SLAC TN 73-14
Fred Hall
December 1973
Revised March 1974

CRYOGENIC REFRIGERATORS USING NEON AS REFRIGERANT

Possibility of using neon to refrigerate magnets to cryogenic temperatures to reduce electrical resistance losses has been raised (1).

Practicality of economic gain in region of cryogenic, non-superconductive cooling has been questioned (2).

Neon as a Refrigerant

High pressure stream must be at least at 30 atmas (3) to achieve reasonable yields of LNe. Low pressure stream should be 1.5 atma to retain a positive pressure at compressor suction. Neon at 30 atmas can be chilled below critical point to about 36°K as a gas. If then passed through a pressure reducing valve (PRV) to 1.5 atmas, liquid yield will be close to 81%. Boil-off from an evaporator should remove about 1332 J/Mol at 29°K. Three heat exchangers would be needed with a single expansion engine by-passing middle heat exchanger. Compressor/evaporator flow ratio is 2.6 to 1.0. Compressor would have two stages, each with a pressure ratio of 5.5. Entrained compressor lube oil must be completely stripped using a 4-stage removal system.

Nature of Load

At 300°K a magnet of size might draw 3.6 MW of power. Its water-cooled coils might be of Al or Cu. Operation at 29°K should reduce I^2R losses by factor of 25 for Al coils and 100 for Cu coils (4). Heat leakage from 300°K to 80°K and below approximates heat leakage from 300°K to 0°K and should be no more than 75W for a cryomagnet application having aluminized mylar wrapped internals contained in a vacuum tank. Electrical losses at 29°K will be much greater than heat leakage and latter may be disregarded.

Description of Cycle

Published neon thermodynamic data are used (5). High pressure neon points of interest are (1) gas supply at 300°K, 7548 J/Mol, (2) gas from warm end exchanger to expansion engine intake or intermediate heat exchanger at 92°K, 3068 J/Mol, (3) gas from intermediate heat exchanger and to cold ent heat exchanger at 42°K, 807 J/Mol, and (4) gas from cold end heat exchanger to PRV at 36°K, 505 J/Mol. Low pressure neon points of interest are (1) fluids from PRV to evaporator at 29°K, 505 J/Mol, (2) LNe in evaporator at 29°K, 202 J/Mol, (3) vapor from evaporator at 29°K, 1837 J/Mol, (4) vapor from cold end heat exchanger and exhaust from expansion engine at 41.5°K, 2139 J/Mol, (5) cold gas from intermediate heat exchanger at 82°K, 3007 J/Mol, and (6) return gas to compressor suction at 297°K, 7488 J/Mol and just over 1.0 atma.

Magnitude of Load

Assuming Cu coils a 3.6 MW ambient operation, type magnet designed to operate at 29°K would require only 36 KW power input. At 29°K this is a staggering refrigeration load. One W is 1 J/S. Up to 36,000 J/S would have to be continuously removed. Up to 70.2 Mol/S neon mass flow would be needed. This is 1417 g/s, or 1898 #/min, or 3744 SCFM. Cp/Cv for neon is 1.64 which is very close to that of helium, so an n value of 1.4 can be used. P_2/P_1 per stage would be 5.5. $[(P_2/P_1)^{\frac{n-1}{n}} - 1]$ would be 0.628. BHP/CFM would be 2x1.4x14.7x144x1x0.628/33000x4x.8 equaling 0.3525. Motor input power would be close to 0.31 KW/CFM. Compressor input power would be about 1161 KW.

Comparison of Over-all Power

Operating a 3.6 MW magnet at ambient temperatures requires 3,600 KW. Operating a cryogenic magnet at 29°K requires 36 KW plus 1161 KW or 1197 KW. Saving would be 2403 KW. Compressor W power/W refrigeration is 32.3. This is same as 150 HP per ton of refrigeration. COP is 36 KW/1161 KW or 0.031. Ideal COP is 29°K/(300°K - 29°K) or 0.107. Thus neon refrigerator can attain 30% of carnot performance.

Can we Improve on Above?

Only slight improvement if any can be obtained using neon which at 1 atma boils at 27°K and freezes at 24°K. Possible use of hydrogen is disregarded due to ever-present possibility of leaks, fires and/or detonations. There remains helium. First let us dispose of aluminum coils. Below 29°K there is little reduction in resistivity of aluminum. At 29°K resistivity of aluminum is 4 times that of copper. To use aluminum coils would require 1161 KW x 4 + 36 KW x 4 or 4788 KW. This would be an 1188 KW loss. Cryogenic coils immersed in liquid neon need to have their tank wrapped with multi-layer super insulation and hung within a second vacuum tank. It appears practical to remove existing Al coils and replace same with cryogenic Cu coil assemblies. New magnets would be designed to use Cu coil assemblies.

Helium as a Refrigerant

Using helium, a Cu coil temperature of 4.6°K is attainable using commercially available refrigerators (6). In absence of superconductivity, reduction of copper resistivity below that at 29°K is only a factor of three. Load would be 36 KW/3 or 12 KW. Existing LASS refrigerator using 240 SCFM of helium gas provides 100W of refrigeration with LN_2 precooling at 4.6°K. Some 120 units would be required at an equipment cost of over $9,000,000. Forget using helium for cryogenic magnets. Operating a superconducting magnet at 4.6°K essentially eliminates electrical loss. Now helium refrigerator merely counteracts 75W leakage from ambient. Only one RCBC-type refrigerator at 180 SCFM and without LN_2 precooling would be needed to do this, for a 3.6 MW ambient operation size magnet assembly. Refrigerator and compressor cost would be about $60,000. Addition of superconductive coil to Cu coil assembly should not increase bulk size by much. Cu coils are still needed to shunt power, should superconductivity be temporarily lost.

Costs of Power

Average cost of SLAC electrical energy in next few years is estimated at 8 mils/KWHR (7). Assuming 5000 HR annual operation, cost per KW demand will be $40. For 10-year useful life of a large magnet, this is $400 per KW demand. To operate a 3.6 MW ambient, operation size magnet at 29°K requires 1198 KW. To operate a superconducting magnet of same size at 4.6°K requires about 180 SCFM helium @ 0.26 KW for a total of 47 KW. Power saving would be 1151 KW. Power costs would be reduced $460,000 or $46,000 per year.

Conclusion

Technology of constructing a heat sink to be operated at 29°K or 4.6°K are identical. Commonly an intercept heat shield at about 77°K which is temperature of LN_2 at 1 atma is used in large cryogenic installations. This should not be necessary for a 3.6 MW ambient operation sized magnet coil assembly. Nor would it be practical since an intermediate heat shield considerably increases bulk of cryogenic portion of over-all magnet assembly. I expect fabrication of a 3.6 MW ambient operation sized superconducting magnet coil assembly would cost considerably less than $460,000 more than cost of a 3.6 MW ambient operational coil assembly designed to operate at 29°K, and is therefore justifiable. Likewise, greatly reduced cost of neon refrigerators designed to operate at 29°K as compared to 4.6°K helium refrigerators is of no importance due to corollary costs required to install a large recirculated neon compressor plant with its attendant supply and return piping. We can do better using helium from our existing central system at about 180 SCFM a throw to service superconducting magnets which presently at ambient temperature require some 3.6 MW power input.

Pay Back Period

Yesterday we were stuck with operation at ambient temperatures. Today we are no longer so stuck. Tomorrow we can go superconducting. If we go superconducting, we will save \$ and conserve energy. Pay back period for conversion of a 3.6 MW ambient operation, Al coiled magnet to use of superconducting and Cu coils, will be much quicker than production of a brand new unit requiring much steel and steel fabrication. In either case it seems logical and economical to go superconducting. Over-all power saving is 3553 KW x \$400/KW or \$1,421,000 after 50,000 HR of operation.

Use of Neon Refrigerators Elsewhere

At SLAC we have an existing central helium recirculating and superconducting magnet design, fabrication and operational expertise. This is not true everywhere. Use of neon refrigerators would be quite simple and trouble free. Use of a neon refrigerator for 29°K operation of appropriate types of electrical equipment would reduce I^2R losses by 99% and might well be attractive to others as a way of conserving power. If used at SLAC for cryogenic operation of equivalent of 3.6 MW magnet at ambient temperatures, saving after 50,000 HR operation would be \$961,000, which is \$460,000 less than saving attainable at SLAC by designing large magnets to operate in superconducting mode.

Superconducting Coil Material Development

Literature relating to cryogenics reveals some progress in developing alloys which go superconducting at higher and higher temperatures. Present state of art falls short of neon refrigerant temperature range. Practical applications require high values of threshold field strength, threshold currents and transition temperatures in conductors. Conductors having a transition temperature of 22°K might not be useful in a magnet coil due to too low a threshold current. Range of interest is 25°K to 30°K. If in future a composite material should be developed which can be used in magnet coils designed for operation at over 25°K, neon refrigerators become quite attractive. Compressor power for 75 W of refrigeration in this temperature range to circulate 0.195 Mol/S of neon would be only 3.25 KW. Refrigerator would be very compact and economical to procure and operate. If such a development occurs, small neon refrigerators could be used almost anywhere for superconducting DC coils mounted on stators of electrical generators and motors which schematically would be similar to equipment now in service except AC coils would be on rotors.

Hybrid Neon-Helium Refrigerators at 4.7°K

Previously (8) there was interest at SLAC in using a cold compressor in an all-helium refrigeration cycle. This interest was dispelled and rejected (9). Use of a hybrid system composed of a helium cycle operated between 4.7°K and 32°K, together with a neon cycle operated between 300°K and 29°K, should be feasible. Helium portion of system would be rated at 75W refrigeration at 4.7°K. Ten atma gas points are 32°K, 717.4 J/Mol; 17°K, 382.8 J/Mol; 9.76°K, 192.6 M/Mol; and 5.0°K, 65.0 J/Mol. Liquid yield in evaporator would be 88.2%. Return gas at 1.5 atma would have points at 4.7°K, 117.6 J/Mol; 9.5°K, 245.2 J/Mol; 15.85°K, 382.8 J/Mol; and 31.7°K, 717.4 J/Mol. Flows would be 1.43 Mol/S through evaporator, 0.54 Mol/S through expander having high pressure gas at 17°K, 45.5 J/Mol-°K, and 1.97 Mol/S cold compressor throughput. Cold compressor would be immersed in liquid neon and helium compression would be isothermal. Helium volumetric flow at compressor intake would be 2 litres per second or 4.24 CFM. Helium compressor power would be 2.5 x 1.97 x ln 10 atm/1.5 atm x 1/0.94, or 10 KW, which in turn is refrigeration load of neon portion of system. Neon mass flow would be 19.5 Mol/S or 1040 SCFM and compressor drive motor input power would be 322 KW. Using our previous example of a 3.6 MW magnet operated at ambient saving using a superconducting unit cooled by a helium and neon hybrid system is 3278 KW worth $1,311,200 after 50,000 HR operation. This is $110,000 less than all-helium refrigeration at 4.7°K. It is assumed neon expander would drive cold compressor.

Hybrid Neon-Helium Refrigerators at 9.5°K

It is much more likely that suitable conductor materials could be developed for magnet coils operated at 9.5°K than 29.0°K. A hybrid neon refrigerator in combination with a helium cold gas refrigerator is of potential interest. Helium refrigerator portion of system would again be rated at 75W. Ten atma points are 32°K, 717.4 J/Mol and 17°K, 382.8 J/Mol. Points at 1.5 atma are 9.5°K, 245.2 J/Mol, 15.85°K, 382.8 J/Mol, and 31.7°K, 717.4 J/Mol. Helium cold gas flow would be 75 J/S ÷ (382.8 J/Mol-245.2 J/Mol) which is 0.55 Mol/S or 0.57 l/S = 1.2 CFM. Helium Cold Compressor power would be 5.5 KW. Neon compressor flow would be 10.7 Mol/S or 572 SCFM and compressor power would be 177 KW. Saving over 3.6 MW for ambient operation would be 3,423 KW worth $1,369,000. This is only $52,000 more than all-helium refrigeration at 4.7°K. Hybrid Helium-Neon refrigerators for 9.5°K operation should cost less than all-helium refrigerators for operation at 4.7°K. Components are a neon compressor, three neon-neon heat exchangers, a neon expander, a neon PRV, a neon evaporator, a helium cold gas compressor, a helium-helium heat exchanger, a helium expander, and helium supply and return connections for superconducting magnet coils. Basic cycle could be operated over a temperature range from $4.7^{\circ}K$ (100% saturated gas) at 1.5 atma to approximately $18.3^{\circ}K$ (80% expansion efficiency with no helium-helium heat exchanger used). Further interest in this approach depends on availability of superconducting material suitable for magnet coils within this temperature range. At $18.3^{\circ}K$ helium flow reduces to 0.37 Mol/S which is 0.79 CFM and helium compressor power to 1.9 KW. Neon flow would be 5.7 Mol/S or 197 SCFM and neon compressor power would be 61 KW. Total input power at $18.3^{\circ}K$ would be only 14 KW more than 47 KW required for all helium refrigeration at $4.7^{\circ}K$.

Availability and Quality of Neon Refrigerants

Present supplier of industrial gases to SLAC (10) receives crude neon from Chicago. Typical crude neon contains 77.5% neon, 22.0% helium and 0.5% of nitrogen. Crude neon can be supplied for use in neon refrigerators. Nitrogen traces are easily removed by cryogenic purifiers before using crude neon in refrigerators. Helium would cycle with neon, but would provide no refrigerating effect at $29^{\circ}K$. Presence of 22% helium would add to cost of neon compression by 28%.

Present supplier can strip pure neon from crude neon but at added cost. On other hand, transport of 75 l dewars of LNe is less expensive than delivery of crude neon by gas tube trailers.

Present supplier furnishes 5660 Sl cylinders of spark chamber gas (SCG) to SLAC. This is a 90% neon, 10% helium mix. To provide SCG from crude neon, it is necessary first to strip pure neon from crude neon and then recontaminate it with precise amounts of helium. This requires liquefaction of neon so that cost of SCG is close to that of an equivalent quantity of LNe.

Present cost for 90% neon-10% helium, or 80% neon-20% helium mixes is close to $120 per 5600 Sl cylinder containing 4.6 Kg of SCG. This is $26 per kilogram which is quite expensive. Present cost of crude neon is half that of spark chamber gas F.O.B. Chicago. Cost of LNe is close to $26 per kilogram F.O.B. Chicago.

At 1.0 atm and $27^{\circ}K$, density of LNe is 1.2 kilograms/l so bulk cost of LNe could be as high as $28/l or over 15 times that of LHe. Is law of supply and demand alive and well? To convert previous example magnet drawing 3.6 MW at ambient to cryogenic operation at $29^{\circ}K$ would require dewars of up to 1700 l liquid capacity at an initial charge of 24-75 l dewars at an estimated cost of $57,000 for LNe or $42,000 for crude neon in 2.5 SLAC-owned tube trailers plus time and cost of SLAC site liquefaction.

Use of crude neon would increase above case by 28% of 1161 KW or 325 KW @$400 or $130,000. Over-all performance and economy would favor use of LNe boil-off to cool a system to 29°K followed by a fast fill using purchased LNe to reach on-line status. All other applications discussed hereinbefore would require far less cold end LNe volumetric capacity. It is concluded that high cost of LNe should not inhibit consideration of neon refrigerators.

Absolute Helium Purifiers

Neon refrigerators could be used to absolutely strip all known contaminants of recirculating helium refrigeration systems at reasonable cost. Bulk of such purifiers would be small and heat leakage from ambient would be nominal. All traces of moisture, lubricating oil and heavier gases would be stripped. Helium side flow can be full flow for any system at practically no loss in helium supply pressure. Development of a small neon refrigeration system to strip helium stream contaminants is under way (11).

Cryogenic Operation of Positron Source

I^2R losses of positron source solenoid is 0.85 MW when operated at ambient. Heat from positron target irradiation is not known (12) although tests are scheduled to determine this. If heat from beam energy is in tens of W then superconducting operation at 4.7°K could be considered. If heat from beam energy is in KW, then helium refrigeration is not practical, but neon refrigeration would remain a possibility.

References

(1) Private communications with Bill Brunk

(2) Private communications between Bill Brunk and Steve St.-Lorant as related to writer by Bill Brunk

(3) Presently atm is used in USA and ata is used in Europe; I prefer atma which speaks to an atmosphere of pressure, but also reminds us of its absolute nature.

(4) Barron Cryogenic Systems. Fig. 2-13, page 42.

(5) Barron Cryogenic Systems. Table C-3 page 637 and Fog. D-6 page 650.

(6) CTi Model 1400 for instance

(7) Private communications with Al Tseng and Paul Edwards

(8) Private communication with Steve St.-Lorant and G. I. Ratliff

(9) Fred Hall - Superslac Interim Study #10 dated 052870

(10) Linde Division of Union Carbide Corporation

(11) Work Order to PED Instrument Shop

(12) Private communications with Al Lisin