ENERGY DOUBLER REFRIGERATION LOAD

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January 1979

INTRODUCTION

Presented here is an estimate of the Energy Doubler refrigeration load based on the components design. The actual steady state refrigeration load will, of course, depend on quality control factors that are not considered here and that are related to: component fabrication, installation (parts touching in the junction boxes) and cryostat operating conditions (residual helium pressure in the insulating vacuum space, thermoacoustic oscillations). Not all components received the same design attention as the dipoles and quadrupoles, and no detailed evaluation is included here for the feed boxes, turnaround boxes, transfer lines and other plumbing.

The values used in this estimate are derived whenever possible from measurements made on actual components, or assembled cryostats. The quality control factors mentioned above require that actual heat load measurements be performed in strings of magnets and make the effort involved in propagating errors in this estimate academic at this time. For the sake of easy identification many values are expressed by numbers with more digits than their accuracy justify.

HEAT LEAK PARAMETERS

The basic data that entered in this estimate are presented next as they apply to the dipoles:

Infrared Load

From the measured .302 W conducted by one of the 35 supports,[1] the estimated 1.0 watt conducted by the anchor and the measured[2] liquid N_2 load of 21. W of a Model 14 cryostat (surface area 3.44 m^2) we obtain the infrared load through the dimplar insulation: I_{N_2} = 2.74 W/m^2 into the shield. The infrared load on the 2Ø tube as calculated from Stephan Boltzmann law for an emissivity of .05 is I_{He} = .116 W/m^2. Since Model 135 cryostats have a shield area of 3.680 m^2 and a 2Ø area of 3.289 m^2, the infrared loads are $2.74 \times 3.680 = 10.08$ W into the shield and $.116 \times 3.289 = .381$ W into the helium region.

Conduction Load

The anchor load into the 4 K environment can be inferred to be .164 W from boil-off measurements.[2] Measurements of heat conduction[3] for the trapezoidal supports and standoffs underneath them suggest values of .38 W and .0865 W respectively. Therefore, the conduction load into the Model 135 dipole cryostats through the supports is expected to be $35 \times .38 + 1. = 14.30$ W into the shield and $35 \times .0865 + .164 = 3.191$ W into the helium region.

Vent Pipe Load

The horizontal part of the vent pipe conducts heat by convection in its trapped helium gas and by conduction along the wall. An unreported measurement of this convection yielded a value near 1 W, from room temperature to near LN_2 temperature. For the old mitered 1" o.d., .049" thick vent pipe the load into the shield and helium environment was expected to be 1.66 W and .108 W respectively.

Instrumentation Leads Load

This calculated heat load into the helium environment is based on a 3/16 o.d., .020" wall, 81" long stainless steel tube filled with 11 copper wires (#30 gauge) insulated with Tefzel. The total load of

.156 W is 68% due to Tefzel. The calculation assumes no touching, no gas conduction or LN_2 sinking.

Junction Box Heat Load

This heat load is assumed to be due to just infrared radiation. It is based on the "ham can" areas of .104 m^2 in the bellows section (upstream end) and .035 m^2 in the square section (downstream end). Into the shield we have (.104 + .035) × 2.74 = .381 W. For the helium environment as represented by two black tubes (bellows) of .01 m^2 and a stainless (ε = .1) tube of .08 m^2 area, we obtain $q = 1.55 \times 10^{-9}\ T^4$ watt where T is the temperature of the "ham can" shield. This temperature has been observed[2] to run as high as 100 K contributing therefore with up to .155 W.

The above numbers are summarized in Table I. Table II was made for the quadrupole cryostat in a similar manner. The areas involved in infrared estimates are: 2.34 m^2 for the shield and 1.813 m^2 for the 4 K environment. The "ham can" area is again taken as .104 m^2 and (8"/12") × 1.06 = .069 m^2 for the bellows section. The vent pipe calculations are based on .049" wall tubes of stainless (1" o.d. for 2Ø, 1/2" o.d. for N_2 and 1.5" o.d. for 1Ø) with 1 watt of convection in the horizontal length.

The manufacturer[4] quoted characteristics (2.7×10^{-3} liters per ampere hour per pair at optimum current and 40% less in standby) were used for the gas cooled Efferson-type leads. Based on measured resistance of the safety lead (R = 4.9 mΩ) the extra heat developed in a pair of safety leads during an Energy Doubler dump is

$$2 \times \int_0^\infty (I_0 \ell^{-t/10})^2\, R\, dt = .049\, I_0^2 \text{ Joules.}$$

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Because of the quality control factors mentioned in the introduction, extrapolation from the totals in Tables I and II for the entire Doubler cannot be trusted but is an interesting exercise anyway. A particular point presently underlining this mistrust is formed by the indications of a larger steady state heat leak than Table I predicts and the indications that only the lower supports are in full contact after cooldown.

A satellite refrigerator is supposed to have a typical load of 32 dipoles and 8 quadrupoles. In steady state it should provide for $32 \times 3.992 + 8 \times 2.918 = 151.$ watts of refrigeration at 4.5 K plus the demand of one feedbox, two turnaround boxes and perhaps some other plumbing. While ramping with the canonical[5] ac loss of 400 J/30 sec for a dipole and a guessed 200 J/30 sec for a quadrupole the additional refrigeration of $32 \times 13.33 + 8 \times 6.67 = 480.$ watts will be needed. Neglecting eddy currents in the shields, the dipoles and quadrupoles above will require $22.43 \times 32 + 12.49 \times 8 = 818.$ watts of refrigeration at 80 K and will consume .39 g/sec of liquid helium in steady state plus .41 g/sec when in ramping operation through their gas cooled leads. In these last two numbers are included the consumption of the two 5 kA leads of one feedbox (.19 g/sec steady state plus .28 g/sec when ramping).

A satellite should therefore be capable of providing $151 + 480 = 631.$ watts at 4.5 K and handle $(.39 + .41) \times 3600/125. = 23.04$ ℓ/h of liquid helium for the leads back to the Central Helium Liquefier.

Extrapolating further for 24 satellites, the Energy Doubler (not counting losses from transfer lines, turnaround boxes, feed boxes and eddy currents in the shield) will require $24 \times 818 = 19.6$ kW from the liquid N_2 source. This is equivalent to the power absorbed by the vaporiation of 445 ℓ/h of liquid N_2.

The total mass flow rate of helium returned for reliquefaction to the Central Helium Liquefier directly from the gas cooled leads is equivalent to $24 \times 23.04 = 553$ ℓ/h of liquid helium.

REFERENCES

[1] M.Kuchnir, "Measurements of Heat Conduction Between 300K and 80K", Fermilab TM-744, September 1977.

[2] M.Kuchnir, "E22-14 Cryostat Boil-Off", Fermilab TM-740, July 1977.

[3] M.Kuchnir, "Thermal Performances of Mechanical Supports", Proceedings of the Miami Meeting of the AICHE (November 1978).

[4] American Magnetics, Inc., P.O.Box R, Oak Ridge, Tenn. 37830.

[5] M.Wake, D.Gross, R.Yamada, D.Blatchley, "AC Loss in Energy Doubler Magnets", IEEE Transactions, MAG-15, 141 (1979).

TABLE I

DIPOLE Model 135 Cryostat	Steady State Load			Ramping Load		
	80 K Watt	4 K Watt	Evap. g/sec	80 K Watt	4 K Watt	Evap. g/sec
Infrared (main body)	10.08	.381				
Supports Conduction	13.30	3.028				
Anchor	1.00	.164				
Vent Pipe (Mark 1 Model)	1.66	.108				
Instrumentation Leads		.156				
Infrared (Junction)	.38	.155				
4K Cooling	-3.99					
Cryostat Eddy Current						
a.c. Losses (400 J/30 sec)					13.333	
TOTALS	22.43	3.992			13.333	

TABLE II

QUADRUPOLE (As of Aug 78 Dwgs)	Steady State Load 80 K Watt	Steady State Load 4 K Watt	Steady State Load Evap. g/sec	Ramping Load 80 K Watt	Ramping Load 4 K Watt	Ramping Load Evap. g/sec
Infrared (main body)	6.41	.210				
Infrared (Junction)	.19	.008				
Supports Conduction	3.04	.680				
4 K Cooling	-.90					
Vent Pipe for LN_2	.27					
Vent Pipe for 1Ø	1.91	.496				
Vent Pipe for 2Ø	1.57	.325				
1 Safety Lead (5 kA)		1.000			Quench Heat	
3 Correction Leads (200 A)		<<.284	.017			.011
6 Correction Leads (50 A)		<<.142	.009			.006
Instrumentation Leads		.156				
TOTALS	12.49	2.918*	.026			.017

* << is taken as 10%