Cryogenics 49(7): 371-375, 2009

Proposed designs for a “dry” dilution refrigerator with a 1K condenser

Matthew I. Hollister* and Adam L. Woodcraft
Institute for Astronomy, Royal Observatory, Blackford Hill, Edinburgh, EH9 3HJ, UK

Recent development of “dry” dilution refrigerators has used mechanical cryocoolers and Joule-Thomson expansion stages to cool and liquefy the circulating ^{3}He. While this approach has been highly successful, we propose three alternative designs that use independently-cooled condensers. In the first, the circulating helium is precooled by a mechanical cooler, and liquified by self-contained ^{4}He sorption coolers. In the second, the helium is liquefied by a closed-cycle, continuous flow ^{4}He refrigerator operating from a room temperature pump. Finally, the third scheme uses a separate ^{4}He Joule-Thomson stage to cool the ^{3}He condenser. The condensers in all these schemes are analogous to the “1-K pot” in a conventional dilution refrigerator. Such an approach would be advantageous in certain applications, such as instrumentation for astronomy and particle physics experiment, where a thermal stage at approximately 1 K would allow an alternative heat sink to the still for electronics and radiation shielding, or quantum computer research where a large number of coaxial cables must be heat sunk in the cryostat. Furthermore, the behaviour of such a refrigerator is simplified due to the separation of the condenser stage from the dilution circuit, removing the complex interaction between the 4-K, Joule-Thomson, still and mixing chamber stages found in current dry DR designs.

Keywords: Dilution (E), Pulse tube (E), Sorption coolers (E), Joule-Thomson coolers (E)

I. INTRODUCTION

Ultra-low temperature cryostats, such as dilution refrigerators (DRs), traditionally require the use of liquid helium baths to precool the circulating ^{3}He gas to 4K, followed by a pumped ^{4}He stage at ∼1K (the “1-K pot”) to condense the gas. The need to transfer liquid helium makes such refrigerators specialised systems requiring considerable experience to operate successfully. A considerable number of working hours are required to cool a cryostat to 4 K, while the cost of liquid helium to cool and maintain the temperature of large liquid cryostats may be an issue. A common cause of problems with conventional systems once operating is the pumped condenser stage, which, feeding from the main helium bath, is prone to blockages. In an effort to simplify the design of the DR, a system including a heat exchanger and Joule-Thomson expansion stage was developed (usually referred to as a Joule-Thomson (or JT) heat exchanger). The enthalpy of the ^{3}He gas pumped from the still is used to cool the incoming gas in a counterflow heat exchanger, followed by Joule-Thomson expansion through an impedance. The expansion cools the helium to 1–2 K at low pressure. The ^{3}He then liquifies in the still heat exchanger [1, 2].

Liquid cryogen-free, or “dry”, cryogenic systems have become prevalent in recent years. Such designs are typified by ease of operation over conventional liquid cryogen cryostats. Once the development of mechanical cryocoolers made coolers capable of reaching near-liquid helium temperatures readily available, it was a logical step that ultra-low temperature refrigerators such as the dilution refrigerator would be matched to these coolers to produce fully dry systems. Numerous examples of these dry refrigerators have been described, variously using Gifford-McMahon coolers [3], hybrid Gifford-McMahon/pulse tube coolers [4], and later two-stage pulse tube coolers [5]. Early GM-type cryocoolers generally did not reach base temperatures of 4 K; this was not a problem for the dry dilution refrigerator designs, since the JT stage would cool the instreaming gas below the inversion temperature in the counterflow exchanger. As cryocoolers with greater cooling power and base temperatures below 4K have become available, the practice of using the JT stage continued. More recently, development on improvements to the heat sinking of the incoming ^{3}He capillary by using the cooling power of the pulse tube regenerator [6] has allowed cryostats to be constructed with lower input temperatures at the JT stage, reducing the cooling demands on the expansion stage [7, 8]. Later development has removed the JT stage altogether [9].

There are disadvantages to the use of Joule-Thomson exchangers. Since the temperature at the output of the JT stage may be as high as 3 K, applications that require a thermal sink at ∼1 K are required to utilise the cooling power of the still, since there is no pumped ^{4}He stage. This is also true for newer cryostats without JT stages. Use of JT stages already places greater demands on the still cooling capacity than in a conventional DR in order to fully liquify the ^{3}He [2], and further loads due to the experiment may begin to degrade the performance of the mixing chamber. Furthermore, interaction between the JT and other tem-

---

*E-mail: matt.hollister@physics.org,
Tel: +44-131-6688375, Fax: +44-131-6688264

perature stages complicates the behaviour of the DR in comparison to refrigerators with separate condenser stages, where an unknown or varying heat load on the pumped ^{4}He stage has little effect on the operation of the dilution circuit. DRs using JT stages and cryocoolers operate with high condensing pressures during the early stages of circulation and condensation of the helium mixture. This often requires the inclusion of a compressor in the circuit. Operation in this way is contrary to the usual practice of keeping the condensing pressure below 1 atmosphere to avoid leaks out of the DR.

A specific example of an application requiring a ∼1 K stage is that of astronomical instruments operating detectors at milliKelvin temperatures, such as the SCUBA-2 camera [10]. This instrument uses a pulse tube DR to cool arrays of superconducting detectors to <100 mK, with amplifiers and a large radiation shield (approximately 100 kg mass), at ∼1 K cooled by the still (see Ref. [11] for details of the thermal design). The still of this dilution refrigerator runs at a temperature of ∼0.95 K, rather than ∼0.7 K as normally expected for a DR [12].

Future astronomical instruments of this type (for example, the shortwave camera for the Cornell-Caltech Attacama Telescope [13]) will place even greater demands on the 1K cooling capacity of cryostats. For such applications, it would be a considerable advantage to have a thermal stage at ∼1 K capable of condensing the circulating ^{3}He as well as providing a cooling sink for cold electronics and structures. This would isolate the still from the considerable external loading, allowing the circulation rate in the dilution circuit to be controlled by electrical heating.

The cooling power required at the condenser stage may be estimated from the heat capacity and latent heat of evaporation of ^{3}He. Taking the load on the condenser to be the power required to cool ^{3}He from ∼4 K to ∼1 K and condense the gas, the estimated condenser load as a function of the circulation rate of ^{3}He in the dilution circuit is shown in Fig. 1. In order to be useful for the application discussed, the condenser stage would need to be capable of providing 5–10 mW of capacity in addition to the cooling power required to condense the circulating ^{3}He. Also plotted are the maximum cooling powers of the DR mixing chamber at temperatures of 10, 25 and 100 mK, taking the maximum cooling capacity, $\dot{Q}_{max}$, to be [12]

$$\dot{Q}_{max} = 84\dot{n}_3 T_{mc}^2 \tag{1}$$

where $\dot{n}_3$ is the ^{3}He circulation rate and T_{mc} is the temperature of the mixing chamber.

To achieve this goal, but maintaining the dry design, we propose three DR designs with a 1-K condenser. The first concept uses closed-cycle ^{4}He sorb-pumped coolers. Such an approach is common to provide a condensation point in pumped ^{3}He refrigerators (e.g. [14]). As an alternative to this, the second scheme uses a continuously-operating ^{4}He refrigerator, with a room temperature pump circulating the gas. The third concept uses Joule-Thomson expansion of ^{4}He in a stage independent from the dilution circuit to cool the ^{3}He condenser. This paper outlines the three designs.

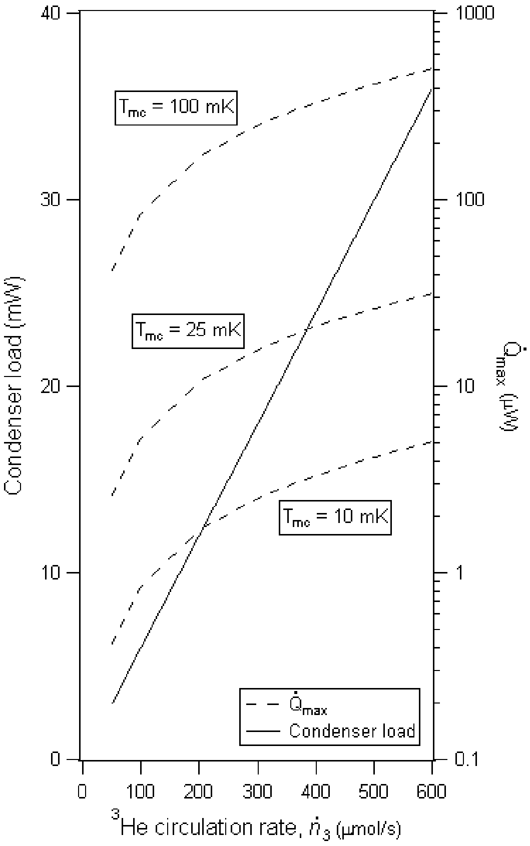

FIG. 1: Plot of the predicted load on the condenser due to the circulation of ^{3}He in the dilution circuit as a function of circulation rate, $\dot{n}_3$ (solid line). Also shown are the maximum cooling powers, $\dot{Q}_{max}$, as a function of ^{3}He circulation rate for mixing chamber temperatures of T_{mc}=10, 25 and 100 mK (broken lines).

II. SORPTION COOLED CONDENSER

A schematic of the proposed design is shown in Fig. 2. A pulse tube cooler precools the incoming ^{3}He gas to ≤4 K before the gas flows in to the condenser stage. The condenser is cooled to ∼1 K by a ^{4}He sorption cooler. Combining ^{4}He and ^{3}He sorption coolers to pulse tubes is an established concept, described previously by a number of authors

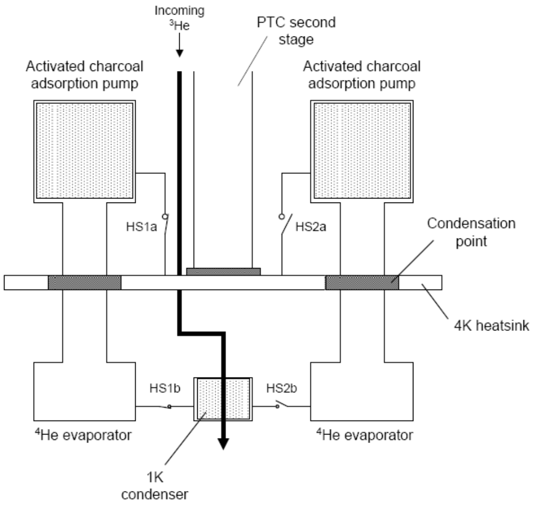

FIG. 2: Schematic of the proposed sorption cooled condenser scheme. For details, see text.

(e.g. Duband *et al.* [15].) Cryostats providing 0.3 or 1 K temperatures in this way are available commercially from several suppliers such as Janis [16] and Air Liquide [17].

In order to provide continuous cooling to the condenser, a second sorption cooler is used, such that one cooler may be recycled while the other is operating. The operating cooler is shorted to the condenser via a gas-gap heatswitch (HS1b in Fig. 2), while the recycling cooler is isolated by a similar switch in the off state (HS2b). Similarly, the charcoal pump of the operating cooler is connected to the second stage of the pulse tube cooler by a switch (HS1a), while the pump of the recycling cooler is isolated by opening the equivalent switch (HS2a). The recycling cooler uses the second stage of the pulse tube as a condensation point for the helium.

A conceptual cycle of the condenser stage could take the form of the following. Once one sorption cooler expends its liquid helium supply, the evaporator and the charcoal adsorption pump are isolated from the condenser and the 4 K plate respectively by opening the appropriate heatswitches (for example, HS1b and HS1a), while the second cooler takes the load by closing the equivalent heatswitches to maintain the condenser temperature. The exhausted cooler is then recycled. Once the other sorption cooler is expended and isolated, the heatswitch to the condenser (HS1b) is closed.

This scheme would require relatively large, high-power ^{4}He sorption fridges to be practical. A system using 1 mole of liquid ^{4}He would be capable of providing 10 mW of cooling power at 1 K for around 2.4 hours, and would require $\sim$ 100 g of charcoal in the sorption pump volume [18]. Assuming a condenser load of 30 mW (enough to support a ^{3}He circulation rate of 400 μmol/s with an additional 6 mW of background loading from the experiment) as an example, a hold time of 8 hours could be achieved with 10 moles of ^{4}He and 1 kg of charcoal. The size of the sorption coolers represents a potential limitation of this condenser approach.

III. PUMPED ^{4}HE CONDENSER

It has been demonstrated previously that helium may be liquified using a 4 K pulse tube cooler [19]. A condensation stage for a DR could therefore be provided by a continuously-operating ^{4}He refrigerator, fed from a closed-circuit reliquefaction system. A schematic of such a system is shown in Fig. 3. As before, the ^{3}He in the dilution circuit is cooled by the PTC second stage and the condenser, while ^{4}He is cooled and condensed in a separate circuit. The pressure of the liquid ^{4}He in the return line of the second circuit is reduced by pumping, cooling the condenser stage.

The estimated evaporation rate of ^{4}He (and therefore the minimum liquefaction rate) for DRs with circulation rates up to 600μMol/s is shown in Fig. 4. The evaporation estimate assumes that the available cooling power of the pumped ^{4}He stage is $\simeq 0.5\dot{n}_4 L$, where $\dot{n}_4$ is the evaporation rate and

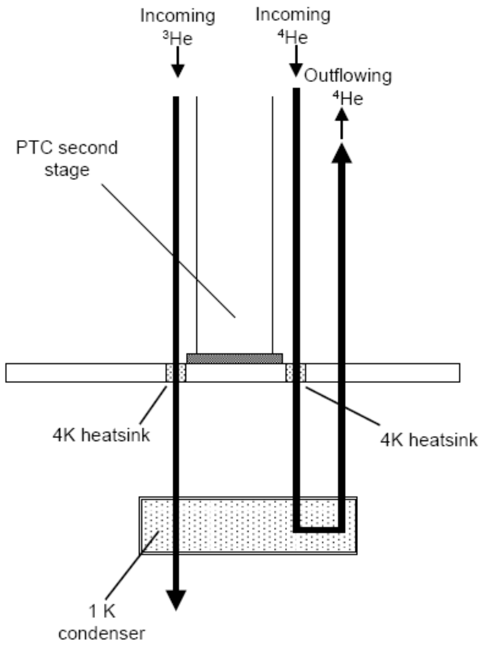

FIG. 3: Schematic of the proposed pumped ^{4}He cooled condenser scheme. For details, see text.

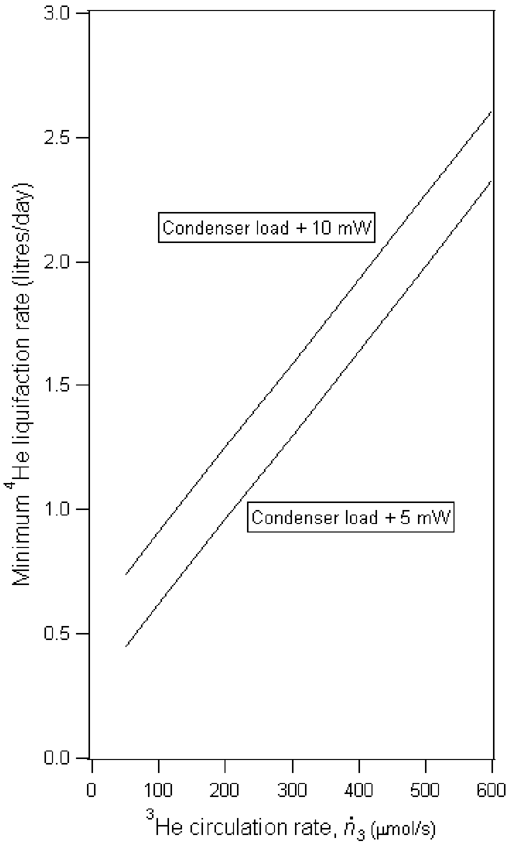

FIG. 4: Estimated evaporation rate of ^{4}He in litres per day as a function of ^{3}He circulation rate, $\dot{n}_3$ in the dilution circuit. Curves are shown for the predicted condenser load (see Fig. 1) with an additional 5 and 10 mW heat input.

L is the latent heat of of ^{4}He [12]. Evaporation rates are given assuming additional capacities of 5 mW and 10 mW. These liquefaction rates could easily be sustained. For example, Ref. [20] reports a liquefaction rate of 21.4 litres per day.

While this scheme potentially provides considerably more cooling power than the sorption-cooled condenser described above, there are disadvantages in that a continuous flow cooler would require a room temperature pump and plumbing, although this is no different from a conventional wet DR.

IV. INDEPENDENT JOULE-THOMSON CONDENSER

An alternative continuous flow condenser scheme employs a closed cycle Joule-Thomson circuit to cool the ^{3}He condenser. Using ^{4}He, such a circuit is capable of reaching temperatures <1.5 K. Such coolers are available commercially [21], and are capable of providing the necessary cooling power for this application. The system referenced operates the JT circuit with an open cycle, however a closed cycle JT expansion cooler may be produced with the inclusion of a suitable compressor and cold trap arrangement.

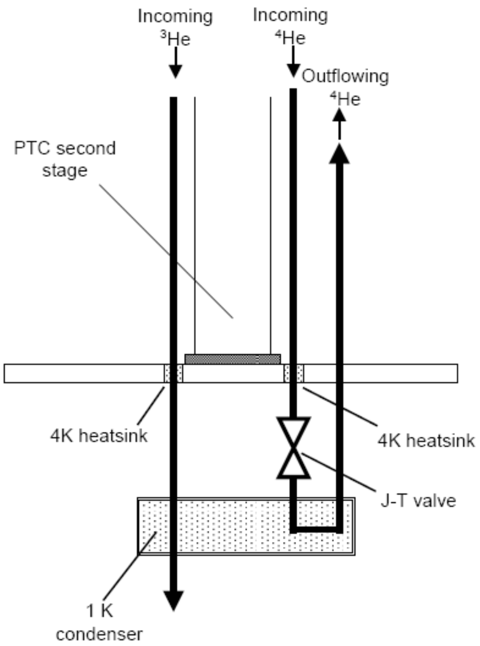

FIG. 5: Schematic of the proposed Joule-Thomson expansion cooled condenser scheme. For details, see text.

A schematic for this scheme is shown in Fig. 5. The approach is similar to the pumped ^{4}He condenser described above, but in this case a J-T valve is included on the input side of the ^{4}He circuit.

V. CONCLUSIONS

We have described the concept of three alternative schemes for the construction of the condenser stage of a dry dilution refrigerator, based either on ^{4}He adsorption coolers or a continuous flow cooler operating from room temperature, in place of the expansion stages used in current designs. Such designs would be advantageous for applications, such as astronomical instruments, that require a ∼1K thermal stage for heatsinking electronics, optical components and large cold structures, as an alternative to relying on the cooling capacity of the still. The use of self-contained sorption coolers has an advantage over the continuous flow schemes in that no additional room temperature pumps are required and there are no impedances in the condenser stage to plug. The disadvantage of the sorption scheme is that it requires two separate coolers and heat switch systems to provide continuous operation. Furthermore, continuous flow schemes potentially offer more cooling power, as would be required for large, high-flow rate dilution refrigerators. All schemes have further advantages in that the operation of the DR is simplified by separation of the condenser stage from the dilution circuit, removing the complex thermodynamics associated with conventional dry designs using a Joule-Thomson expansion stage.

Many current dry DR designs are able to support high ^{3}He flow rates using small PTCs providing 0.5 W at 4 K on the second stage, although some designs (e.g. those of Leiden Cryogenics [22]) use larger pulse tubes (1–1.5 W at 4 K) as standard. Given the need of the designs discussed here to cool and condense circulating ^{4}He for the 1-K stage, it is likely that a larger PTC would be required. The demands on the second stage of the PTC would be minimised by utilising the heat exchanger designs for the pulse tube discussed in Refs. [6, 9].

Although an alternative approach would be to combine a readily-available dry DR with an independent 1 K cooling system for radiation shielding and wiring, this may not be a practical solution for all applications. The dilution refrigerator designs described herein have an advantage of simplicity in that both cooling stages are combined within a single system.

Acknowledgments

The authors would like to thank Simon Chase of Chase Cryogenics for useful information regarding the design of ^{4}He sorption refrigerators.

MIH is supported by a Research Studentship from the UK Science and Technology Facilities Council.

[1] J. Kraus, “New condensation stage for a He^3–He^4 dilution refrigerator,” *Cryogenics*, vol. 17, pp. 173–175, Mar. 1977.

[2] K. Uhlig, “^{3}He/^{4}He dilution refrigerator without a pumped ^{4}He stage,” *Cryogenics*, vol. 27, pp. 454–457, Aug. 1987.

[3] K. Uhlig and W. Hehn, “^{3}He/^{4}He dilution refrigerator with Gifford-McMahon precooling,” *Cryogenics*, vol. 33, pp. 1028–1031, Nov. 1993.

[4] Y. Koike, Y. Morii, T. Igarashi, M. Kubota, Y. Hiresaki, and K. Tanida, “A dilution refrigerator using the pulse tube and GM hybrid cryocooler for neutron scattering,” *Cryogenics*, vol. 39, pp. 579–583, Nov. 1999.

[5] K. Uhlig, ““Dry” dilution refrigerator with pulse-tube precooling,” *Cryogenics*, vol. 44, pp. 53–57, Jan. 2004.

[6] A. Ravex, T. Trollier, J. Tanchon, and T. Prouvé, “Free third-stage colling for two-stage 4 K pulse tube coolers,” in *Cryocoolers 14*, Proceedings of the International Cryocooler Conference, pp. 157–161, June 2006.

[7] T. Prouvé, H. Godfrin, C. Gianése, S. Triqueneaux, and A. Ravex, “Pulse-Tube Dilution Refrigeration below 10 mK for Astrophysics,” *Journal of Low Temperature Physics*, vol. 151, pp. 640–644, May 2008.

[8] K. Uhlig, “Condensation stage of a pulse tube precooled dilution refrigerator,” *Cryogenics*, vol. 48, pp. 138–141, Mar. 2008.

[9] K. Uhlig, “^{3}He/^{4}He dilution refrigerator with high cooling capacity and direct pulse tube precooling,” *Cryogenics*, vol. 48, pp. 511–514, Nov. 2008.

[10] W. Holland, M. MacIntosh, A. Fairley, D. Kelly, D. Montgomery, D. Gostick, E. Atad-Ettedgui, M. Ellis, I. Robson, M. Hollister, A. Woodcraft, P. Ade, I. Walker, K. Irwin, G. Hilton, W. Duncan, C. Reintsema, A. Walton, W. Parkes, C. Dunare, M. Fich, J. Kycia, M. Halpern, D. Scott, A. Gibb, J. Molnar, E. Chapin, D. Bintley, S. Craig, T. Chylek, T. Jenness, F. Economou, and G. Davis, “SCUBA-2: a 10,000-pixel submillimeter camera for the James Clerk Maxwell Telescope,” in *Millimeter and Submillimeter Detectors and Instrumentation for Astronomy III.*, vol. 6275 of *Proceedings of the SPIE*, p. 62751E, July 2006.

[11] A. L. Woodcraft, F. C. Gannaway, D. C. Gostick, and D. Bintley, “Thermal design of the SCUBA-2 instrument detector stage and enclosure,” in *Astronomical Structures and Mechanisms Technology.* (J. Antebi and D. Lemke, eds.), vol. 5498 of *Proceedings of the SPIE*, pp. 446–454, Oct. 2004.

[12] F. Pobell, *Matter and Methods at Low Temperatures.* Springer-Verlag, third ed., 2007.

[13] G. J. Stacey, S. R. Golwala, C. M. Bradford, C. D. Dowell, G. Cortes-Medellin, T. Nikola, J. Zmuidzinas, T. L. Herter, S. J. Radford, J. P. Lloyd, A. W. Blain, R. L. Brown, D. B. Campbell, R. Giovanelli, P. Goldsmith, P. M. Harvey, C. Henderson, W. D. Langer, T. G. Phillips, A. C. S. Readhead, and D. P. Woody, “Instrumentation for the CCAT Telescope,” in *Millimeter and Submillimeter Detectors and Instrumentation for Astronomy III.*, vol. 6275 of *Proceedings of the SPIE*, p. 62751G, July 2006.

[14] M. J. Devlin, S. R. Dicker, J. Klein, and M. P. Supanich, “A high capacity completely closed-cycle 250 mK ^{3}He refrigeration system based on a pulse tube cooler,” *Cryogenics*, vol. 44, pp. 611–616, Sept. 2004.

[15] L. Duband, L. Clerc, and A. Ravex, “Socool: A 300 K-0.3 K pulse tube/sorption cooler,” in *Advances in Cryogenic Engineering CEC* (S. Breon,

M. Dipirro, D. Glaister, J. Hull, P. Kittel, V. R. R. Pecharsky, J. Theilacker, S. van Sciver, J. I. Weisend, and A. Zeller, eds.), vol. 613 of *American Institute of Physics Conference Series*, pp. 1233–1240, May 2002.

[16] Janis Research Company, Inc., 2 Jewel Drive, P.O. Box 696 Wilmington, MA 01887-0696, USA (http://www.janis.com).

[17] Air Liquide Advanced Technologies, 2, Rue de Clémencière, BP 15, 38360 Sassenage, France (http://www.dta.airliquide.com).

[18] S. Chase. Personal communication.

[19] C. Wang, "Helium liquefaction with a 4 K pulse tube cryocooler," *Cryogenics*, vol. 41, pp. 491–496, July 2001.

[20] C. Wang and R. G. Scurlock, "Improvements in performance of cryocoolers as condensers," *Cryogenics*, vol. 48, pp. 169–171, Mar. 2008.

[21] Advanced Research Systems, Inc., 7476 Industrial Park Way, Macungie, PA 18062, USA (http://www.arscryo.com).

[22] Leiden Cryogenics B.V. Galgewater no.21, 2311 VZ Leiden, The Netherlands (http://www.leidencryogenics.com).