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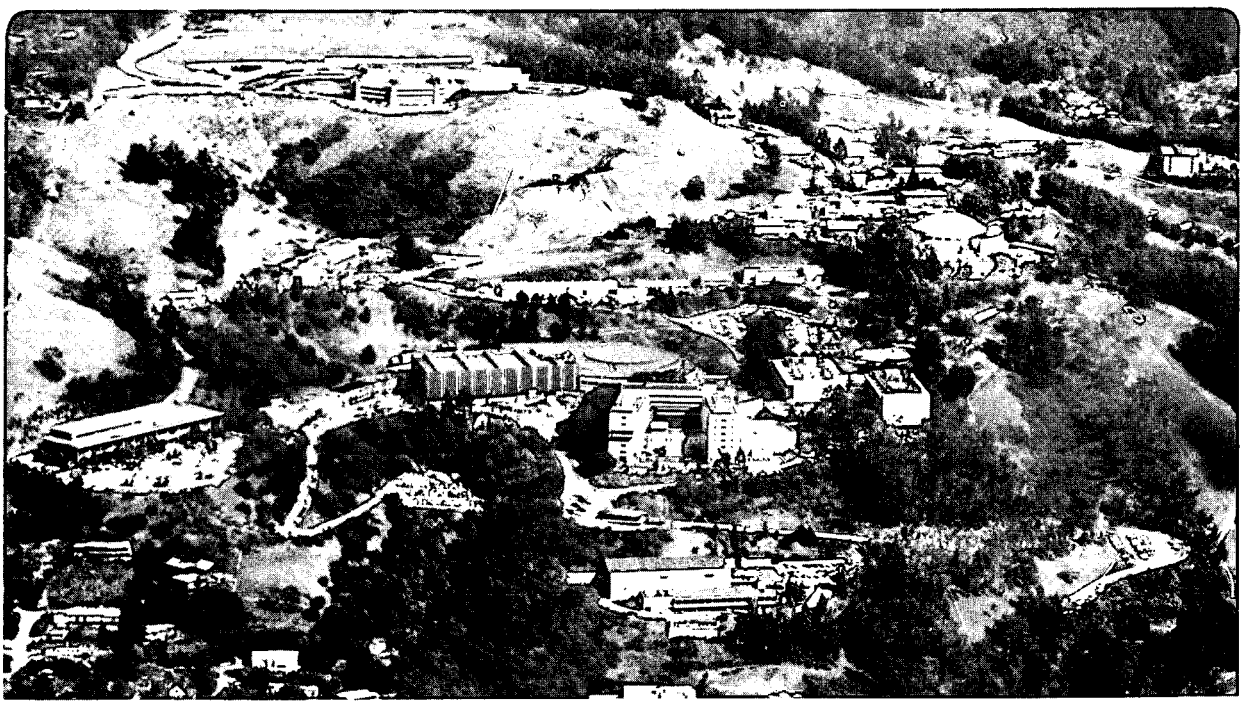

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ENGINEERING NOTE

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PROGRAM — PROJECT — JOB

HIGH FIELD MAGNET DEVELOPMENT

CRYOGENIC SYSTEMS

TITLE

REFRIGERATION POWER FOR 1.8 K

SUMMARY

A brief survey was made of some large helium refrigerators for the purpose of predicting the power requirements for the refrigeration of a large magnet system operating at 1.8 K. For three existing systems which operate in the range of 1.8 to 1.9 K the reciprocal of the coefficient of performance (COP) varies from 1200 $W_{in}/W_{1.8K}$ for two systems which use LN precooling to 2000 for one which does not. An estimate of the power requirement is made based on the addition of another JT expansion (and heat exchangers) to the best of the 4.5 K refrigerators surveyed. On this basis it appears as though the power requirement might drop to as low as about 670 $W_{in}/W_{1.8K}$. The refrigeration cost including power (at 1200 $W_{in}/W_{1.8K}$ and 6¢/kw hr) and liquid nitrogen (at 7¢/l) comes to \$0.09/hr/$W_{1.8}$ with the cost for the power much larger than that for the LN. The above LN cost includes only that for the refrigerator and not for the magnet cryostats.

ANALYSIS

The performance specifications of some large helium refrigerators are tabulated in Table I. The 1st 6 machines produce refrigeration and/or liquid at about 4.5K. The last 3 are built primarily for the purpose of producing refrigeration at 1.8 or 1.9K. All of the units except for the last use LN cooling. This last unit, in terms of the coefficient of performance (COP), is not too efficient. This may or may not be related to the non use of LN pre cooling. It is suggested in (6) that this is a result of small heat exchangers. The reciprocal of the COP as tabulated in Table I can be compared to that for an ideal Carnot machine which is $\frac{T_\infty}{T} - 1$. Where T_∞ is the temperature of the surrounds or upper reservoir. Using $T_\infty = 293$ one obtains 64 for $T = 4.5K$ and 162 for $T = 1.8K$. It is left as an excercise for the reader to devide these figures by those in the table and thus obtain the "% Carnot".

It is of interest to speculate, based on the figures of Table I, how good we might do in terms of COP for a 1.8K system based on the adaption of the best of the above 4.5K machines. From Table 1, the minimum compressor power is 277 $W_{in}/W_{4.5K}$. From (9) the enthalpy gain of the He II coolant in the cold sink is 19.75 J/g (JT heat exchanger effectiveness = 0.8) which compares to the latent heat of vaporization at 4.5K of 19.1 J/g. The ratio of compressor work to refrigeration becomes

$$\frac{19.1}{19.75}(277) = 268 \ W_{in}/W_{1.8}$$

For the vacuum pump power reference (7) indicates 170 KW for 340 W at 1.8K which gives a ratio of 500 $W_{in}/W_{1.8}$. The vacuum pump system at Stanford (three stage roots and one stage piston) has an input power of about 100 KW (input pressure 10-15 torr) (8). For a refrigeration power of 330 W the vacuum pump power is then $\frac{100 \times 10^3}{330} = 303 \ W_{in}/W_{1.9K}$

TABLE I
PERFORMANCE SPECIFICATIONS OF SOME LARGE REFRIGERATORS

Description	Reference	Mfg	LN Pre Cool	Mass Flow Comp. g/s	Input Power KW	Max Refrig. W	Max Lique-faction l/hr	1/C.O.P. W_{in}/W_T	Ratio Max Refrig. / Max Lique. J/g	LN Flow l/hr ($\frac{l/hr}{W_T}$)
Liquefier Two Air products Turbines + wet exp.	1	CCI in const.	Yes		931	—	1440	—	—	—
FNAL Satellite Recip expanders 1 wet, 1 dry	1	CCI	Yes	40	214	440	94	486	135	—
For MSU Recip expanders 2 dry + wet 2 stage screw c. 400 W + 100 l/hr	1	CCI in const.	Yes	62	201	725	225	277	93	—
LBL Bldg 58 1 dry expander	2	CCI	Yes	40	214	260	68	823	110	43 (.17)
LBL Bldg 56 2 turbine expand.	3	CTI	Yes		650	1800	350	361	148	
FNAL Central liq.	4	CTI	Yes	1268	8940	12000.	4875	745	71	2665 (.22)
1.9K Stanford 3 recip expanders 2 dry, 1 wet 4 stage vac pump 3 stage compr.	5	ADL	Yes	60	400	330 @ 1.9K	—	1210	—	67 (.20)
1.8K - Karlsruhe 1 piston expander 5 stage vac. pump 3 stage compressor	6	Messer Griesheim	Yes	50	436 (1.8K) 230 (4.3K)	370 350	— 85	1180 657	119	Closed cycle
1.8K - Karlsruhe 2 turbine exp 8 stage vac pump	7	Linde	No	148	690	340 @ 1.8K	110	2029	—	0

For the purposes here use 400 W/W for the vacuum pumping power. So that the total input power (excluding LN) is 670 $W_{in}/W_{1.8K}$. So it appears as though there is room for considerable improvement as compared to the existing units. Returning to reality, at 1200 $W_{in}/W_{1.8K}$ and power cost of 0.06 \$/KWhr the input power cost would be 0.072 \$/$W_{1.8K}$-hr. For the LN cost we use the highest consumption rate tabulated in Table I of 0.22 ℓ/hr/W_T and a LN cost of 0.07 \$/ℓ which results in a cost of 0.015 \$/$W_{1.8K}$-hr. The total power and LN cost then becomes 0.087 \$/$W_{1.8K}$-hr. For example a 1KW machine would have a power and LN cost of 87 \$/hr. Except in the very large machines the power and LN cost is likely to be small in comparison to the labor cost for operation and maintenance.

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