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MULTIPLE ELEMENT VAPOR COOLED CURRENT LEADS FOR THE FERMILAB ENERGY SAVER CORRECTION ELEMENTS

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ABSTRACT

The development of the Energy Saver at Fermilab requires the installation of nearly 500 correction coil packages, each containing three elements operated at a nominal 50A each. This necessitates twelve penetrations from ambient conditions to liquid helium at each quadrupole package. The design and test results of complete package containing all twelve vapor cooled conductors will be discussed in full.

INTRODUCTION

A number of papers have been written over the past several years dealing with the subject of vapor cooled current leads. Most, if not all, treat the problem from a unique point of view, that is, each treatment differs from any other, sometimes by a great deal. It seems too that only a few provide any practical means to evaluate the given proposals. The number of actual leads described is far short of the number of theories suggested.

The purpose of this work then is essentially twofold. First, it will address the problem as it relates to the Fermilab Energy Saver. Second, it will provide the guidelines and specifics necessary for the solution of similar problems elsewhere. In doing so we will start effectively from scratch, finally to arrive at a working example currently in use at Fermilab.

SYSTEM REQUIREMENTS

The correction element packages for the Energy Saver are made in basically two styles, an OSQ (8P-6P-4P) and a DSQ (2P-6P-4P). They, as well as a number of other special components, are installed in what has come to be known as the "spool piece", downstream from each quadrupole magnet. At most spool locations one of each type will be installed. Since each needs independent power, twelve leads are required at each location. The design current for each of the six coils, and thus for each lead, is 50A.

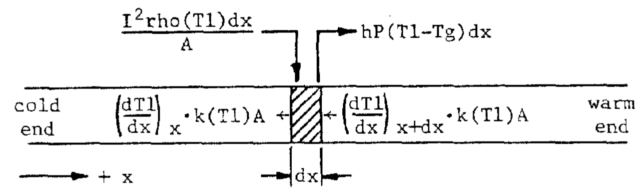
Physically, the Saver is installed directly below the present main ring magnets (conventional). This geometry poses height limitations on any protrusions from Saver components, including the spool. In the case of the current leads this limitation is on the order of 30-35 cm. Any more length would have caused serious installation problems.

In addition, during certain failure modes potential differences between adjacent lead pairs and individual leads to ground could reach 1.5kV. Potentials between two leads from the same coil on the other hand are low in all cases (< 100 V). The lead spacing then due to these constraints was set at 0.32 cm between two leads from the same coil and 0.96 cm between adjacent pairs as well as between individual leads and ground.

Finally, in order to minimize the possibility of plugging the flow to any lead as well as to decrease to one the controlled exit, all twelve leads would share a common cooling stream.

ANALYSIS

The following model describes the heat flow along the conductor as well as the interaction between the lead and the gas.



Where:

A=cross-sectional area of conductor (sq cm)
I=current (A)
h=heat transfer coefficient (W/sq cm/deg K)
P=wetted perimeter (cm)
T1=lead temperature (deg K)
Tg=gas temperature (deg K)
rho(T1)=conductor resistivity (ohm-cm)
k(T1)=conductor thermal conductivity (W/cm/deg K)

A heat balance on an element of length dx yields:

$$\left[\left(\frac{dT1}{dx}\right)_{x+dx} - \left(\frac{dT1}{dx}\right)_{x}\right] k(T1)A + \frac{I^2 rho(T1)dx}{A} - hP(T1-Tg)dx = 0$$

Or:

$$\frac{d^2T1}{dx^2} = \frac{hP(T1-Tg)}{k(T1)A} - \frac{I^2 rho(T1)}{k(T1)A^2}$$

The equation for gas equilibrium gives:

$$mdot \cdot Cp \cdot \frac{dTg}{dx} = hP(T1-Tg)$$

Or:

$$\frac{dTg}{dx} = \frac{hP(T1-Tg)}{mdot \cdot Cp}$$

Where:

mdot=cooling gas flow rate (gm/sec)
Cp=specific heat at constant pressure for helium (J/gm/deg K)

As in the solution of any system of equations we first define those parameters which are fixed. In this case we know that the cold end temperature of both the lead and the gas (T1 and Tg respectively) is 4.7 deg K, the current is 50A and Cp (assumed constant over the entire temperature range) is 5.15 J/gm/deg K. Further we will initially assume that a reasonable value for the heat transfer coeff, h, is 0.2 W/sq cm/deg K. It later will be shown that the solution is quite insensitive to significant variations from this initial value.

Finally, we know the conductor material. Copper was chosen for several reasons. It obviously has good electrical properties, is readily available, and lends itself well to fabrication requirements.

In order to achieve the highest surface area /cross-section ratio practical, as well as to have a conductor that is easily formed, the Fermilab lead package utilizes 0.127 mm thick copper foil.

The thermal dependence of rho and k, for the material, were determined experimentally for several temperatures, which then were fit to well documented curves (1). Twenty-one points from these curves are used as data values. Points between data values are determined by linear interpolation (see fig. 1).

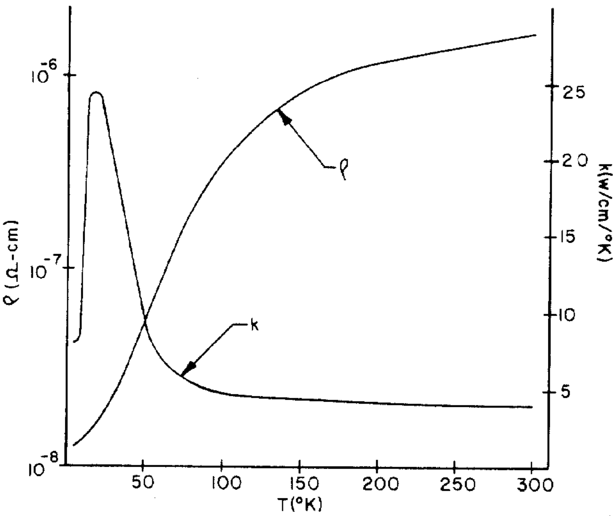


Fig. 1 rho and k vs. temperature for OFHC copper (RRR=100)

An iterative integration routine was written for a computer generated solution to the above equations. This algorithm, when given all necessary constants and variable parameters will search for a simultaneous solution which yields the desired lead length corresponding to Tl=300 deg K. In addition it will generate the temperature distribution as a function of length for both the lead and the gas, the heat flux into the cryostat, and the components of heat removed, i.e. conduction and resistance heating.

Although not immediately obvious, the solution to this set of equations is rather sensitive to the initial value of dTl/dx at the cold end (see fig. 2). Therefore, this parameter is initialized quite small (say 0.1 deg K/cm). If the integration routine fails to find a solution using this value, dTl/dx is incremented upward and the solution restarted. This process continues until Tl=300 deg K corresponds to the desired lead length.

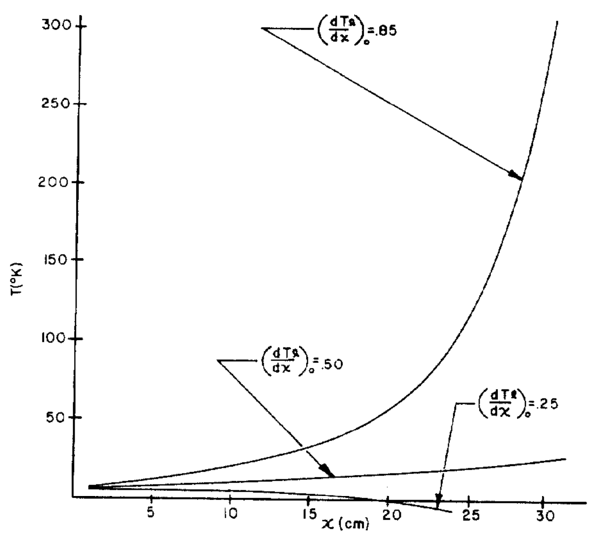


Fig. 2 Solution character as a function of initial dTl/dx

If we assume that the cooling stream is generated from the heat flux into the cryostat (self-generated flow) we can readily calculate a new value for mdot at each trial dTl/dx, i.e. mdot=(dTl/dx)*k(4.7)*A/Hv (where Hv is the latent heat of vaporization of helium at 4.7 deg K, J/gm).

Figure 3 shows the complete output from a typical run of the above outlined routine.

LEAD PARAMETERS

WETTED PERIM=1.000 CM
X-SECT AREA=.010 SQ CM
XFER COEFF=.20 W/SQ CM/DEG K
CURRENT=50. AMPS
FLOW=.003323 GM/SEC
LEAD TEMP (COLD END)=4.7 DEG K
GAS TEMP (COLD END)=4.7 DEG K
TEMP GRADIENT (COLD END)= .8520 DEG K/CM
HEAT FLUX INTO CRYOSTAT=.066 W

X	TLDDOT	TLDOT	TL	TGDOT	TG
0.000	-.0513	.8520	4.7000	0.0000	4.7000
5.000	.1666	1.6224	10.7823	1.6081	10.6447
10.000	.1560	2.4185	20.9224	2.4052	20.7166
15.000	.3254	3.5325	35.4597	3.5049	35.1598
20.000	1.1715	6.7959	59.4768	6.6973	58.9037
25.000	4.4649	19.5511	118.2984	19.1706	116.6581
29.989	15.2953	61.8620	300.0149	60.5883	294.8308

HEAT INVENTORY

RESISTANCE HEATING=1.75 WATTS
CONDUCTION DISSIPATED=3.22 WATTS
HEAT REMOVED BY GAS=4.96 WATTS

Fig. 3 Computed lead characteristics

The only parameter we know little about is h. As mentioned earlier the solution is not influenced to any great extent by variations from the chosen value of 0.2 W/sq cm/deg K. Figure 4 shows the effect of these variations on the heat flux into the cryostat.

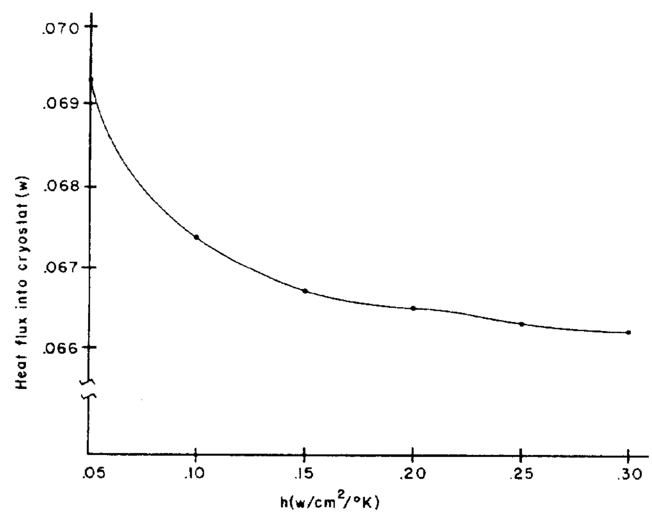


Fig. 4 Heat flux at cold end as a function of h

All that remains is choosing, from a set of input conditions, those which result in a lead with characteristics compatible with the system as a whole. As stated previously, one early constraint imposed on this design was height. Coupled with other considerations, such as constraints on the total diameter of the assembled package (approx. 6-7 cm) and maximum allowable total mass flow (<1.25 l/hr for all 12 leads) we arrived at a set of parameters to meet these criteria. Figure 3 is in fact the output for these conditions. Figure 6 shows the temperature gradient as a function of length for this lead as well.

CONSTRUCTION

Now that the geometry has been defined for each individual conductor we need to develop a means of packaging twelve such leads in a manner compatible with the hi-pot requirements and the single flow path constraint. In effect we need to build a heat exchanger which provides ample conductor/gas contact without adding a large heat path of its own.

Starting with two G-10 tubes, one (the inner tube) with an outside diameter equal to the inside diameter of the other (the outer tube), we machine a rectangular thread 2.4 mm deep, 4.0 mm wide, 6.35 mm pitch on the outside of the inner tube and on the inside of the outer tube. Along the length of the inner tube are machined 12 shallow slots for the conductors to lay at their required spacing.

The tubes then are nested one inside the other with the foil in between. With the matching threads lined up we form a rectangular helical path nearly 800 cm long with 60% contact to the copper foil (this 60% is the cause of the derating of wetted perimeter from 1.6 cm actual to 1.0 cm analytical.

Figure 5 shows this package as it mounts in the final assembly of the spool piece. Also shown are the inner and outer vacuum regions as well as the exit stream temperature control valve. The latter for metering the flow for varying load factors on the lead package.

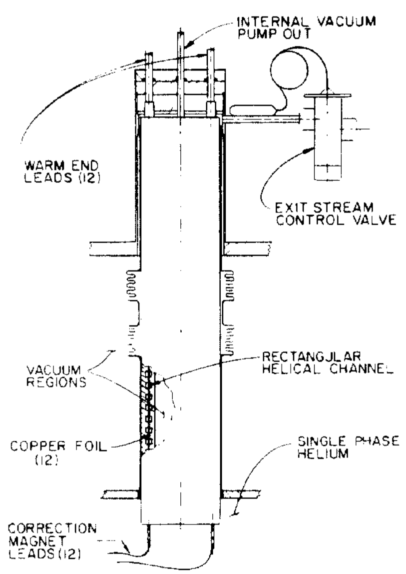


Fig. 5 Complete lead package (installed)

TEST RESULTS

As stated in a previous section this lead package is presently a working component of the Fermilab Energy Saver. Prior to the fabrication of any number of these units, however, (250 are required) a test unit was fabricated with a geometry identical to that of figure 5. Since all of the lead properties are in one form or another dependent on the temperature profile of each conductor clearly any significant deviations from expected parameters will manifest themselves in a change in gradient as a function of length.

Our test lead then was provided with 11 voltage taps along the length of one conductor, all conductors wired in series.

This data combined with the resistivity vs. temperature information provides an easy check of the temperature profile for an individual conductor. The test was run with the lead operating at 50A continuous with an equivalent flow of .0033 gm/sec per conductor.

Figure 6 is a comparison plot of the predicted temperature profile vs. the actual profile as obtained from the test lead described above.

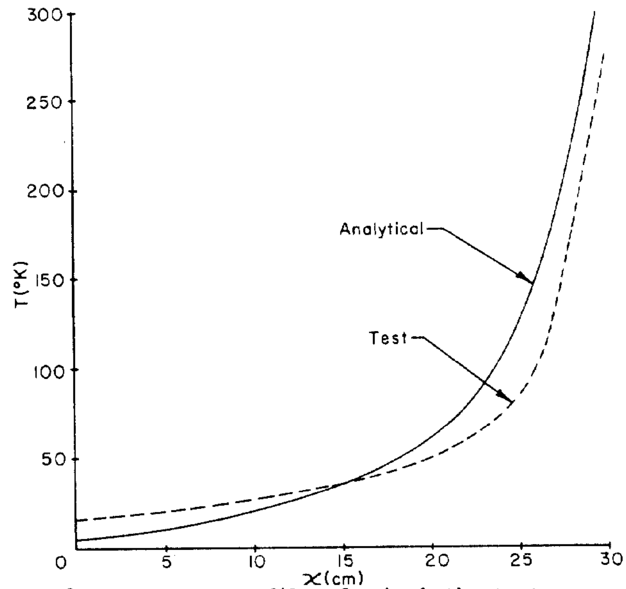


Fig. 6 Temperature profiles for both the test lead and the analytical model

In addition to the above test we were concerned with the possibility of damaging the lead if flow were interrupted for a significant length of time with full current in all 12 leads. This condition was measured as voltage drop across one conductor with 50A flowing. Over a period of 10 minutes we detected a steady rise of 100 mV with no gas cooling. Tests show that in all likelihood this condition will cause a quench in the local correction package, tripping the power supplies off. If not, adequate detection time exists to cut power before damage to the lead results.

SUMMARY

Hopefully, within the scope of this report, the basis for the design of not only the Fermilab lead package, but leads in general, has been made clear. The techniques described are applicable to virtually any set of design constraints.

A further report, including the FORTRAN source program for the above analysis as well as additional comparisons of parameters vs. lead characteristics can be obtained from Fermilab Internal Report TM-1028, by this author, available from the Fermilab Technical Information Office.

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