,000 rpm) for the turbine and 7800 rev/s (470,000 rpm) for the compressor, resulting in a compact system with a very high power density and efficiency. The recuperators utilize Creare's silicon slotted plate technology, which has been demonstrated to a Technology Readiness Level of 5 [1, 2]. These recuperators are extremely light and compact. The other components are the aftercooler, thermal interface heat exchangers, control electronics, and tubing, which are all relatively compact and simple components.

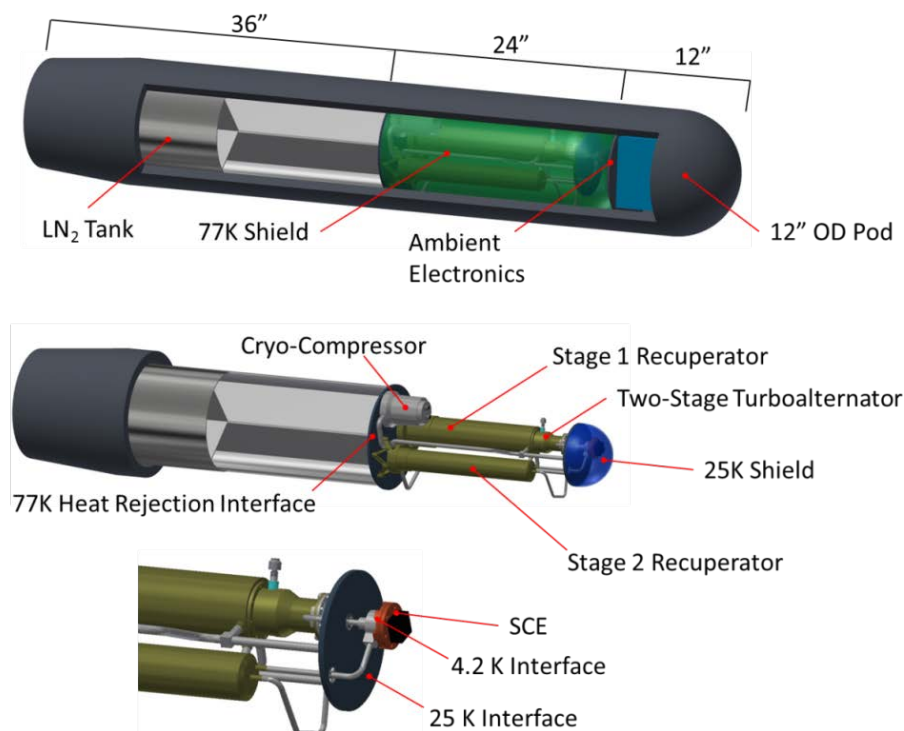
Figure 3 shows a notional packaging concept for the cryocooler integrated into a 12 in. pod. The pod is divided into three compartments. The forward compartment houses the ambient electronics; is nominally 12 in. long; and houses the cryocooler control electronics, signal conditioners and processors for the cryo-electronics. The middle compartment houses the cryocooler and is nominally 24 in. long. The aft compartment houses the liquid nitrogen tank and is nominally 36 in. long. The overall length and design of the aft compartment is notional, and will likely be tailored for specific mission durations. The aft compartment shown in Figure 3 provides nominally 32 hrs of operation. The cryocooler will be mounted on the bulkhead between the aft and middle compartments, and will reject heat through the bulkhead directly to the liquid nitrogen. The bulkhead is manufactured from aluminum to ensure that radial temperature gradients are negligible.

Vacuum insulation is required to reduce nitrogen boil-off and thermal parasitics to the cryocooler. Low conductivity penetrations are used to support the cryogen tank. A primary shield that is conductively cooled by liquid nitrogen extends from the aft compartment to the middle compartment encasing the Stage 1 and 2 cryocooler components. The middle compartment is evacuated to reduce thermal parasitics. The overall liquid nitrogen boil-off rate due to parasitics is 0.2 liter/hr, which is considerably less than the boil-off rate due to the cryocooler at peak power.

A secondary shield encases the Stage 2 components and operates at nominally 25 K. The surfaces of the shields are coated with a low emissivity coating and wrapped in multi-layer insulation to reduce the radiative heat exchange between the cold and warm surfaces. Penetrations through the shields for fluid, structural, and electrical connections utilize radiation baffles to prevent direct views from warm to hot components. The predicted parasitic heat load to the first cryocooler stage is 30 mW and to the second cryocooler stage about 1 mW.



**Figure 2.** Cycle schematic for RTB cryocooler with cryogenic heat sink.



**Figure 3.** Packaging of cryogenic system into a 12-inch pod.

Based on our packaging and integration concept, we estimated the overall mass of the cryocooler is 8.2 kg. The mass value includes the mass of the shields and cryocooler supports, but does not include the mass of the cryogenic electronics, pod, liquid nitrogen tank, and liquid nitrogen.

In comparison to commercial cryocoolers, the Creare cryocooler requires orders of magnitude less input power and is smaller and lighter. In addition, the underlying cryocooler technology has been developed for the rigors of space flight and is expected to be equally suitable for airborne applications. Table 1 provides a comparison of 4 K cryocoolers. The current state-of-the-art cryocoolers are the SRD/SRDK product line produced by Sumitomo Heavy Industries. These are Gifford-McMahon style cryocoolers that are designed for indoor usage, reject heat at ambient temperature, and have a maintenance interval of 10,000 hrs. The cryocoolers comprise a coldhead and compressor attached using high pressure flexlines. Model SRDK-101D-A11B is the lowest capacity unit and the most compact and lightweight. It requires 1300 W of input power at 60 Hz to simultaneously provide 100 mW of refrigeration at 4.2 K and 5 W of refrigeration at 60 K. The masses and volumes for the cryocooler components are 7.2 kg and 13 liters for the coldhead, and 42 kg and 81 liters for the compressor. Model SRDK-305D-A31C provides 400 mW of refrigeration at 4.2 K, requires 4800 W of input power, weighs 111 kg, and has a volume of 250 liters. These cryocoolers are too big and too heavy and require too much input power for small platforms. In addition, they do not meet the environmental requirements for airborne applications.

**Table 1.** Comparison of 4 K cryocoolers.

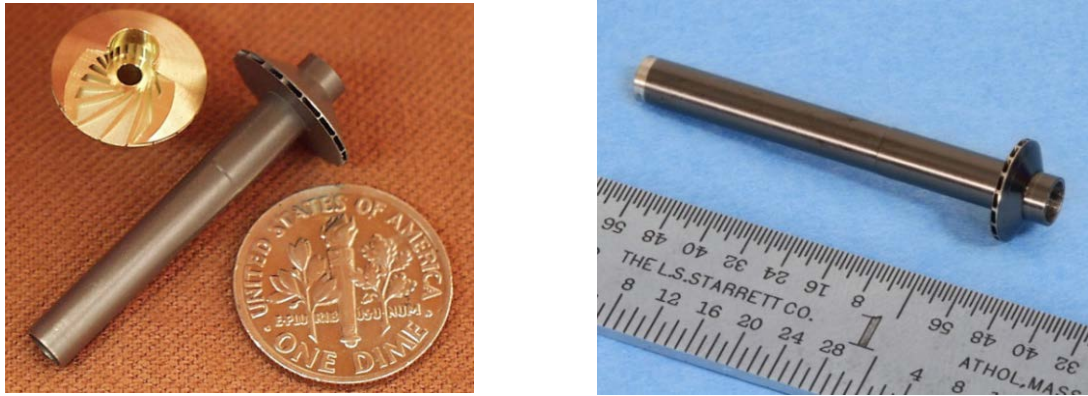
	Creare UAV Cryocooler	Sumitomo SRDK-101D-A11B	Sumitomo SRDK-305D-A31C
Maturity	Design	Commercial	Commercial
Heat rejection temperature	77 K	300 K	300 K
Stage 1 refrigeration	800 mW @ 25 K	5.0 W @ 60 K	20 W @ 40 K
Stage 2 refrigeration	200 mW @ 4.2 K	100 mW @ 4.2 K	400 mW @ 4.2 K
Input power	<50 W	1300 W	4800 W
Mass (refrigeration system)	8 kg	49 kg	111 kg
Volume	20 liters	94 liters	250 liters
LN2 boil-off rate	0.9 liter/hr	N/A	N/A

### 3. Cryo-Compressor Proof-of-Concept Testing

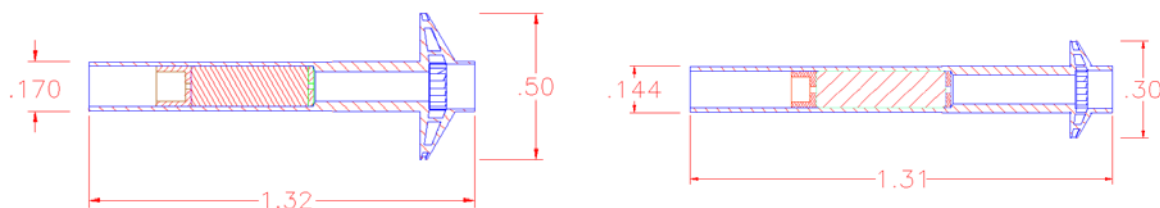
The key innovation of this cryocooler concept is the operation of the compressor at cryogenic temperatures. This was not previously demonstrated and has several benefits. First, it enables the compressor to achieve a very high compression ratio in a single stage, because the density of helium at 77 K is four times that at room temperature. To achieve this high compression ratio at room temperature would require three centrifugal compressors connected in series with total input power of 250 to 300 W. Second, the high pressure ratio significantly increases the specific cooling power of helium flow, and thus reduces the helium gas flow rate in the system. This in turn reduces the size and mass of the recuperators. Most importantly, the input power to compress the helium is reduced due to the lower enthalpy rise that is required to compress a gas at lower temperatures. These features substantially reduce the size, mass, and input power of the cryocooler, making it ideal for SWaP-sensitive applications.

Proof-of-concept testing was performed using an existing cryo-circulator. The difference between a cryo-circulator and cryo-compressor is the operating speed, and consequently the pressure ratio produced. The circulator operates at lower speeds, pressure ratios, and flow rates than a compressor to serve its intended function. A comparison between the circulator and compressor rotors is shown in Figure 4. The circulator utilizes a 7.6 mm (0.3 in.) impeller and 3.6 mm (0.14 in.) shaft, and operates at up to 2000 rev/s at 70 to 80 K. The cryo-compressor utilizes a 12.7 mm (0.5 in.) impeller and 4.3 mm (0.17 in.) shaft, and

operates at up to 7800 rev/s at 80 K. The bending critical frequencies are nominally the same so that the shaft dynamics are similar. The shaft surface speed, a critical parameter for bearing performance, is 106 m/s for the cryo-compressor. To obtain the same shaft surface speed for the circulator, we must operate the circulator at a speed of up to 9500 rev/s at 80 K.



**Photographs of Rotors**



**Key Dimensions of Rotors (dimensions given in inches)**

**Cryo-Compressor**

**Circulator**

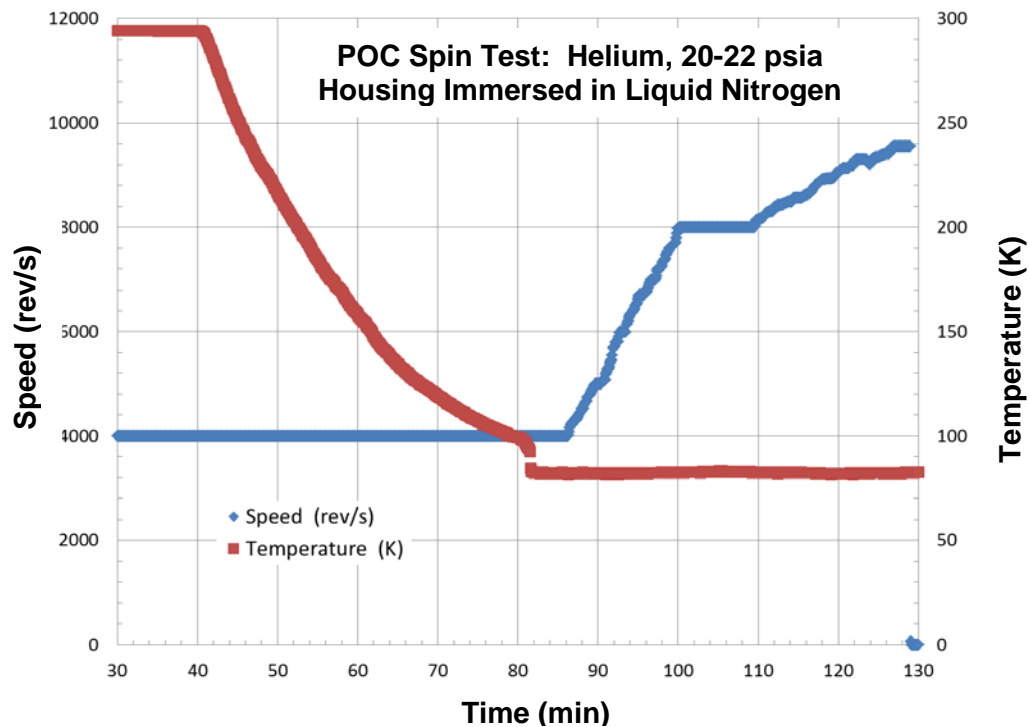
**Figure 4.** Comparison between cryo-compressor and circulator rotors.

Operation at 77 K is achieved by immersing the circulator assembly in a dewar filled with liquid nitrogen. The tests were performed in an existing open-loop test facility. The test results are shown in Figure 5. The cryo-circulator was cooled from 300 K to 77 K while operating at a speed of 4000 rev/s. Once at 77 K, the speed was gradually increased while monitoring the displacement probes for signs of instability. The speed was increased to a maximum value of 9600 rev/s, at which point we stopped the test. Higher speeds were possible, but we did not want to risk hardware as the performance gains of the cryocooler at higher speeds are not significant. The maximum speed demonstrated is the highest we have yet achieved with a fully functional turbomachine at cryogenic temperatures. Prior demonstrations at higher speeds and at cryogenic temperatures were with simple shafts. Based on these successful results, we initiated the build of the cryo-compressor.

#### **4. Cryo-Compressor Development**

The cryo-compressor design is based on an existing permanent magnet motor compressor developed for operation at 300 K [3]. The key changes are selection of compatible materials for operation at cryogenic temperatures and optimization of the aerodynamics for operation at the design conditions. The assembled cryo-compressor is shown in Figure 6.





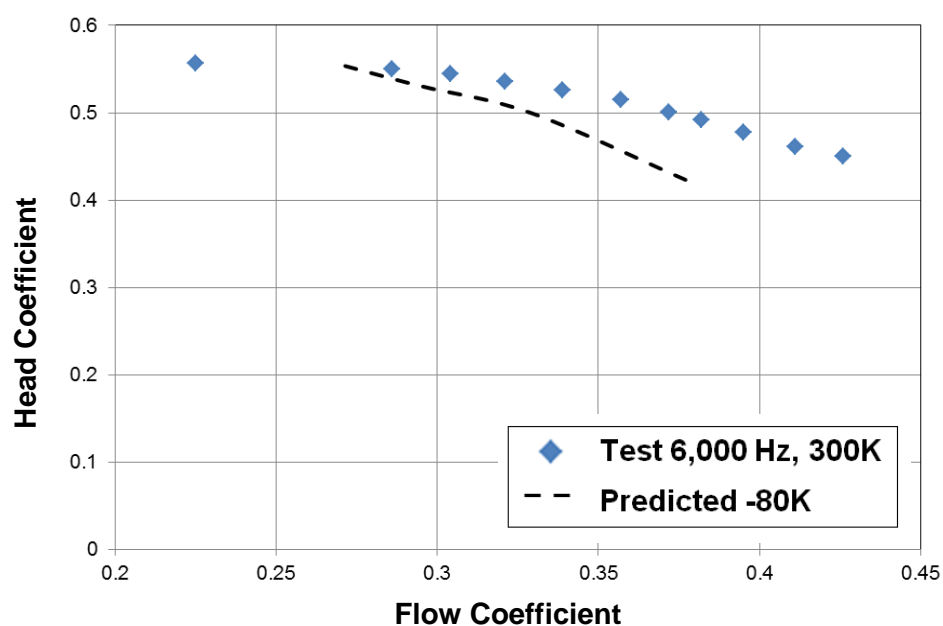
**Figure 5.** Cooldown curve for cryo-circulator demonstration to high speeds.



**Figure 6.** Assembled cryo-compressor ready for testing.

Initial testing was performed at ambient temperature. We performed spin tests with the cryo-compressor at ambient temperature in an open-loop helium test loop to assess journal bearing stability up to the design operational speed. We performed several tests where the rotor speed was limited to less than the design speed due to bearing instability. After each test, we incrementally reduced the operating clearance in the journal bearings to enable higher operating speeds. After a few iterations to the journal bearing settings, the rotor attained the design operating speed of 8,000 rev/s.

Following our successful spin test, we performed a test to characterize the compressor performance at room temperature. This test provides an initial indication of the performance and screens for gross performance discrepancies that need to be addressed before investing the time in a cryogenic test. The test data are presented in Figure 7, which compares data taken at room temperature against our performance predictions for the compressor at 80K. The performance of the compressor is characterized by plotting its non-dimensional head rise (head coefficient) versus its non-dimensional flow rate (flow coefficient). The performance of the compressor at cryogenic temperatures is expected to be slightly better due to the higher Reynolds number. From the figure, we note that the performance curve is smooth and regular, and that it is close to our performance predictions for the machine at cryogenic temperature. Proper performance of the compressor at ambient temperature is a necessary but not sufficient condition for proper cryogenic performance. Future testing will be focused on testing at up to 8,000 rev/s at 80 K using a liquid nitrogen heat sink.



**Figure 7.** Ambient-temperature test of cryo-compressor compared to cryogenic performance predictions. The test data match performance predictions well, indicating that the compressor is operating close to expectations.

## 5. Conclusions

Creare is developing a low temperature tactical cryocooler for cooling superconducting electronics and spectral-spatial holography systems. The cryocooler provides refrigeration at 4.2 K, and rejects heat at 77 K through boil-off of liquid nitrogen. The cryocooler is predicted to reduce each SWaP parameter by an order of magnitude as compared to the current state-of-the-art 4.2 K cryocooler. The nitrogen boil-off rate is reasonable, enabling long duration missions using a small dewar of liquid nitrogen.

The key innovation is the use of a cryo-compressor that drastically reduces cryocooler size, weight, power, and cost for tactical missions. Initial proof-of-concept testing indicates that the operational requirements for the cryo-compressor are achievable, and initial performance testing shows that the performance will exceed predictions.

Future work involves testing the cryo-compressor at design operating conditions, completing the development of the remaining cryocooler components, and testing the cryocooler in a laboratory and then operational environment. Successful completion of this program will dramatically improve high-speed digital communications from small platforms.

**Acknowledgments**

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