Cryogenic Current Leads

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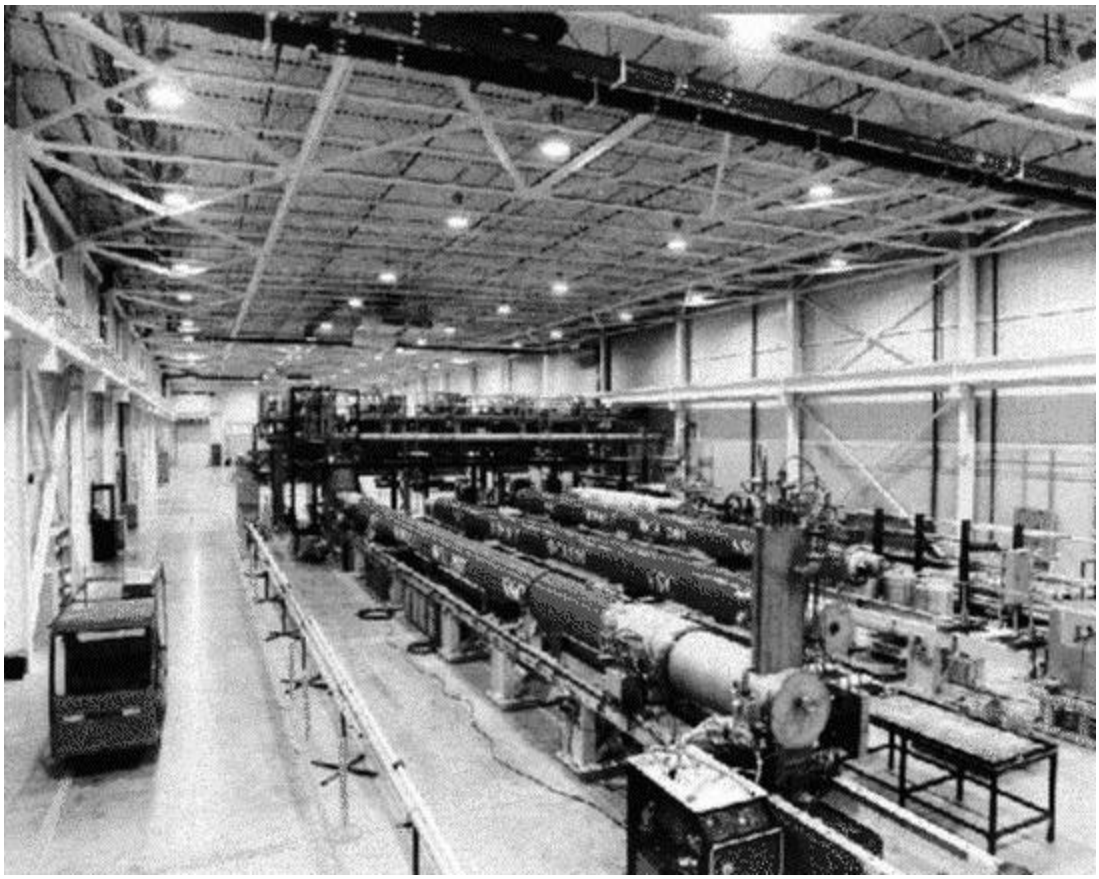
Short Course
CEC/ICMC, Montreal, Canada
July 1999

Topics that will be addressed in this presentation include . . .

- Applications of cryogenic current leads:
  - To supply power to a low temperature device and make the transition from room temperature to low temperature.
- Analysis of current leads:
  - 1-D energy balance
  - Conductor properties (Copper)
- Conduction cooled vs. forced flow / vapor cooled.
- Optimization of cryogenic current leads:
  - McFee approach (conduction cooled)
  - Minimization of refrigeration load (Forced Flow / Vapor Cooled)

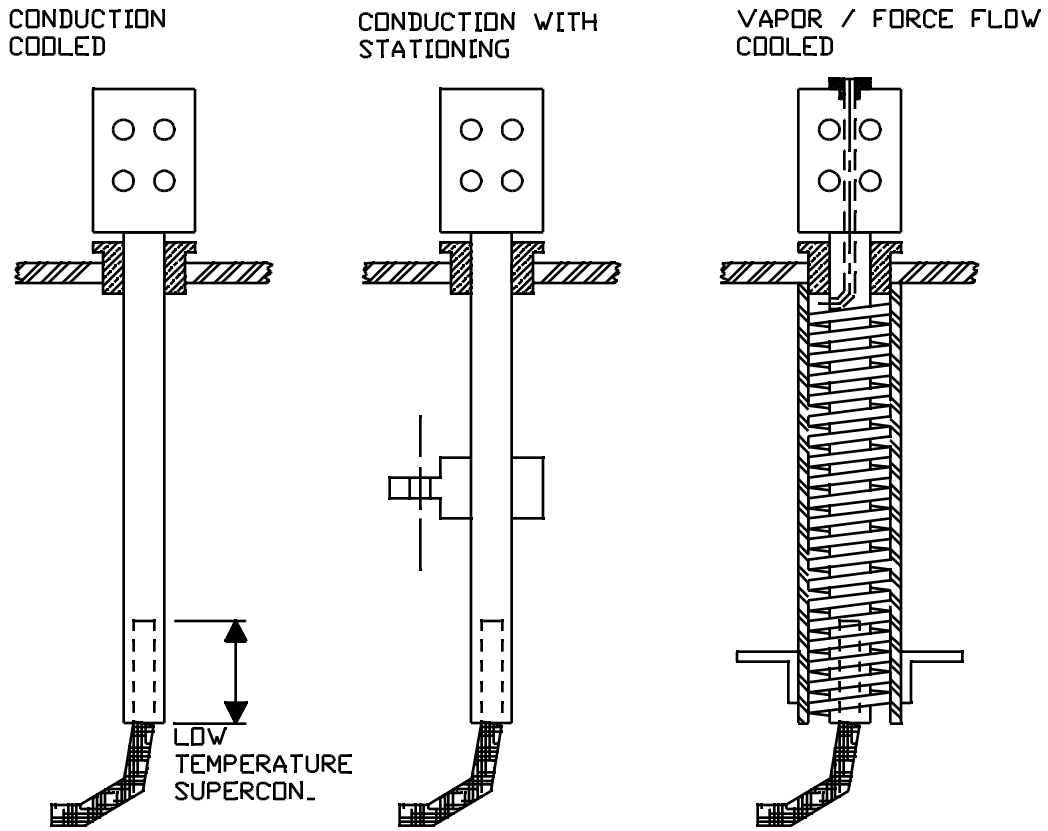
Current leads are used to power superconducting magnets



Designs will be needed for superconducting power applications.

- Superconducting transmission line terminations
- Transformers
- Fault current limiters

Choice of current lead configurations depends on the system configuration.



In most cases a 1-D energy balance is sufficient to analyze a current lead.

Energy balance for the conductor:

$$\frac{f(\gamma_c C_c A_c T_c)}{f\tau} = \frac{f}{fx}(\lambda_c A_C \frac{fT_c}{fX}) + \frac{\rho I^2}{A_C} + hP(T_c$$

Energy balance for the fluid (cooled):

$$\frac{f(\gamma_v C_v A_v T_v)}{f\tau} = \dot{m}_v \frac{fe_v}{fx} + hP(T_v - T_c)$$

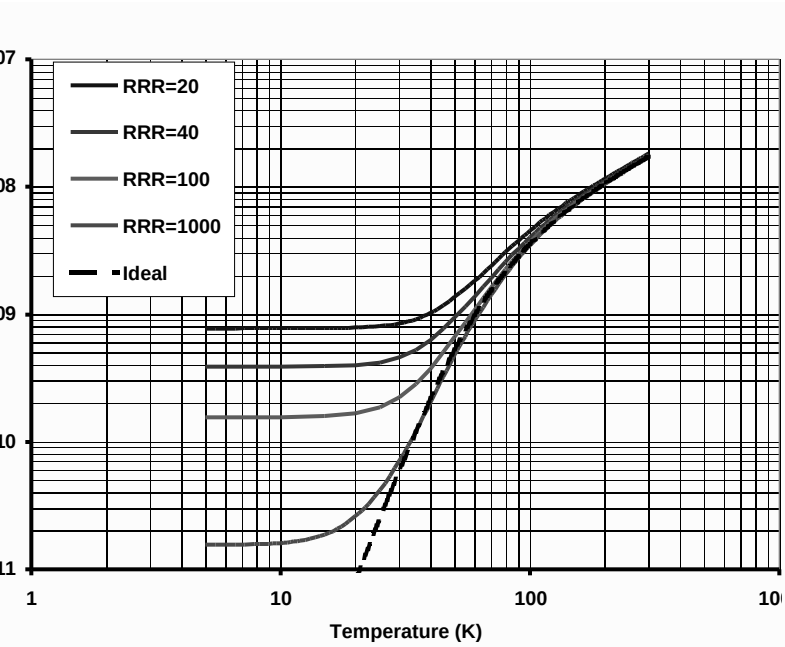
Heat transfer coefficients - empirical correlations.

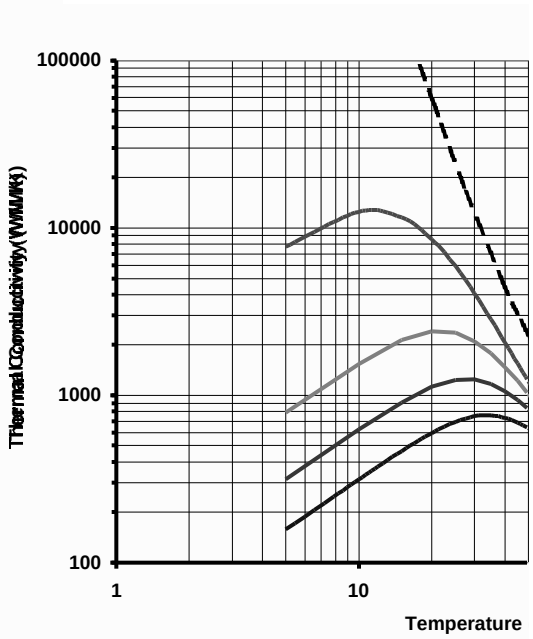
Helium & conductor properties - database

Copper properties vary with temperature and RRR.

- Residual Resistivity Ratio, RRR, depends on condition of material.

$$RRR = \frac{\rho_{273K}}{\rho_{4K}}$$





ptimization by McFee method is a good arting place for conduction cooled leads

- An analytical solution for the optimum shape factor, IL/A, and minimum heat transfer $[Q_L]_{min}$. (Minimize Carnot Refrigeration)

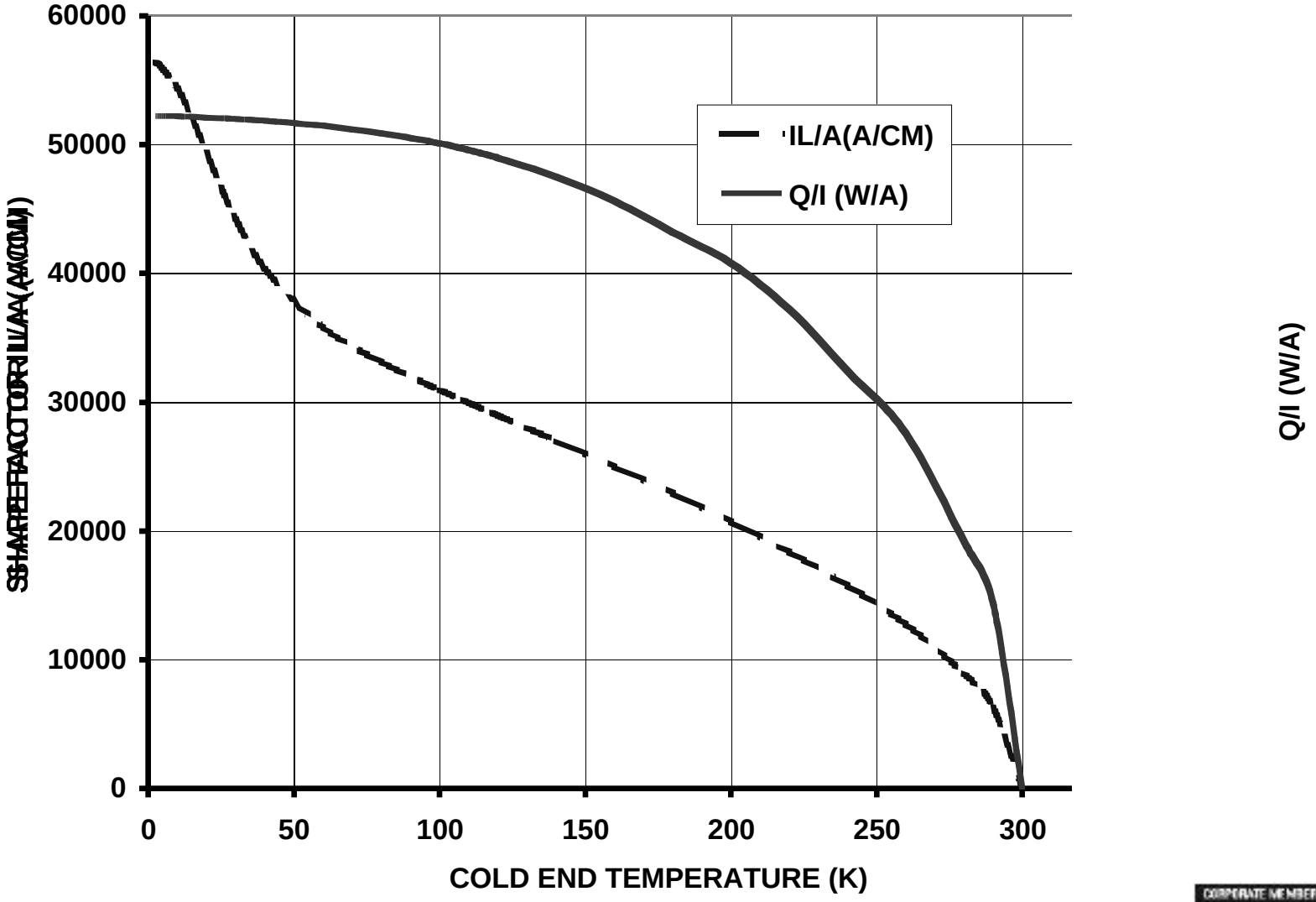
$$[Q_L]_{\min} = I\left[(\rho k)_{avg}(T_H - T_L)\right]^{1/2}$$

$$\frac{IL}{A} = \frac{1}{I}\left[\frac{[Q_L]_{\min}}{\rho_L} - \int_{T_L}^{T_H} \frac{d^{3/4}\sqrt{1/\rho}}{dT} Q(T)\,dT\right]$$

$$Q(T) = \left[2(\rho K)_{avg}(T_H - T)\right]^{1/2}$$

$$(\rho k)_{avg} = \frac{1}{T - T_L}\int_{T_L}^{T} \rho(T)k(T)\,dT$$

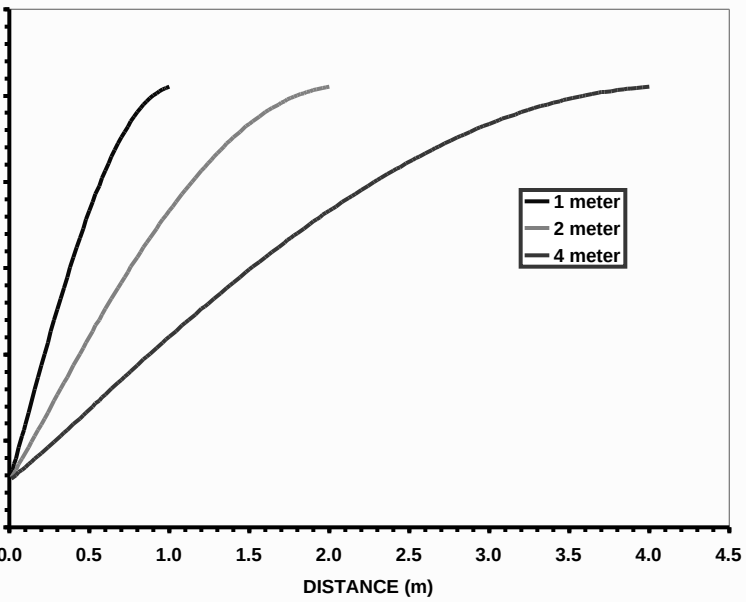
McFee design chart for conduction cooled leads, RRR=100.

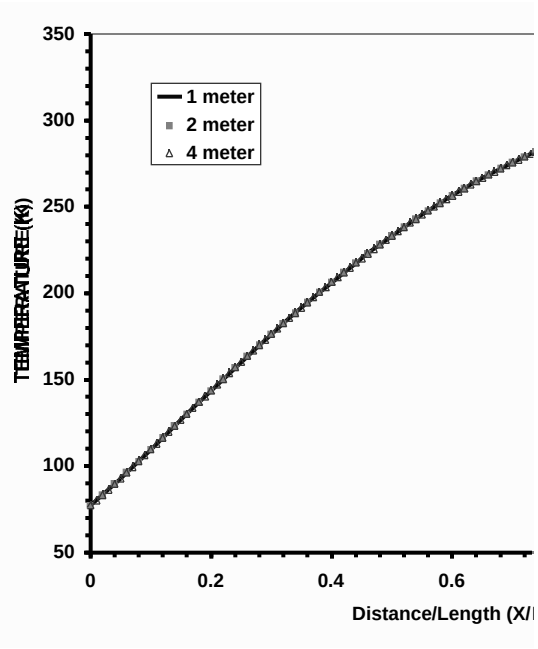


Optimized temperature profiles are simila

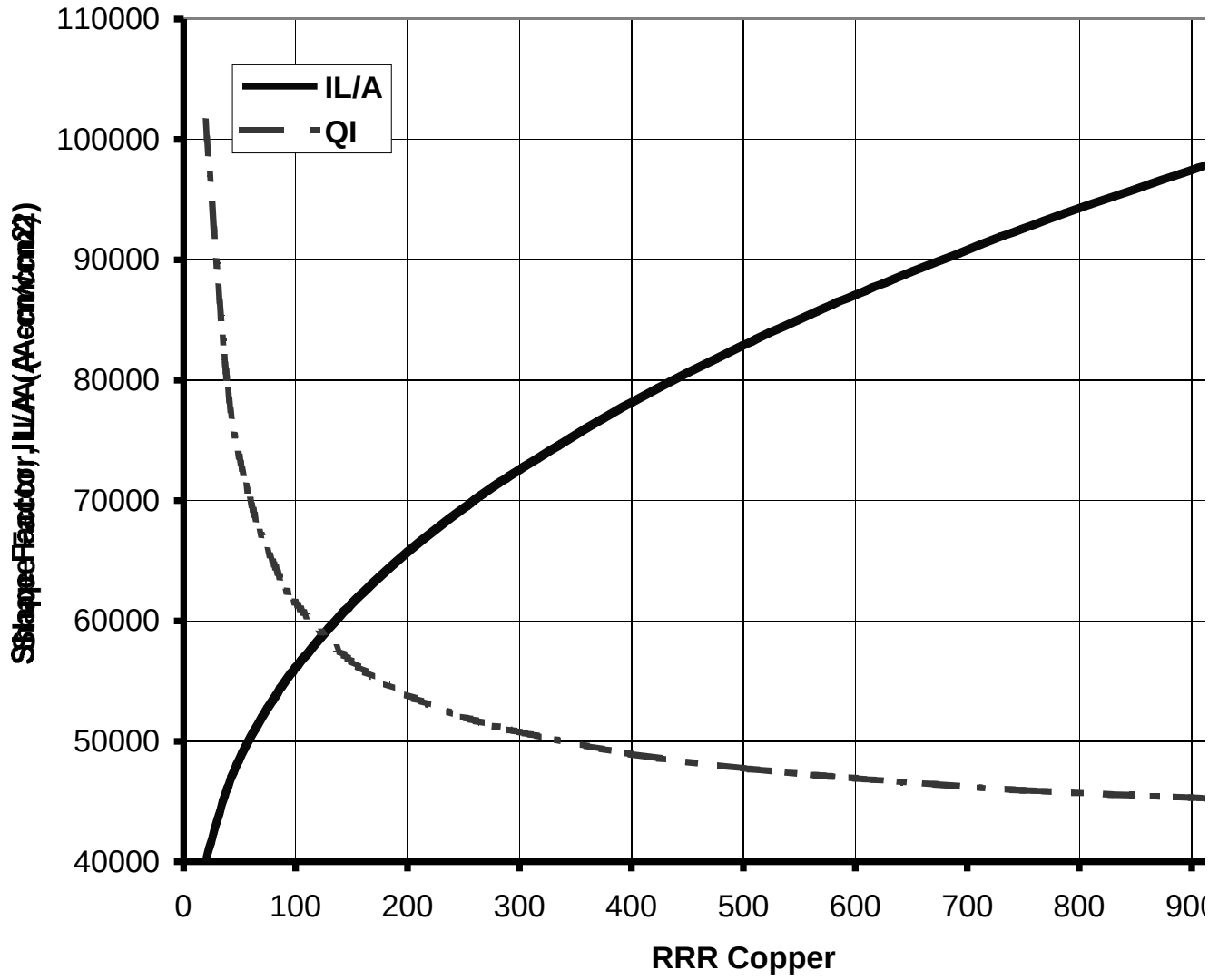
- Numerical solution for same IL/A.
- No heat load from warm end (***X=L***).

$$\left.\frac{fT_c}{fx}\right|_{x=L} = 0$$



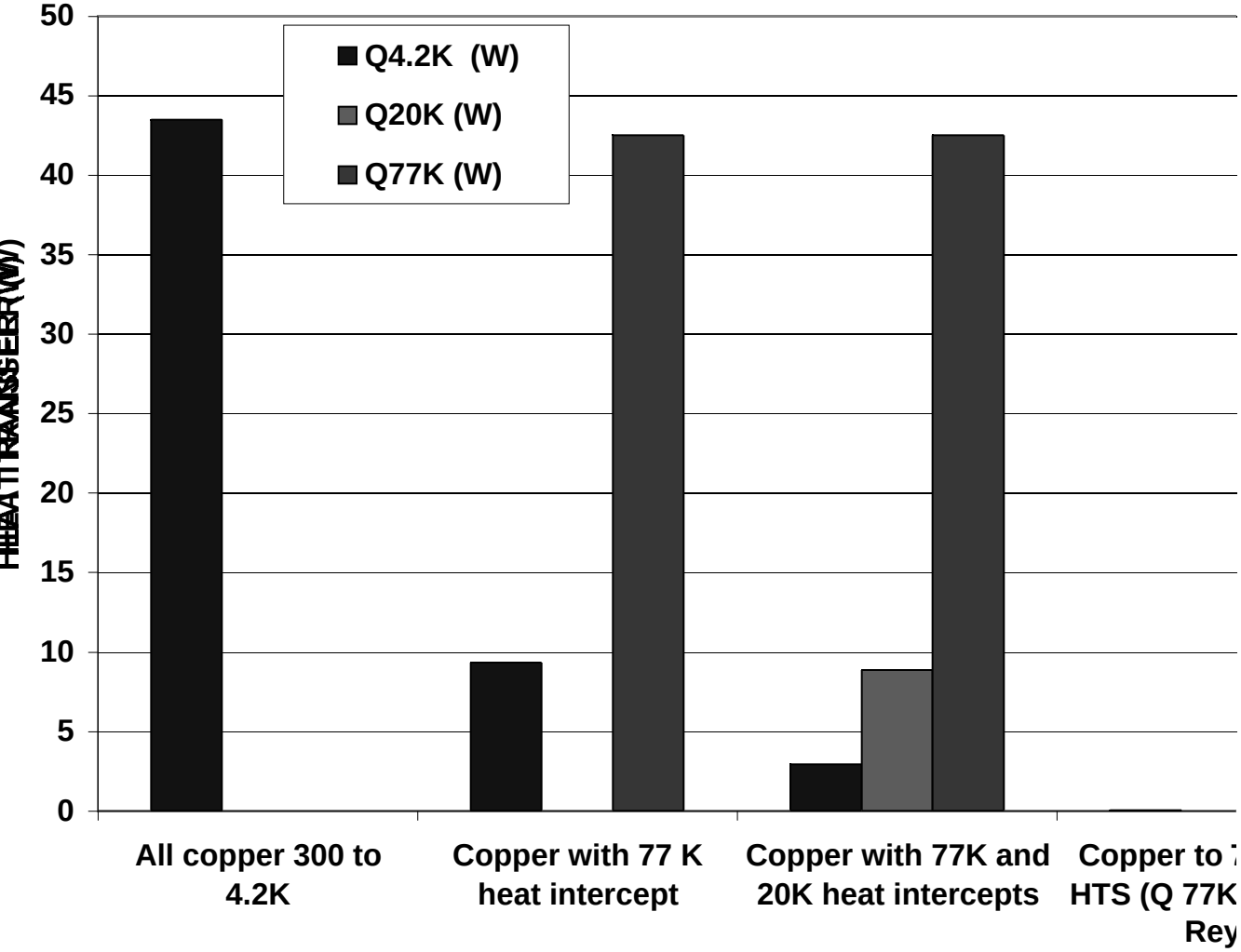


esign parameters for a lead going from 300K to
K vary with copper RRR using McFee's method

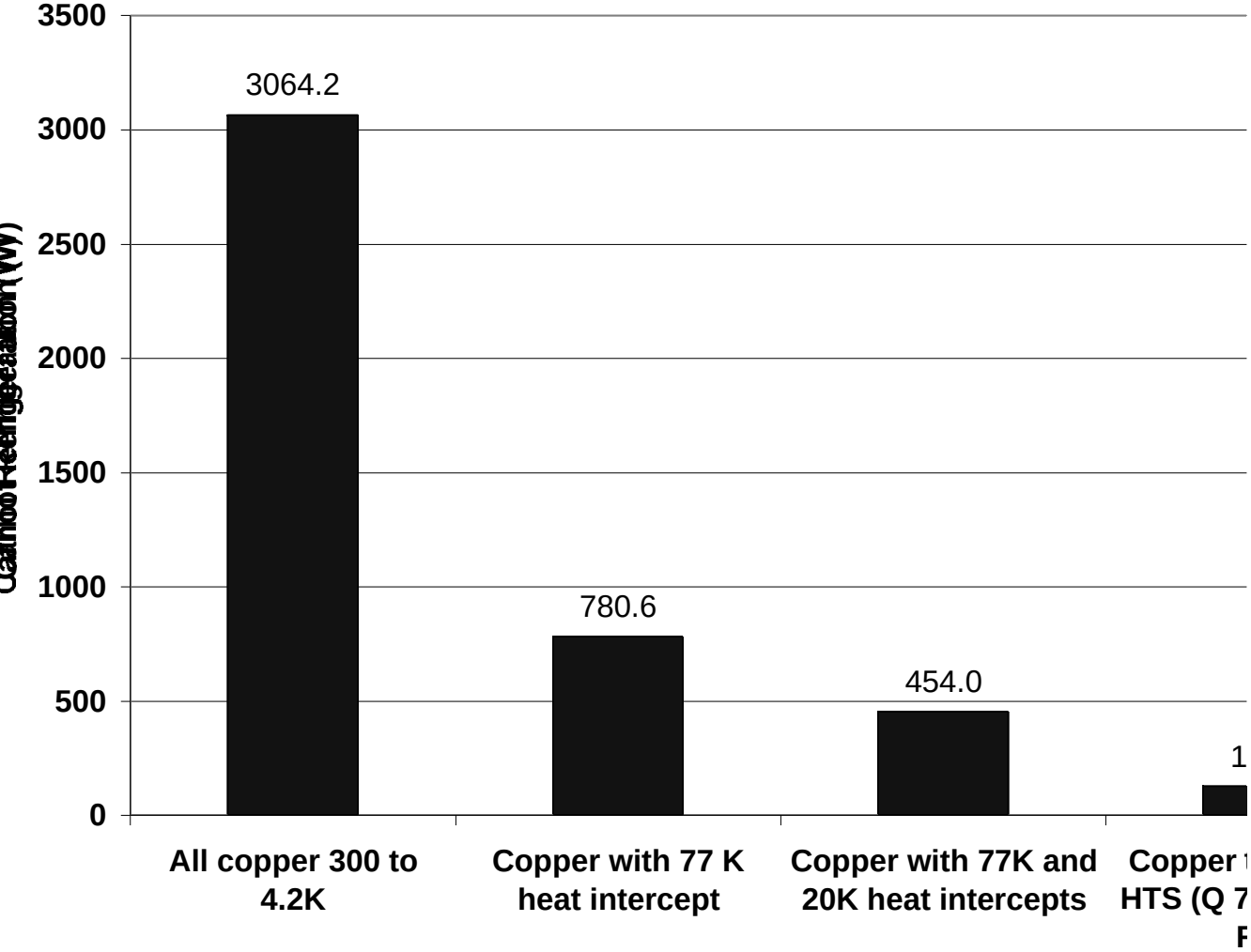


Heat Load (W/A)

Heat loads can be determined from McFee analysis for different lead configurations. Using a I=1kA lead as the basis.

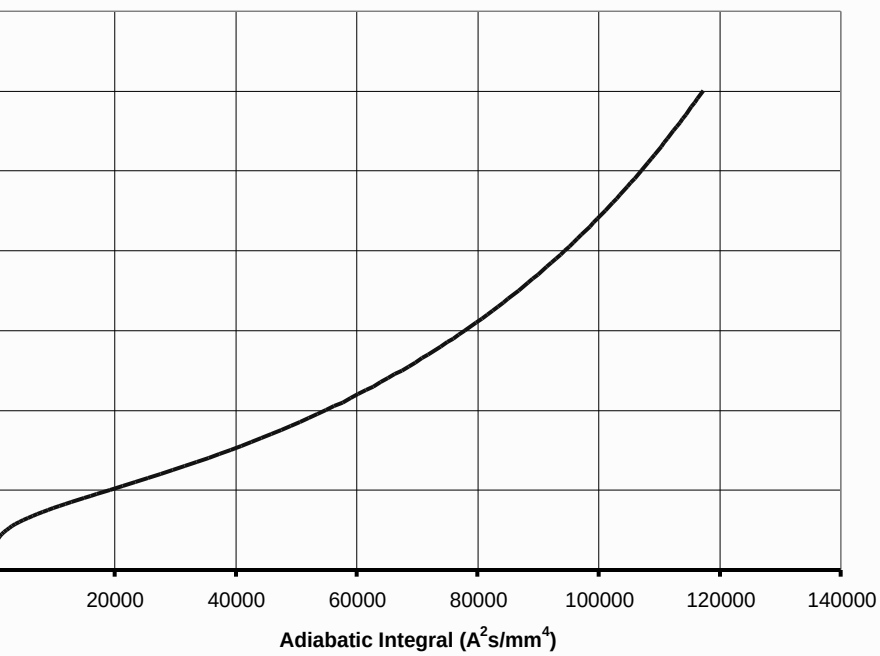


Heat loads from McFee analysis illustrate potential benefits of heat stationing and use of HTS leads for I=1kA.



Fault current heating of conductor can b estimated by adiabatic energy equation.

- Adiabatic integral for copper conductor.



- Energy Equation:

$$\frac{1}{A^2}\int_{\tau=0}^{\tau=t} I^2 d\tau =$$

- At initial T, read integral.
- Calculate current integral, add to value at initial T.
- Find limiting (adiabatic) temperature.

Vapor/forced cooled leads are more complicated than conduction cooled.

Analysis includes solution of helium energy balance.

Heat transfer surface area considerations

- Seek large surface perimeter to cross sectional area
- Examples of commonly used surface area designs
  - Helical or spiral fin (> 10 cm^2/cm^3)
  - Thin foils
  - Braided conductor (> 100 cm^2/cm^3)

Models can be validated by comparing with experimental data.

Operational performance of many lead designs are similar.

	I (A)	*Q (@I=0) (W)*	*Q/I (W/kA)*	*m (g/s)*	*m/I (g/s/kA)*
Hera	**6500**	**20.8[a]**	**3.2+/-0.3 [a]**	**0.34**	**0.052**
KEK	**7000** **10000**	**7.47** **10.4**	**1.07** **1.04**	**0.387** **0.506**	**0.055** **0.049**
AMI (1.4 lit/hr/kA)	**6600**			**0.321**	**0.049**
JINR/LHE	**4000** **6000 (6 kA)** **(7 kA)** **(9 kA)**	**4.0 (2.5)** **6.0 (4.0)** **6.72 (3.5)** **7.02 (6.0)**	**1.0** **1.0** **1.12** **1.17**	**0.2** **0.3** **0.316** **0.351**	**0.05** **0.05** **0.053** **0.059**

[a.] Values shown are for combined heat leak and boil-off

- References:
- Ben-Zvi, B. V. Elkonin, J. S. Sokolowski, and D. Sellmann, "Current Leads for HERA," Nuclear instruments and Methods in Physics Research, A276, 1989
- K. Maehata, S. Kawasaki, K. Ishibashi, Y. Wakuta, H. Kawamata, and T. Shintomi, " Operational Performance of Spiral Fin Current Leads," Cryogenics, V33, No.7, 1993
- American Magnetics Inc., Oak Ridge, Tennessee, Catalog.
- V.D.Bartenev and Y.A.Shishov. “Force-cooled current leads for the force-cooled superconducting magnets of the Nuclotron”, Cryogenics 31:985 (1991).

Model validation is accomplished by comparing it with experiments.

6.6 kA test lead description

- Heat exchanger - Spiral fin design.
- Forced flow cooling with 4 bar (supercritical) helium.
- Core diameter = 1.59 cm
- Length = 83.5 cm
- Nb-Ti LTS extends into first 30 cm of lead.

Current ramp up at 6 A/s, hold at 5000 A, down at -4 A/s.

Flow controlled off of top end temperature (set at 253 K).

Temperature sensors, voltage taps along lead.

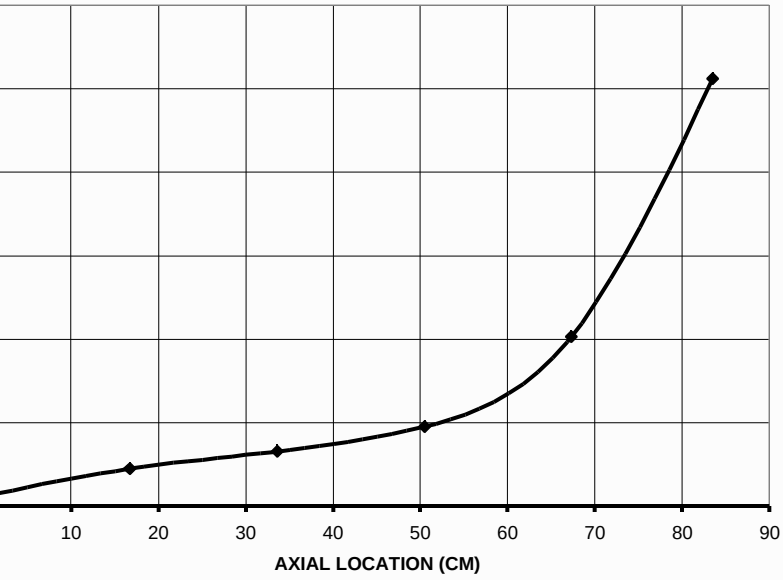
Model uses finite difference derivative approximations and the numerical method of lines.

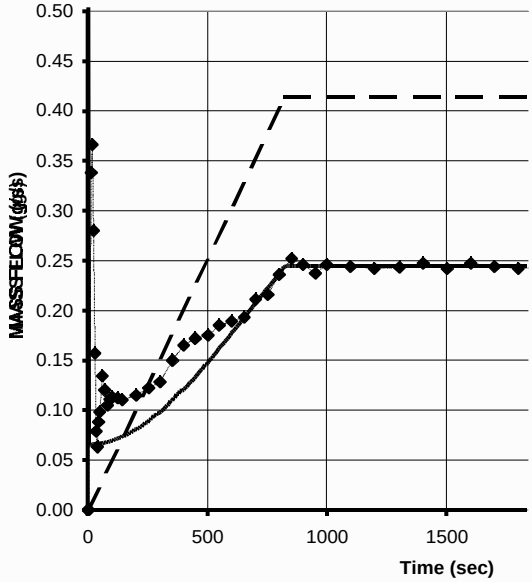
Current lead test apparatus at University of Wisconsin - Madison

- HTS lead test rig picture courtesy of Professor John Pfotenhauer, University of Wisconsin-Madison

Time dependent analysis of 6.6 kA forced flow superconducting magnet lead test.

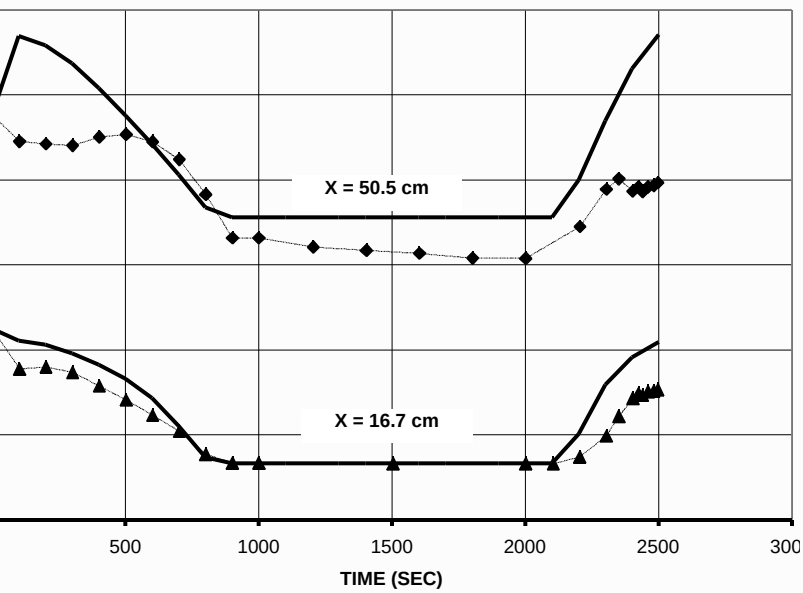
- Initial conditions were fit from measured temperature data
- Flow control model agrees well with data

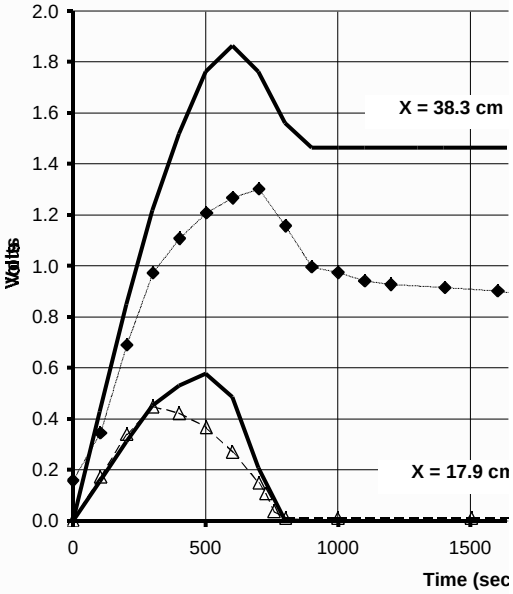




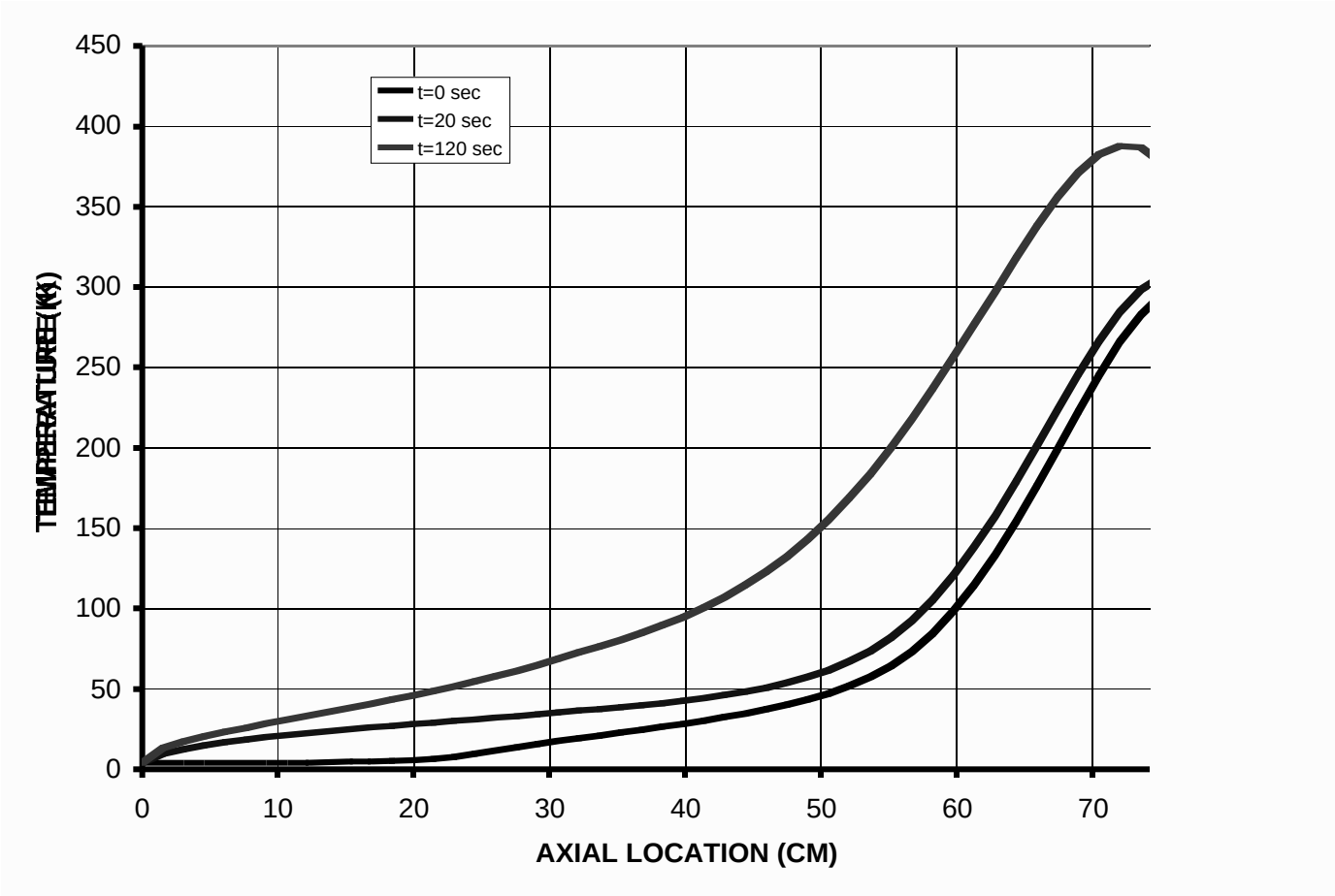
Transient response at different axial locations can be simulated well.

- Temperatures vary with current and mass flow
- Voltages along lead vary with current and mass flow





Simulated loss of cooling situation shows long time constant at top but short response time at cold end.



Fixed cold end temperature is not the best boundary condition to apply!

Optimization can be performed on basis of minimum Carnot refrigeration.

- The Carnot work contains both refrigeration and re-liquefaction terms:

$$\dot{W}_{Carnot} = \dot{m}_v w_{reliq} + \left(\frac{T_{vh} - T_{vc}}{T_{vc}}\right)\dot{Q}_c$$

- Generally, at much less than the design operating current, (i.e. I=0 A) there is a distinct minimum.
- For operation near the design operating current, the minimum Carnot work is at the lowest safe flowrate.

$$w_{reliq} = T_1(s_1 - s_f) - (h_1 - h_f) \quad 6819(J/g)$$

Description of the10 kA lead design in this optimization discussion.

- Carnot work minimized over range of diameters for a given length.
  - Mass flow constraint $\dot{m}_{opt} < \dot{m}_{\max}$
  - Heat load constraint $\dot{Q}_{opt} < \dot{Q}_{\max}$
- Lead description
  - Heat exchanger - Spiral fin design.
  - Forced flow cooling with 4 bar (supercritical) helium.
  - Core diameter = 2.2 cm
  - Length = 129.4 cm
  - Nb-Ti LTS extends into first 15 cm of lead.
- For given dimensions, there is a set of optimal operating conditions.

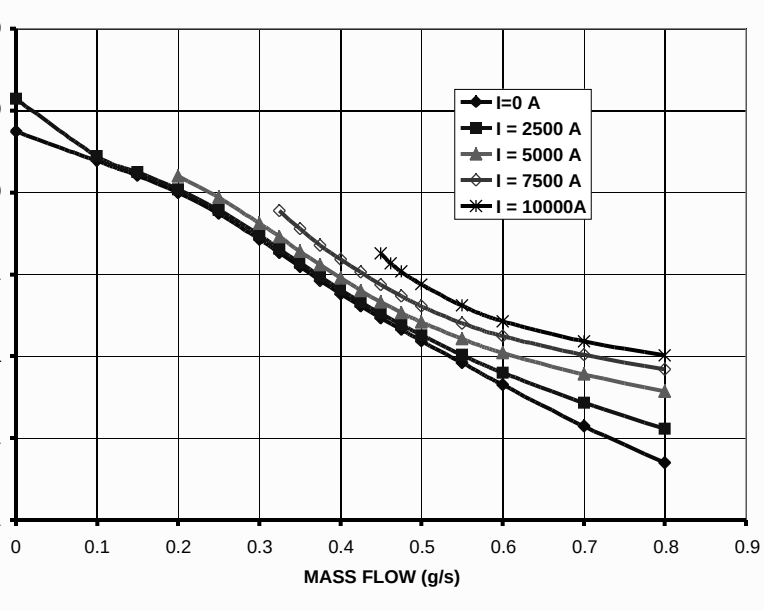
- Reference: Q. S. Shu, J. A. Demko, R. Domam, D. Finan, T. Peterson, I, Syromyatnikov, and A, Zolotov, IEEE Transactions on Applied Superconductivity, Vol. 3, No. 1, 1993, pp408-412.

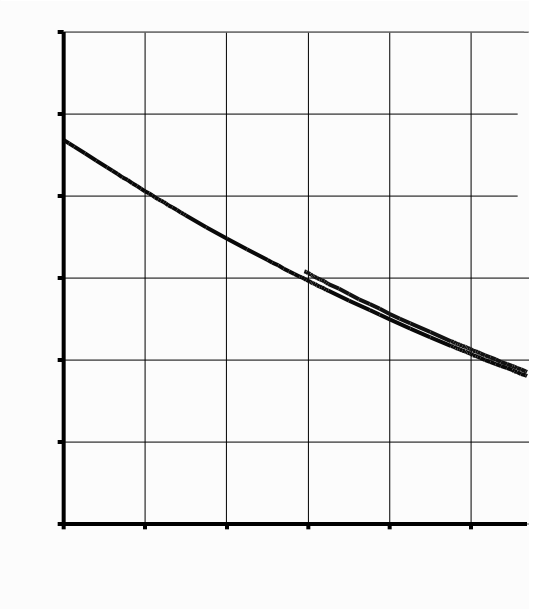
10 kA lead design showing installation into He dewar.

– Figure inserted manually from reference

Optimizing operation of 10kA forced flow cooled superconducting magnet lead.

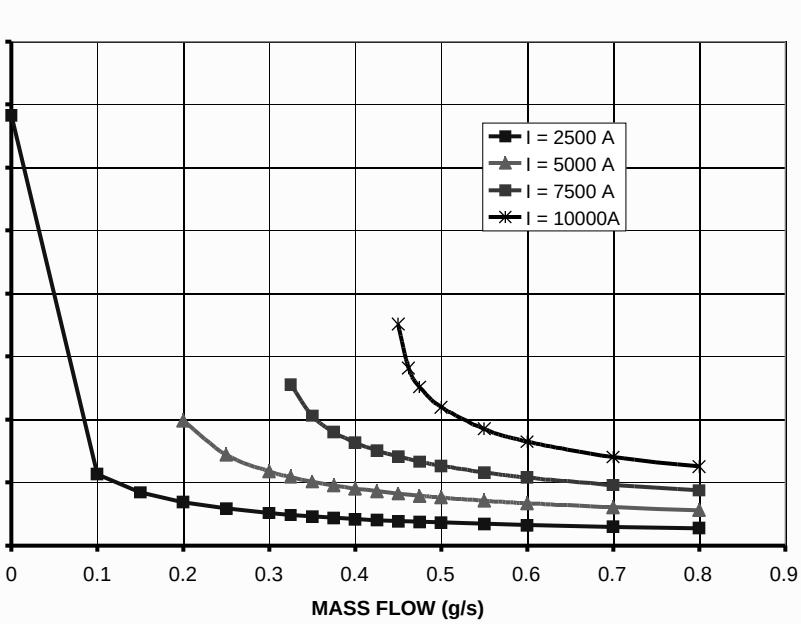
- The calculated heat load will decrease with mass flow.
- The calculated top end temperature can be set by adjusting mass flow.



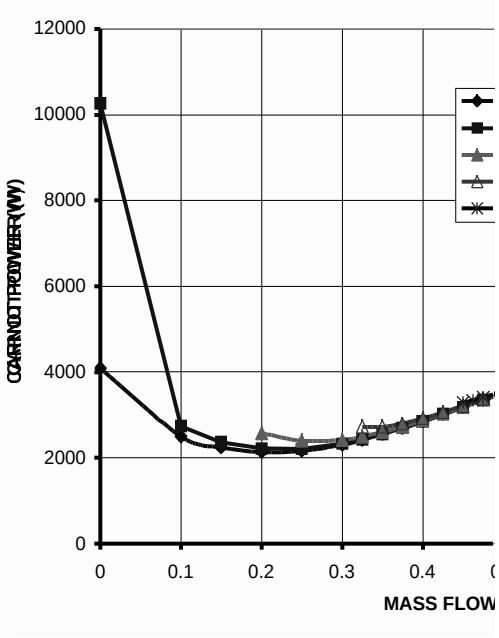


Optimizing operation of 10kA force flow cooled superconducting magnet lead.

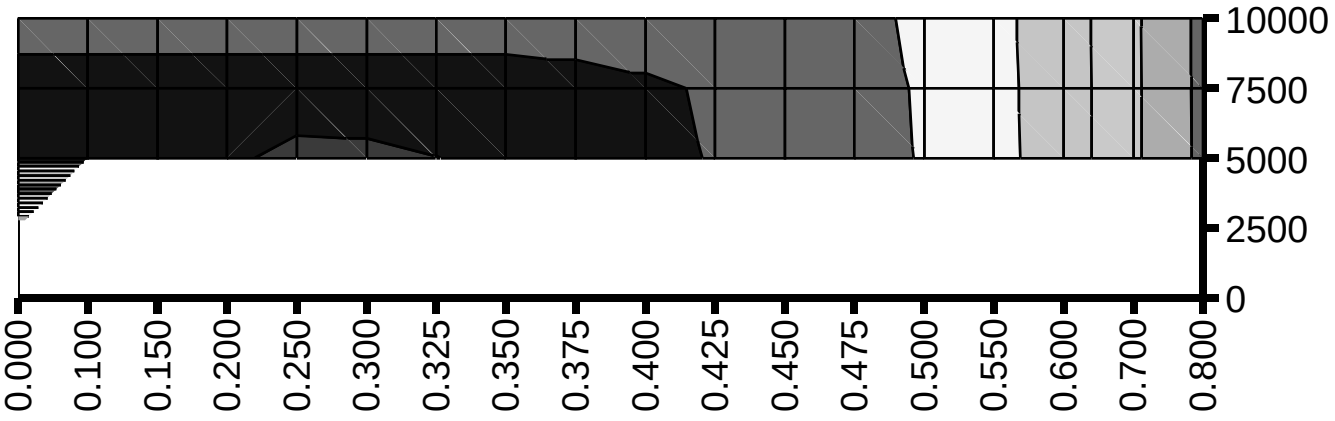
- Voltage drop calculated across lead decreases with mass flow.



- Calculated Carnot power has a minimum value for each operating current.

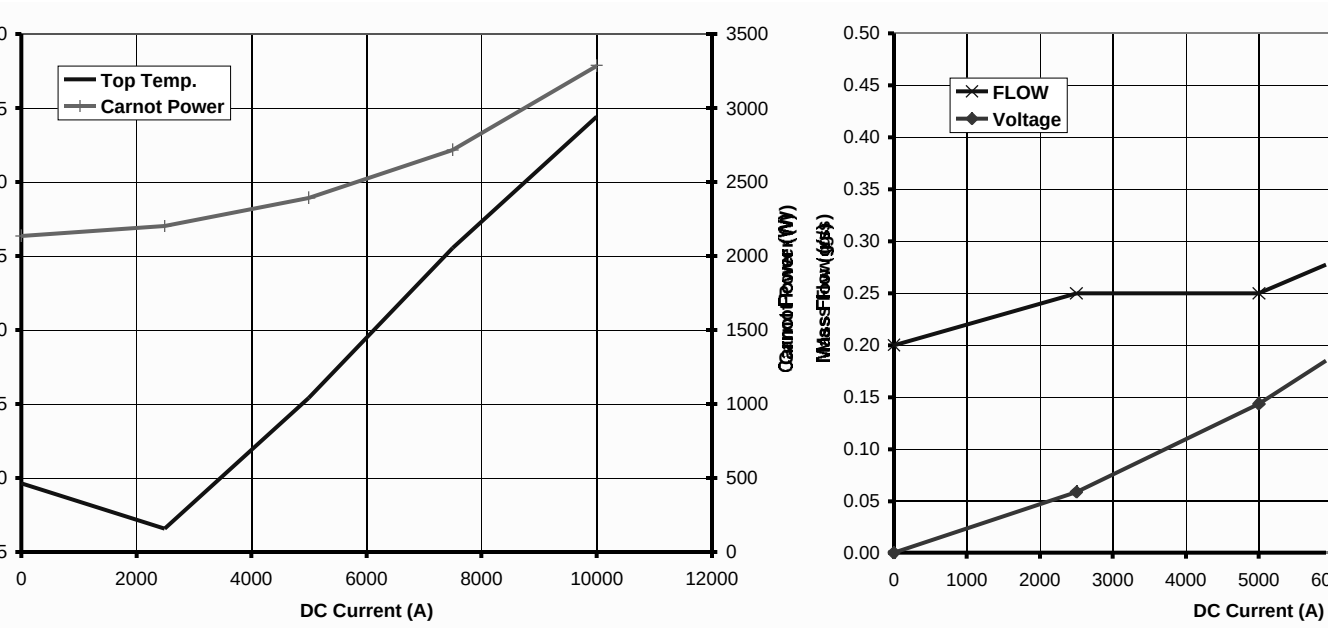


Carnot power contours show optimal safe operating regions for 10kA lead.



ptimized operation of 10kA forced flow ooled superconducting magnet lead.

- Optimal steady state cooling flow can be determined from Carnot power.



Summary

Current leads can be designed for different operating modes.

- ***Conduction cooled***
- ***Forced flow / vapor cooled.***

Thermal optimizations have different approaches.

- ***Conduction cooled: McFee method.***
- ***Forced/vapor cooled minimizing Carnot power.***

There is a thermally optimized operating line.

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