STATUS: LARGE-SCALE SUBATMOSPHERIC CRYOGENIC SYSTEMS

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Abstract

In the late 1960's and early 1970's an interest in testing and operating RF cavities at 1.8K motivated the development and construction of four large (300 Watt) 1.8K refrigeration systems. In the past decade, development of successful superconducting RF cavities and interest in obtaining higher magnetic fields with the improved Niobium-Titanium superconductors has once again created interest in large-scale 1.8K refrigeration systems. The L'Air Liquide plant for Tore Supra is a recently commissioned 300 Watt 1.8K system which incorporates new technology, cold compressors, to obtain the low vapor pressure for low temperature cooling. CEBAF proposes to use cold compressors to obtain 5KW at 2.0K. Magnetic refrigerators of 10 Watt capacity or higher at 1.8K are now being developed. The state of the art of large-scale refrigeration in the range under 4K will be reviewed.

Introduction

The development of the Cornell/CEBAF cavity, operating at 2 Kelvin, and of 10 Tesla magnets operating at 1.8K for CERN's proposed Large Hadron Collider (LHC) are examples of recent interest in pursuing sub-4 Kelvin temperatures for optimal performance of RF cavities and magnets. The successful operation of the toroidal magnets for Tore Supra at 1.8K is a recent demonstration of the technology for reliably attaining such low temperatures on a large scale. This paper describes the status of the technology for obtaining high cooling powers at sub- 4 Kelvin temperatures.

I have chosen 300 Watts of cooling at the sub- 4 Kelvin temperature as the cutoff for "large-scale" refrigeration for helium gas cycles. This allows the inclusion of the four 300 Watt, 1.8 Kelvin machines that were built in the late 1960's and early 1970's, and the 300 Watt Tore Supra refrigerator, while excluding the many smaller 1.8K systems, for example, for the laboratory testing of very high field magnets.

For high cooling powers at temperatures below 4.2 Kelvin one generally thinks of pumping the helium vapor from a helium bath. And for obtaining cooling powers of more than 10 Watts at less than 4.2K this is the only option presently available. However, several groups are doing research and development work with the goal of demonstrating adiabatic demagnetization refrigerators (magnetic refrigerators) operating between 4.5K and 1.8K with cooling powers at 1.8K of 10 Watts or more. The most cooling power reported so far is around one Watt. Even 10 Watts would still not satisfy my criterion of 300W of cooling power to qualify as "large-scale", but it would be sufficiently large to supply cooling for individual accelerator components, such as low-beta quadrupoles. This is large-scale for magnetic refrigeration, and so deserves mention here. Magnetic refrigerators have the advantage of lacking subatmospheric components in the helium circuit, hence the risk of contaminating the helium due to air leaking in is greatly reduced. Reference [1] is a recent, thorough review of the status of magnetic refrigeration.

History

In the late 1960's and early 1970's there was interest in having large-scale cooling at 1.8K for superconducting RF cavities. People have thought of the possibility of superconducting RF cavities since at least the 1940's [2], but the earliest paper I found which specifically mentions a heat load at 2 Kelvin is by H.A. Schwettman, et.al, [3], who at the 1964 Cryogenic Engineering Conference described an application for a linear accelerator which would require 1.2 KW at 2K. This is a bold proposal when one considers that at that time the largest 4.5K refrigerator was of about that cooling power.

In 1967 a refrigerator removing 300 Watts at 1.85 Kelvin was ordered from the Arthur D. Little Co. for work on a superconducting linac at Stanford [2]. Appropriately, Samuel Collins, one of the great innovators in cryogenic engineering, was a designer of this plant [4,5]. In Europe similar efforts were underway; a 30 Watt, 1.8K refrigerator was completed in 1967 [6]. By 1976 three more plants, each producing 300W at 1.8K, were in operation (Table 1). These were all for the support of superconducting RF work.

Table 1

Early 300 Watt, 1.8K Refrigertors

Year	Manufacturer	Customer	References
1967	Arthur D. Little Co.	Stanford	[4,5]
1970	Linde AG	Karlsruhe	[7,8]
1972	Messer-Griesheim	Karlsruhe	[9]
1976	BOC	CERN	[10]

All four of these plants obtained the low temperature bath by pumping on its vapor with many large room-temperature vacuum pumps in series. The low pressure vapor was warmed before reaching the vacuum pumps by counterflow heat exchange with compressed helium (Figure 1). Vapor from a 1.8K bath would be at about .016 atmospheres (12 Torr). Such low pressure gas has very low density when warmed to about 270K, resulting in the requirement of very large pipes to avoid excessive pressure drops upstream of the vacuum pumps (Figure 2). A 1 KW plant, which could have a 4-inch diameter warm suction pipe for 4.5K operation, would need a 36-inch diameter pipe for 1.8K operation. Of course, the heat exchangers become huge, also.

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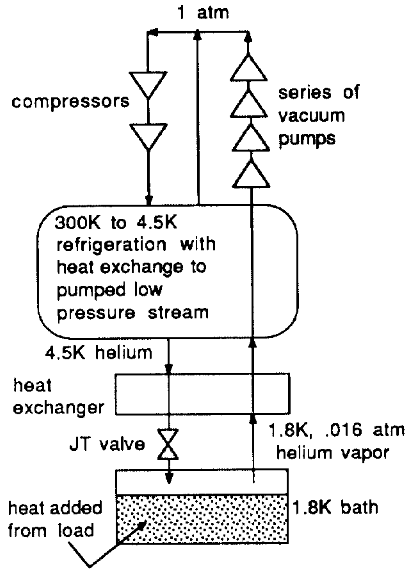

Fig. 1 Simplified flow schematic for a large, 1.8K refrigerator with room-temperature vacuum pumps.

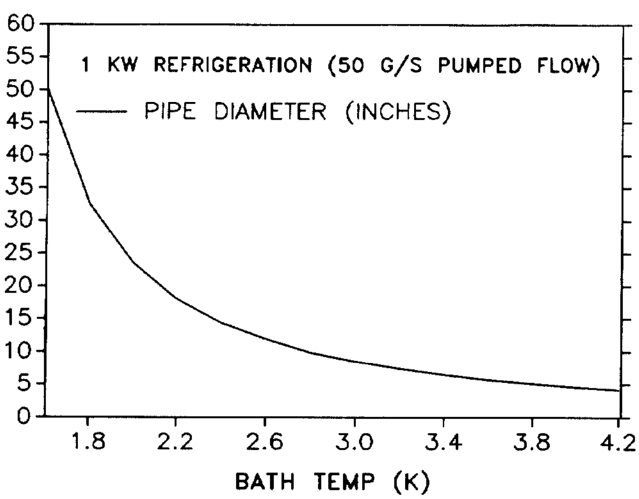

Fig. 2 Warm pumped flow pipe size versus bath temperature.

A solution which is perhaps obvious in principle but was not practical at the time these four large 1.8K plants were built is to pump the helium vapor to a higher pressure at a lower temperature, where its density is greater and volume flow rates correspondingly lower [8]. This possibility has now been realized in practice, and allows the construction of much larger sub- 4 Kelvin refrigerators than would otherwise be practical.

Recent Large Sub- 4 Kelvin Refrigerators

Two helium refrigerators of at least 300 Watts capacity below 4K have been built since the four described above, a third is now under construction, and others have been proposed recently. The three existing or under construction (Table 2) all incorporate cold compressors for pumping on the lowest temperature helium bath.

Table 2

Modern Refrigerators with More Than 300 Watts Cooling Power at less than 4K

Manufacturer	Customer	Capacity	Status
Koch Process Systems (with Rotoflow)	Brookhaven/ Isabelle	13.7KW at 2.6 - 4.2K	Tested, not operating
L'Air Liquide	Euratom CEA in Cadarache, France	300W at 1.75K	Operating
CVI (with L'Air Liquide)	CEBAF	4.8KW at 2.0K	Construction

The Isabelle helium refrigerator at Brookhaven National Lab [11,12] is not only the largest in the world in terms of cooling power below 5K but also the first large plant to utilize cold compressors as an integral part of its cycle design. Its capacity is 13.7 KW in the range 2.6K to 4.2K. There are no warm vacuum pumps in the helium cycle, and four stages of cold compression. The four wheels for the four stages of centrifugal cold compression are on a single shaft, a Rotoflow design [13]. Unfortunately for the world of cryogenics, due to the cancellation of Isabelle this plant has only operated briefly.

The Tore Supra refrigerator, built by L'Air Liquide for Euratom-CEA in Cadarache in southeast France provides 300 Watts of cooling at 1.75K. [14,15,16] It has been operational since April, 1988, and provides us with our only recent operational information about a large, modern, low-temperature refrigerator [17]. It is a demonstration of the state-of-the art of large-scale sub- 4K refrigeration, and as such is the prototype for the next generation of even larger plants such as the CEBAF refrigerator. Therefore even though the design has been presented several times in the cryogenics literature. I will briefly review its unique features and operational history.

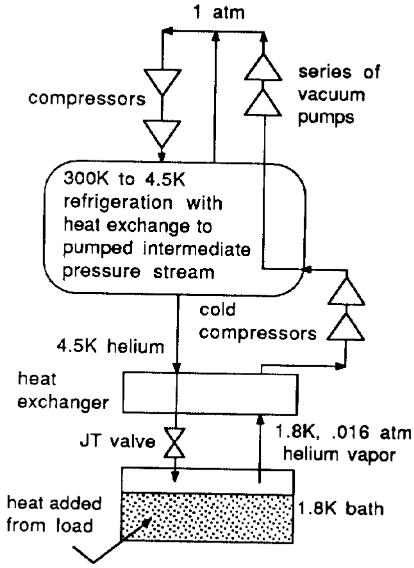

Fig. 3 Simplified flow schematic for combined cold and warm vacuum pumping for a large, 1.8K refrigerator like Tore Supra.

Figure 3 is a simplified flow schematic illustrating how the low pressure vapor is pumped away from the low temperature helium bath. Two stages of cold compressors (two separate machines) pump 14 grams per second of helium vapor from about 4K, 13 mbar, to about 15K 80 mbar. After this flow is warmed to room temperature by counterflow heat exchange with incoming high-pressure helium, it is pumped to atmospheric pressure by two stages of liquid ring pumps.

The cold compressors [18] are centrifugal-type machines, with each stage driven by an electric motor at 80K. The first stage has a 12 cm diameter wheel rotating at about 25000 RPM, the second an 8 cm diameter wheel operating at about 40000 RPM. The isentropic efficiency is 0.57 for each stage. The shaft carrying the motor rotor and impeller rides on actively controlled magnetic bearings, which eliminate low-temperature contact between moving parts and the associated problem of low-temperature lubrication, provide a stiff support against pressure upsets, and allow adjustment of clearances.

Operationally the Tore Supra refrigerator has experienced a few problems, but not with the cold compressors or the 1.8K portion of the system [17]. The most feared consequence of running a cryogenic system subatmospheric, an air inleak, has occured twice in the first year of operation of Tore Supra. Once there was a failure of a tube connecting a pressure gauge to a normally subatmospheric part of the system, and the oxygen detector simultaneously was not working, so the air inleak was not detected before major contamination of the system with air occured. This is the only reported air inleak to the normally subatmospheric parts of the system. Dual oxygen analysers are now on line. The other air inleak was of the type that makes operators of positive-pressure cryogenic systems wary of ever going subatmospheric. A normally positive-pressure part of the system went subatmospheric simultaneously with a failure of the pressure gauge, and an electrical feedthrough leaked.

Precautions against contamination of the low-temperature sections of the refrigerator with air include dual 80K activated charcoal adsorbers and a 20K single activated charcoal adsorber. Dual seals with helium gas collection from between them are used throughout the system where helium is sealed from air at valve stems.

In conclusion regarding the Tore Supra, the automatic operation, 1.8K parts of the system, and cold compressors have all been most successful. Efficiencies of the various components of Tore Supra have met design. The overall refrigerator efficiency has exceeded its design value of 0.14 of carnot [19], which would be 1200 Watts consumed per 1.8K Watt absorbed.

The 4.8KW, 2.0K CEBAF cryogenic system [20] is under construction now. It utilizes four stages of cold compression to pump the 238 g/s of flow from 0.03 atm to 1.15 atm [19]. There is no cooling between stages of cold compression, so the temperature goes from 3.3K at the inlet of the first stage to an estimated 26.5K at the discharge of the fourth stage. There is no warm subatmospheric section in the process stream. Figure 4 is a simplified schematic of a similiar arrangement for 1.8K. CVI Corporation, in Columbus, Ohio, is providing the CEBAF refrigerator in collaboration with L'Air Liquide, which is, among other things, providing the cold compressors. This refrigerator takes the cold compressor technology developed for Tore Supra and scales it up in flow and power by more than an order of magnitude.

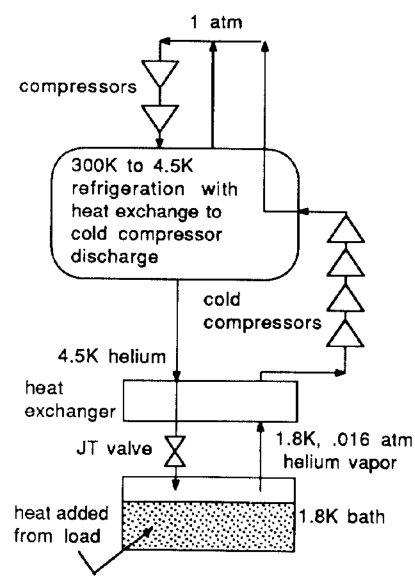

Fig. 4 Simplified flow schematic for a large, 1.8K refrigerator with only cold compressors, no room-temperature subatmospheric lines, an arrangement like CEBAF and (very simplied) Isabelle.

The Choice of Temperature

Helium II (superfluid) exists below 2.17K. A technical reason why 1.8K is often chosen as the operational temperature for stagnant superfluid systems is that the apparent thermal conductivity of helium II is a maximum at 1.9K [21]. Nevertheless, the decision of what temperature to operate a superconducting magnet or RF system at depends at least in part, and probably entirely in the case of large systems, on the overall system cost as a function of temperature. CEBAF provides us with a good, recent example of cost optimization as a function of operating temperature. Capital costs and operating costs for helium refrigeration vary as 1/T for a given low temperature cooling power [22]. In the case of CEBAF, a superconducting RF system, temperature-dependent losses in the RF cavities drive the optimum temperature down to about 2.0K.

A magnet cost optimization by W. Hassenzahl [23], while somewhat out of date regarding costs and technology, illustrates the method for magnet systems. This report estimates that a 1.8K system costs 2.5 times a 4.2K system and that operating costs scale a little faster than 1/T. His result was that for fields of more than 7 Tesla temperatures of 1.8K are more cost-effective than 4.2K

The Future

Many proposals for large low-temperature systems have been made within the past few years. The LHC at CERN would include about 16 miles of 1.8K magnets. The refrigeration required is estimated to be 1360W at 1.8K for each of the eight octants [24]. Superconducting Magnetic Energy Storage proposals have placed huge superconducting coils at 1.8K. One report mentions needing 10 million liters of He II for a 5500 MWh SMES [25]. Both LHC and SMES will certainly require the use of cold compressors like those developed for Tore Supra and CEBAF to pump helium vapor from a low pressure, low temperature helium bath.

Fermilab has two completely different possible atmospheric upgrades as methods of increasing magnetic fields and allowing higher beam energy. The first, for which tests are now in progress, is to lower the pressure of the two-phase helium stream in the Tevatron to 0.8 atm by means of cold compressors added to the satellite refrigerators [26]. These cold compressors are quite different from those discussed above in that the relatively high inlet pressure of nearly one atmosphere results in a much lower volume flow rate, dictating a different kind of machine. This upgrade could increase Tevatron beam energy from 900 GeV to 1000 GeV.

A more extensive upgrade, to about 1.8 TeV per beam, is possible with new magnets operating at around 2K [27]. A conceptual design for upgrading the Tevatron cryogenic system for cooling magnets to around 2K has been developed [28] which would utilize room-temperature pumping through heat exchangers.

Conclusion

The only method presently available for obtaining more than a few Watts of cooling power at temperatures less than 4.2K is to lower the pressure of liquid helium to less than atmospheric pressure. Continuous pumping is required since the helium continuously boils away in proportion to the heat being removed from the load. The temperature attained in the bath is the temperature of helium liquid boiling at that pressure. Magnetic refrigerators show some promise of removing this necessity to run subatmospheric, but are presently limited to at most a few Watts of cooling power at 1.8K.

The pumps in recent large low temperature systems for Isabelle, Tore Supra, and CEBAF are at least partly at low temperature. Cold compressors have been developed for cycles with more than 100 Watts added at the low temperature (more than 5 g/s pumped flow). For helium refrigeration of less than 100 Watts at around 2K, room temperature pumping through low pressure heat exchangers or even just through heaters is generally the choice. From 100 Watts to around 300 Watts at around 2K one may have a choice of cold compressors or room temperature pumping as in the four first 300 Watt 1.8K systems. Above about 300 W at 2K at least the first stage of pumping will probably best be cold, and for very large systems all the pumping may most economically be cold. Power lead flow and liquid storage are at 4.5K in all the large low temperature plants so far.

The efficiency relative to carnot of large 1.8K helium refrigerators can be expected to be between 0.15 and 0.20, slightly lower than what has been attained in recent 4.5K plants. But the operating and capital costs can be assumed to scale with 1/T. Generally, most of the heat load can be intercepted at 4.5K or some other intermediate temperature, so even large low-temperature systems may predominantly provide cooling at 4.5K with some fraction of that flow diverted to be further cooled.

Tore Supra has demonstrated the technology of reliably obtaining large cooling powers at 1.8K, and CEBAF is about to demonstrate that technology scaled up an order of magnitude, for kilowatts of cooling at superfluid temperatures.

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References

[1] John A. Barclay, "Magnetic Refrigeration: A Review of a Developing Technology", in Advances in Cryogenic Engineering, Vol. 33, 1988, pp. 719-731.

[2] W.M. Faribank, "Superconducting Linac", ICEC 1, 1967, pp.1-4.

[3] H.A. Schwettman, P.B. Wilson, J.M. Pierce, and W.M. Fairbank, "The Application of Superconductivity to Electron Linear Accelerator", in International Advances in Cryogenic Engineering, Vol. 10B, 1965, pp. 88-97.

[4] S.C. Collins, and M.H. Streater, "Refrigerator for 1.8K, ICEC 1, 1967, pp. 215-217.

[5] S.C. Collins, R.W. Stuart, and M.H. Streeter, "Closed-Cycle Refrigeration at 1.85K", The Reviews of Scientific Instruments, Vol. 38, Number 11, pp. 1654-1657, November 1967.

[6] W. Baldus and A. Sellmaier, "A Continuous Helium II Refrigerator", Advances in Cryogenic Engineering, Vol. 13, 1967, pp. 434-440.

[7] A. Sellmaier, R. Glatthaar, and E. Kliem, "Helium Refrigerator with a Capacity of 300 W at 1.8K, "ICEC 3, Berlin, 1970, pp.310-314.

[8] W. Baldus, "Helium II Refrigerator for 300 W at 1.8", Advances in Cryogenics Engineering, Vol. 16, 1971, pp. 163-170.

[9] W. Daus and R. Ewald, "A Refrigeration Plant with 300 W Capacity at 1.8K", Cryogenics, Vol. 15, pp. 591-598, October 1975.

[10] A.J. Steel, S. Bruzzi, and M.E. Clarke, "A 300W 1.8K Refrigerator and Distribution System for the CERN Superconducting RF Particle Separator", ICEC 6, Grenoble, 1976, pp. 58-61.

[11] D.P. Brown, et.al, "Design of 24.8 kW, 3.8K Cryogenic System for Isabelle, "in Advances in Cryogenic Engineering", Vol. 27, 1982, pp. 509-516.

[12] D.P. Brown, A.P. Schlafke, and K.C. Wu, and R.W. Moore, "Cycle Design for the Isabelle Helium Refrigerator", in Advances in Cryogenic Engineering", Vol. 27, 1982, pp. 501-508.

[13] D.P. Brown, et.al., "Operating Experiences and Tests Results of Six Cold Helium Compressors", in Advances in Cryogenic Engineering, Vol. 33, 1988, pp. 663-674.

[14] G. Claudet, G. Bon Mardion, B. Jager and G. Gistau, "Design of the Cryogenic System for the Tore Supra Tokamak", Cryogenics, Vol. 26, pp. 443-449, August/September 1986.

[15] Guy M. Gistau, Michel Bonneton, and John W. Mart, "The Tore Supra 300 W - 1.75K Refrigerator Report", in Advances in Cryogenic Engineering, Vol. 33, 1988, pp. 591-597.

[16] Guy M. Gistau and Gerard Claudet, "The Tore Supra 300 W - 1.75K Refrigerator", in Advances in Cryogenic Engineering, Vol. 31, 1986, pp. 607-615.

[17] G. Bon Mardion, et.al., "Initial Operation of the 1.8K Tore Supra Cryogenic System", ICEC 12, 1988, pp. 511-518.

[18] Guy M. Gistau, Yves Pecoud, and Alain E. Ravex, "The 300 W - 1.75K Tore Supra Refrigerator Cold Centrifugal Compressors Report", in Advance in Cryogenic Engineering", Vol. 33, 1988, pp. 675-681.

[19] Guy Gistau, private communication, February 1989.

[20] C. Rode, et.al., "CEBAF Cryogenic Systems", presented at this conference.

[21] G.Bon Mardion, G. Claudet and Peter Seyfert, "Practical Data on Steady State Heat Transport in Superfluid Helium at Atmospheric Pressure", Cryogenics, Vol. 19, pp. 45-47, January, 1979.

[22] C.H. Rode and D. Proch, "Cryogenic Optimization for Cavity Systems", presented at this conference.

[23] W. Hassenzahl, "A Comparison of the Costs of Superconducting Accelerator Dipoles using NBTi, NB_3Sn, and NBTiTa", in IEEE Trans. Nucl. Sci, Vol. N5-28, pp. 3277-3279, June 1981.

[24] G. Claudet, et.al., "Conceptual Study of the Superfluid Helium Cryogenic System for the CERN Large Hadron Collider (LHC)", ICEC 12, 1988. pp. 497-504.

[25] R.W. Boom, et.al., "Two-layer Non-rippled, Superconductive Magnetic Energy Storage Systems", ICEC 11, 1986, pp. 464-468.

[26] T.J. Peterson and J.D. Fuerst, "Tests of Cold Helium Compressors at Fermilab", in Advances in Cryogenic Engineering, Vol. 33, 1988, pp. 655-662.

[27] S.D. Holmes, et.al., "Upgrading the Fermilab Tevatron", presented at this conference.

[28] T.J. Peterson and Jay C. Theilacker, "Cryogenics for a Tevatron Energy Upgrade", presented at the 1988 Summer Study on High Energy Physics in the 1990's at Snowmass, Colorado, June 27-July 15, 1988.