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Cascading pulse tubes on a large diaphragm pressure wave generator to increase liquefaction potential

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Abstract. Fabrum Solutions, in collaboration with Absolut System and Callaghan Innovation, produce a range of large pulse tube cryocoolers based on metal diaphragm pressure wave generator technology (DPWG). The largest cryocooler consists of three in-line pulse tubes working in parallel on a 1000 cm^3 swept volume DPWG. It has demonstrated 1280 W of refrigeration at 77 K, from 24 kW of input power and was subsequently incorporated into a liquefaction plant to produce liquid nitrogen for an industrial customer. The pulse tubes on the large cryocooler each produced 426 W of refrigeration at 77 K. However, pulse tubes can produce more refrigeration with higher efficiency at higher temperatures. This paper presents the results from experiments to increase overall liquefaction throughput by operating one or more pulse tubes at a higher temperature to pre-cool the incoming gas. The experiments showed that the effective cooling increased to 1500 W resulting in an increase in liquefaction rate from 13 to 16 l/hour.

1. Introduction

Callaghan Innovation and Fabrum Solutions have been developing cryocoolers based on metal diaphragm pressure wave generators (DPWG) for pulse tube and Stirling cryocoolers since 2005. The objective of the work is to produce an industrially robust cryocooler for High Temperature Superconductor (HTS) applications and gas liquefaction. The DPWG is a practical alternative to crank or linear-motor driven pressure wave generators. The DPWG has the simplicity and low cost of a lubricated crank system with the diaphragms providing a non-rubbing hermetic seal to maintain a clean cryocooler working gas. Pressure wave generators have been made with swept volumes from 20 cm^3 to 1000 cm^3 [1]–[3]. These have been coupled to pulse tube [4]–[7] and Stirling [8], [9] cold heads. Two of the smaller DPWGs have each achieved over 7000 hours of operation. At the time of writing, the original 1000cc “Alpha” DPWG has had 7300 hours with 5100 of these hours in service as a commercial nitrogen liquefier and the 1000 cm^3 “Beta” DPWG, shown in Figure 1, has 4700 hours, with 3300 hours as a commercial nitrogen liquefier.

Recent development has focused on producing pulse tube cryocoolers for commercial gas liquefaction, either liquid nitrogen for industrial use or for cooling high temperature superconductor (HTS) systems, natural gas (LNG) or liquid oxygen for breathing systems.

Pulse tube cryocoolers produce more refrigeration at a higher efficiency at higher temperatures. When using multiple pulse tubes for an application, this effect can be exploited by using one or more pulse tubes for pre-cooling the gas before passing it to the liquefaction stage. The phase angle between

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pressure and volume in the pressure wave generator changes with the pulse tube temperature. If multiple separate cryocoolers are used, pre-cooling at a higher temperature is straight forward as the individual pulse tubes can run independently with different pressure-volume phase angles in separate pressure wave generators. However, the PTC1000 cryocooler has three pulse tubes sharing the same pressure wave generator. The question then presents, what effect does sharing the compression space and common pressure-volume phase angle have on the pulse tube performances when the pulse tubes are run at different temperatures and therefore would naturally have different pressure-volume phase angles. Since the PTC1000's pressure wave generator is not resonant, the effect should be only between the individual pulse tubes' gas circuits.

This paper presents the results of a test on the PTC1000 cryocooler in which two of the pulse tubes were held at 77 K and the other was held at a higher temperature, thereby increasing the useful refrigeration for nitrogen liquefaction.

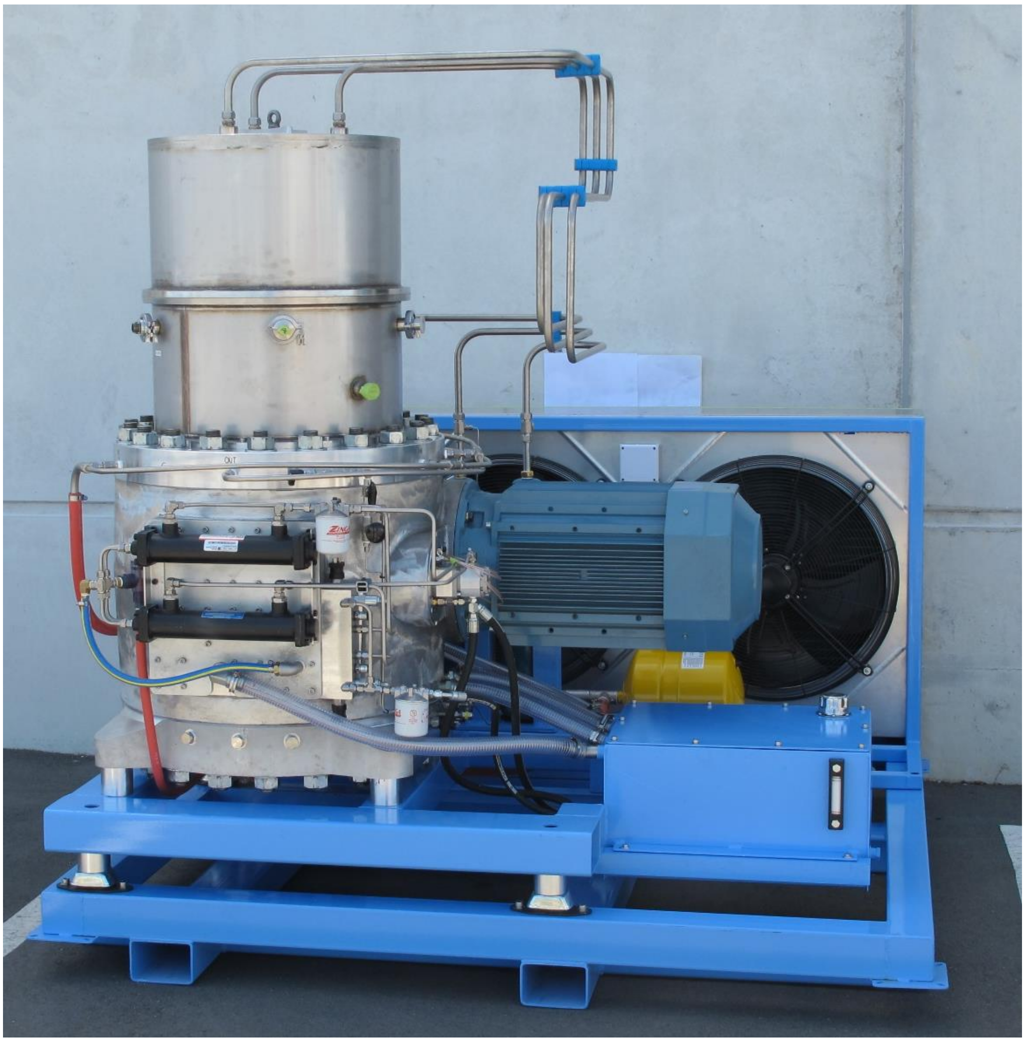

Figure 1: The PTC1000 beta cryocooler, including air cooling and mounted on a subframe ready for integration into a liquefier.

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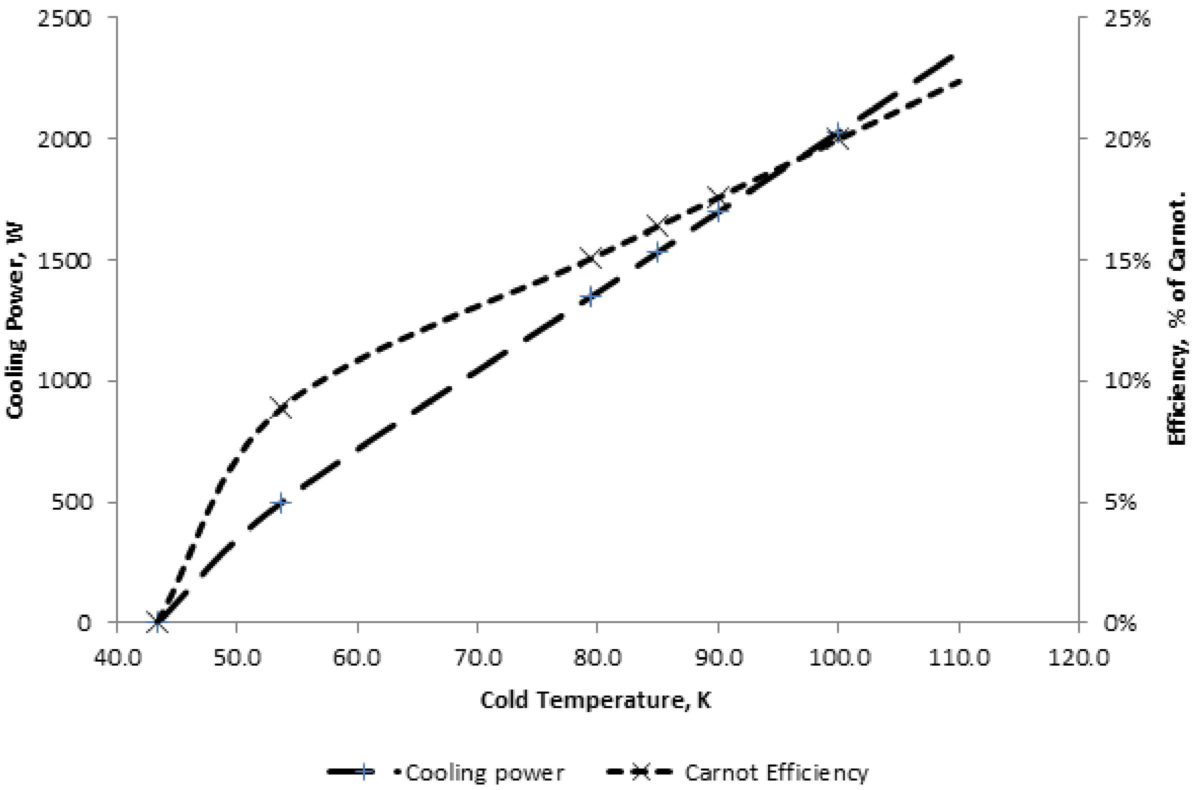

Figure 2: Cooling power of the PTC1000 cryocooler at 47 Hz running speed.

2. Advantages of using one of the pulse tubes for pre-cooling

The PTC1000, Figure 1, combines a 1000 cm^3 swept volume DPWG with three pulse tubes. The PTC1000's cooling curve is shown in Figure 2, 1280 W of cooling is achieved at 77 K. The beta prototype PTC1000 that has been running at Southern Gas Services for the last year has been consistently producing 13 litres of liquid nitrogen per hour when running its nitrogen condensers at 1 bar gauge pressure.

It has been hypothesized that by running all the gas through a heat exchanger on one of the pulse tubes, the pulse tube would run at a higher temperature and pre-cool the gas, which would then be cooled and condensed by the other two pulse tubes. In this manner, the higher cooling power at higher temperatures could be exploited to get more liquefaction for the same cryocooler.

The pulse tubes have been very consistent in their power outputs, with only a difference of a few Watts in cooling power between each pulse tube [10]. Even during cool-down, the pulse tube temperatures kept with a few degrees of each other. The big unknown was how the pulse tubes would behave when one was given a significantly higher heat load than the others, the condition we wished to test. With a single pulse tube, or three pulse tubes at an even temperature, the pressure-volume phase angle changes with temperature. The pressure wave generator, whose movement is driven by a motor-crank mechanism would not be affected the same way a resonant system would, but would the pulse tubes compete for the pressure wave?

To answer these questions, an experiment was performed where one the pulse tubes were electrically heated, with one pulse tube receiving more heat than the other two.

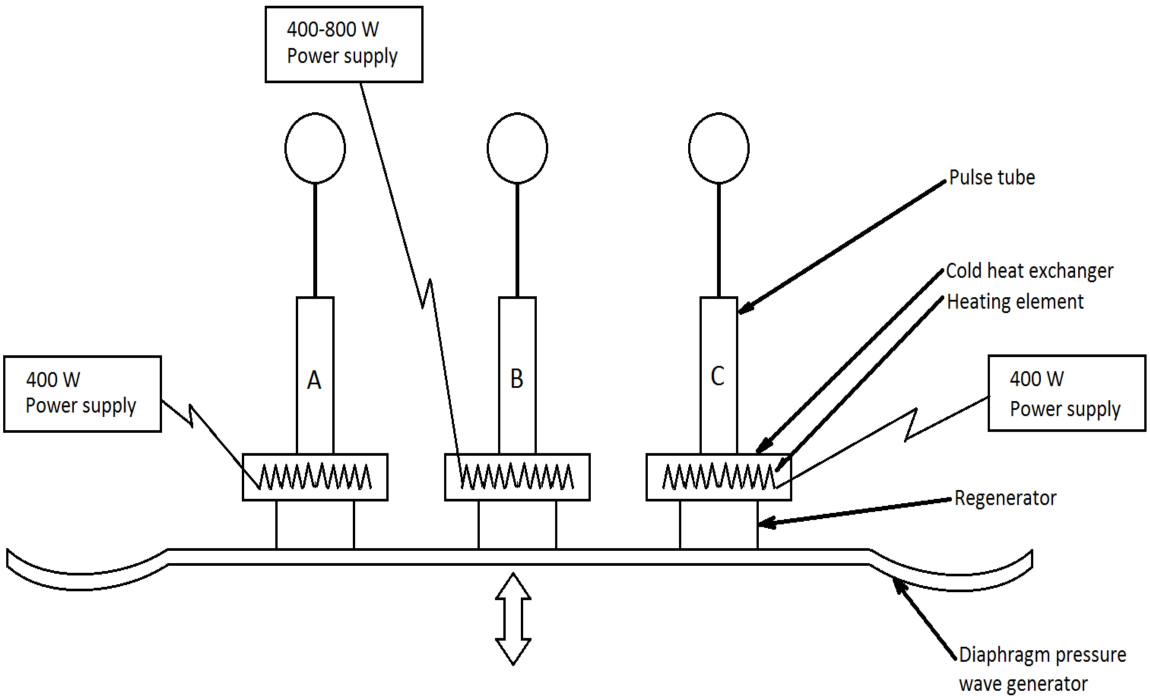

Figure 3: Schematic of the heater experiment

3. Heater experiment

The heater experiment was set up as shown in the schematic in Figure 3. Limited time was available as the cryocooler normally ran at Southern Gas Services, producing liquid nitrogen for sale. On one of the few occasions where it returned to Fabrum Solutions for modifications (as part of the development programme) a day was available for testing. The pulse tubes were previously fitted with heaters to produce the power curves in Figure 2. Two of the pulse tube heaters (pulse tubes A and C) were connected to power supplies delivering 400 W each, and the third (pulse tube B) to a separate power supply with a variable power output. The cryocooler was run, cooling down to approximately 77 K with 400 W applied to each pulse tube.

The mean helium pressure in the cryocooler for the test was 24 bar which is consistent with the total cooling at 77 K of 1200 W being less than the cooling curve in Figure 2 which was generated with the cryocooler at 25 bar gas pressure. The power in pulse tube B was increased in stages up to 800 W, with time to settle to a new temperature at each level.

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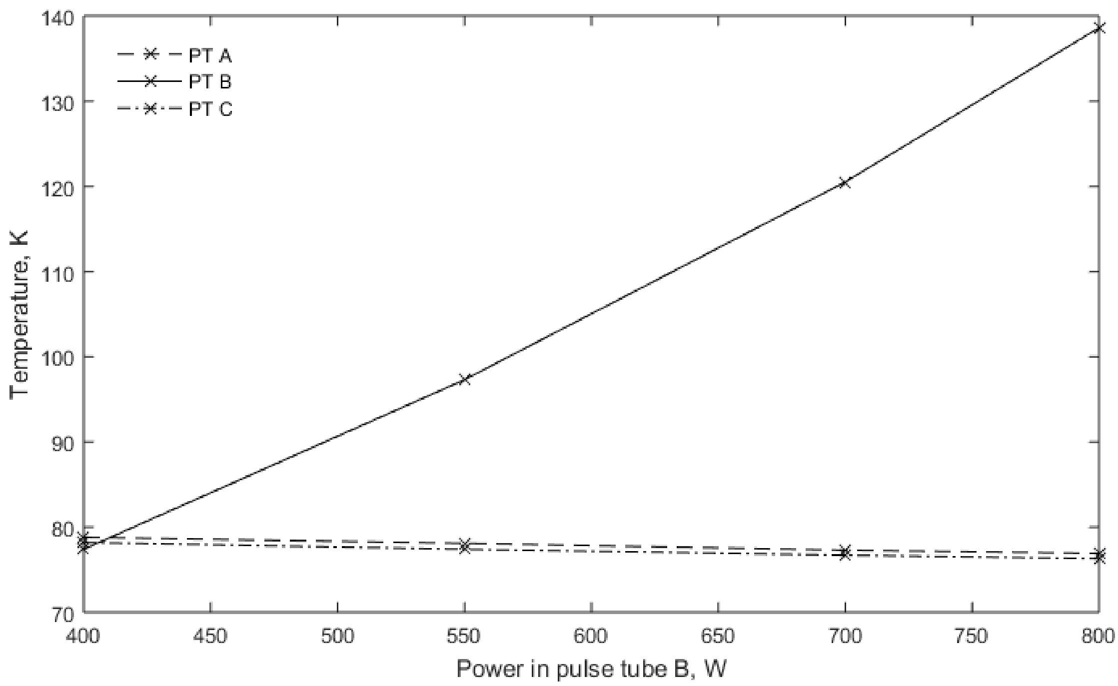

Figure 4: Power vs temperature curve when holding 400 W on each of pulse tubes A and C.

Figure 4 shows the individual pulse tube temperatures for different power levels applied to pulse tube B. The colder pulse tubes dropped slightly in temperature with the increased temperature of pulse tube B.

The pressure-volume phase angle (measured as the phase difference between the DPWG volume and the pressure wave in the DPWG) reduced with increasing temperature of pulse tube B from 31.5°, when all pulse tubes were at the same temperature, to 29.5° when at 138 K. In comparison, the pressure-volume phase angle with all the pulse tubes at 138 K was 23° (measured during cool-down). The motor power reduced slightly with increasing pulse tube B temperature which is consistent with a lower pressure–volume phase angle reducing the acoustic power in the DPWG.

The temperatures of all the pulse tubes remained very stable throughout the test.

4. Liquefaction rates with pre-cooling

The experiment showed that temperatures were stable and greater total cooling was achieved when operating one pulse tube at an elevated temperature. The next question was how does this relate to liquefaction rates?

Figure 5 shows the calculated liquefaction rate for different temperatures of the pulse tube using the experimental power for pulse tube B and assuming 400 W each for pulse tubes A and C. The gas only heat exchanger on pulse tube B is assumed to have a 2° difference between the pulse tube and exit gas. The calculation adjusts the mass flow of gas through the system to ensure all the gas is liquefied. Two situations occur.

The first situation, below 116 K, has the two colder pulse tubes at 77 K producing 800 W and capable of liquefying more gas than the warm pulse tube if it cools the full gas to the pulse tube's temperature. In this case the mass flow can be increased, with the gas exit temperature rising (keeping the pulse tube temperature and cooling power constant by increasing the temperature difference in the heat exchanger) until the liquefaction mass flow in pulse tubes A and C equals the gas cooling mass flow in pulse tube B.

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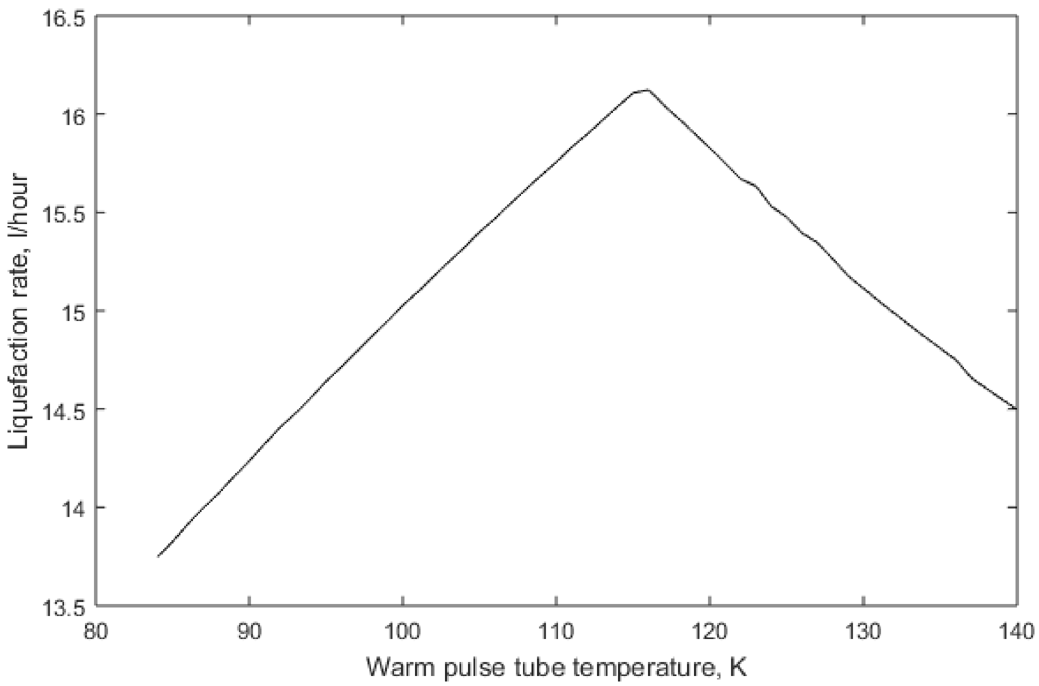

Figure 5: Calculated liquefaction rate for different temperatures of the warm pulse tube B. Note that the base line performance for a 1200 W cryocooler is 13 litres per hour.

The second situation, above 116 K, is when pulse tube B can cool more gas than can be liquefied. In this case, if the mass flow is decreased, then less work has to be done to cool the gas to saturation, leaving more cooling power for condensation. Unfortunately, the warm pulse tube cannot cool the gas below its operating temperature so the extra cooling power is not used on the gas and maintaining the pulse tube temperature would require a heater to stop the extra cooling from cooling the pulse tube.

Therefore, it is hypothesised that if the mass flow is driven by condensation, then this arrangement of pulse tubes will be a stable system, with the temperature of pulse tube B to close to 116 K and a liquefaction rate of 16 l/hour. When pulse tube B is too warm, it will have more cooling power than required to cool the mass flow of gas (driven by the condensation capacity) to its temperature so will cool itself down until the condensation capacity increases until it matches pulse tube B's cooling capacity. When pulse tube B is too cold, the condensation rate will pull more gas through pulse tube B than it can cool, which will warm it up.

The 116 K operating temperature of pulse tube B represents 673 W of cooling, bringing the total useful cooling of the cryocooler in the test from 1200 W to 1473 W. As the input power stayed almost constant, this increases the cryocooler efficiency as a liquefier by 23%.

The warm pulse tube would require a different heat exchanger design to ensure good heat transfer and achieve a low pressure drop when passing the whole mass flow of the liquefier as a gas.

5. Conclusion and discussion

The experiment showed that three pulse tubes running off a single DPWG will run stably with one of the pulse tube at an elevated temperature, resulting in an increased ability to cool gas from room temperature and liquefy it. Modelling of the gas cooling suggests that, when the warm gas flow is driven by condensation, a stable situation occurs where the system will find its own balance of pre-cooling. The stable temperature will be the optimal point for liquid production and is a function of the cooling curve for the pre-cooling pulse tube. For the PTC1000's three pulse tubes, the optimal operating temperature of the warmer pulse tube is 116 K and the pre-cooling is predicted to increase the liquefaction rate from 13 to 16 l/hour.

Testing in liquefaction mode means significant modifications to the heat exchangers. The current heat exchangers have been designed to cool and condense one third of the gas flow each. The pre-cooling heat exchanger will have to be optimised for cooling gas only and to do so with a low pressure drop as it will be passing three times as much gas as flow through it as it did previously. The two condensing heat exchangers will be condensing almost twice the amount each (than they did originally) and should also be optimised for the higher gas and liquid flow rates.

The stability of the pulse tubes when run at different temperatures creates other possibilities, such as running one pulse tube cooler, for sub-cooling liquid nitrogen in applications such as HTS transformers or cables, or multi-staging by using the pulse tubes to pre-cool each other to reach colder temperatures with higher efficiencies.

The next step is to design and construct a new set of heat exchangers which will be fitted to the cryocooler for a full liquefaction test.

Acknowledgements

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