TITLE: Tohoku Bubble Chamber Magnet Heat Leak Summary

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TABLE OF CONTENTS

INTRODUCTION

This magnet system consists of two coils with independent cryogenic, vacuum, and current lead systems. All LHe helium components are shielded with LN2 cooled copper shields. In addition, all supports and the LHe storage dewar neck have LN2 intercepts. To reduce helium boiloff, vaporized gas is collected in the storage dewar and routed back down to all the Randolite & Inconel 718 axial and horizontal supports as an additional thermal intercept. After cooling the last support, the gas stream is split and flows in a serpentine fashion through a series of holes up the two radial stainless steel support arms where it exits near the LN2 intercept.

Dimensions and Conversion Factors

Conduction Heat Leak	Temperature Range (°K)	Area (cm^2)	Effective Length (cm)
Axial Randolite	293-80	25.65	6.0
	80-15	25.65	8.9
	15-4.2	25.65	8.6
Axial Inconel 718	293-80	.495	6.35
	80-15	.495	7.62
	15-4.2	.495	10.48
Horz. Randolite	293-80	25.65	4.76
	80-15	20.27	7.62
	15-4.2	20.27	6.67
Radial Arms	293-80	42.3	25.4
	80-15	42.3	35.6
	15-4.2	42.3	12.7
LHe Dewar Neck	293-80	42.6	24.1
	Middle Tube	35.9	20.32
	Bellows	1.46	10.4
	15-4.2	25.9	30.5
LN2 Neck	293-80	1.77	33

Helium: 1 watt = 1.4 liter/hr = .0486 gm/sec

1 liter = 26.6 SCF (70°F)

Nitrogen: 1 watt = .0224 liter/hr = 5.02×10^{-3} gm/sec

1 liter = 24.6 SCF (70°F)

LN2 BOILOFF

The LN2 is fed from a separate storage dewar into the magnet, back through the interconnecting line and LHe dewar, returning to the LN2 dewar. Flow is accomplished using a thermal syphon technique where the LN2 is routed to the bottom of the system without any connections to the support system. The LN2 shield should theoretically run at ~ 80°K where 2 or 3 °K is attributed to the pressure head. In fact, thermocouple measurements indicate that the shield runs at approximately 90°K. Thermocouples on the axial post give a 100°K intercept temperature. This temperature will be assumed for all LN2 intercepts (Note: The log book shows 95°K and 108°K. The 108°K reading was found to be ~ 8°K too warm when calibrated in LN2.

Axial and Horizontal Supports:

It will be shown latter on that the He gas intercept runs at ~ 10°K average temperature.

Material	Temperature Range °K	Thermal Conductivity (W/cm) Integral
Randolite	293-100	1.1
	100-10	.20
Inconel 718	293-100	16.9
	100-10	4.0
304 Stainless	293-77	27.2
Steel	273-100	21.3

LN2 heat leak = Q (293-100) - Q (100-10)

$$Q = \frac{A}{L}\int_{T_1}^{T_2} K(T)\, dT$$

where the appropriate A and L are taken from the table of dimensions for each section.

For individual supports we get the following LN2 heat leaks using the 100°K intercept temperature.

	LN2 Heat Leak (watts)
Axial Randolite Post	4.1
Axial Inconel 718 rod	1.06
Horizontal Randolite Post	5.4

If the intercepts were at 77°K, the LN2 consumption rate would be about 10% greater.

Vertical Stainless Steel Support Arms:

No heat is assumed to flow past the LN2 intercept for this calculation since the helium gas exits very close to the LN2 intercept temperature.

For the ideal case of a room temperature end and 77° intercept temperature, we get

$$Q \text{ ideal} = 45 \text{ watts per arm}$$

However, frost is observed at the top of the arm.

Assume $T_{warm} = 273K$ and $T_{cold} = 100°K$ for the real case

$$Q \text{ actual} = 35 \text{ watts}$$

Two thermocouples were installed in two of the radial arms 15cm apart to measure the heat leak.

Radial Arm	Tc1	Tc2	ΔT
A	163°K	248	85
B	162	245	83

$$\int_{163}^{248} K(T)\, dT = 11 \text{ W/cm}$$

$$Q \text{ measured} = \frac{42.3}{15} \times 11 = \underline{31 \text{ watts}}$$

Good agreement with the calculated value.

LHe Dewar Neck:

This is a very complex assembly. See the accompaning figure. Only crude approximations will be made due to the additional bellows heat path and possible gaseous conduction. Again the LN2 intercept is assumed to be at 100°K and the top at 273K.

Q outer tube = 38 watts

If the bottom of the bellows is assumed to be at 100°K and the top at 273°K, no heat flows to the LN2 intercept. It is all picked up by the helium gas cooling.

Q bellows = 3.0 watts

In reality this heat is divided between the LN2 and helium gas.

The bellows provides a means to evacuate between the outer warm wall (273 to 100°K) and the middle tube (100°K). A pair of valves protects the bellows in case of a quench. However, if these valves leak helium, the LN2 consumption rate can skyrocket. A copper fin attached to the LN2 intercept is installed to minimize any possible gaseous conduction load on the helium system. Twelve layers of superinsulation were placed between the copper fin and the outer wall.

Area~ $\pi \times 11 \times 10 = 345 \text{ in}^2 = 2230 \text{ cm}^2$

$$Q = KA \frac{\Delta T}{\Delta X}$$

$\Delta x \sim .25'' = .63\text{cm}$

For 1 atm to .1 atm of 293°K helium gas,

$K = 1.55 \times 10^{-3}$ watt/cmK

Worse case: Q = 1050 watts

From Fermilab calculations we get the following calculated heat transfer rates for a 1" path length.

Pressure (Microns)	K effective W/cm^2	Q (watts)
100	.139	310
10	.015	33

The multilayer superinsulation should cut the heat load by a significant factor for pressures above 100 microns, but the exact value is unknown.

LN2 Dewar:

Conduction down than neck 1.4 watts

Blackbody radiation down the neck 1.4 watts

Thermal Radiation $Q = 10.5\ ft^2 \times \frac{3\ BTU}{hr/ft^2} = 3.1 BTU = .92$ watt

10 G-10 1/4"-20 standoffs X3/4" long 2.3 watts

Total for the LN2 dewar = 6.0 watts

A boiloff test was performed, and the measured heat leak was found to be 7.5 SCFH = 13.6 watts. Either there exits a small thermal short or the test was not performed with the dewar under an adequate vacuum.

Thermal Radiation:

In my safety memo on maximum pressures in the Tohoku Bubble Chamber Magnet system, the area of the cryostat was found to be 25,000 in^2 (174 ft^2). The LN2 dewar and LN2 flex line add another 2500 in^2 for a total of 27500 in^2 (191 ft^2).

Sixty layers per inch with a total of 40 layers of superinsulation were used between most LN2 and outer wall shells.

Then for NRC2, $Q/A = .17\ BTU/hr/ft^2 = .088\ watt/ft^2$

$Q = \underline{10\ watts}$

LN2 Shield Standoffs

Assume for the standoffs that the LN2 shield is at 90°K.

Material	$\int_{90}^{293} K\,dT$
G-10 CR	1.35 W/cm
Ti6Al4V	11.9

Standoff Location	Number	Material	Effective Length cm	Area cm^2	Heat Load watts
Base Plate	46	Ti6Al4V	1.59	.183	63
Base Plate	36	G-10	2.22	.32	7
Outer Wall	39	G-10	1.59	.32	11
Inner Wall	30	Ti6Al4V	.79	.097	44
Inner Wall	7	G-10	.95	.32	3
Top Plate	4	Ti6Al4V	1.59	.183	5.5
Interconnecting Line	10	G-10	13.3	.50	.5
LHe Dewar	30	G-10	1.9	.32	25

Total heat flux = 159 watts
from standoffs

All spacers except those in the interconnecting line are threaded rods. The area is based on the O.D., and not all spacers are touching. Thus, 159 watts is an upper bound.

Calculated LN2 Heat Leak Summary:	Watts
8 Axial Randolite Posts	33
4 Horz. Randolite Posts	22
16 Inconel 718 Axial Rods	17
2 Stainless Steel Arms	70
1 LN2 Dewar	5
Standoffs (total)	159
Thermal Radiation	17
LHe Dewar Neck (metallic conduction)	38
LHe Dewar Neck (min. gaseous conduction)	33
Total 394 watts = 8.8 liter/hr	

Caution: It is important to remember that the heat leak can increase by 1000 watts. = 22.4 liter/hr if helium bleeds past the relief valves for the LHe dewar neck bellows.

Measured LN2 Boiloff:

11.5 liter/hr

Gaseous conduction in the dewar neck could easily account for this 30% difference.

LHE BOILOFF

Gas Intercepted Axial and Horizontal Supports:

Using a heat balance approach one can optimize the helium boiloff by choosing the correct intermediate temperature. The approach involves selecting an intermediate temperature T and then calculating the position of the intercept which satisfies the heat balance.

Plotting these values one can find an optimium location and temperature which minimizes the heat leak to 4.2K. This approach was presented in a memo by Pless and Stoughton, June 13, 1979. Summarizing:

$$Q_1 = \frac{A}{\ell_1} \int_{4.2}^{T} K \, dT$$

$$Q_2 = \frac{A}{\ell_2} \int_{T}^{T_{LN2}} K \, dT$$

$$Q_0 = \frac{A}{\ell_1 + \ell_2} \int_{4.2}^{T_{LN2}} K \, dT$$

$Q \text{ gas} = Cp \, (T-4.2) \, Q_1$ Cooling provided by the boiloff gas. Self sufficient case.

$$\gamma = \frac{Q_1}{Q_0}$$

$1/\gamma$ = figure of merit

$$C = \frac{Cp}{\Delta H_{fg}} = \frac{\text{specific heat per unit mass}}{\text{heat of vaporization per unit mass.}}$$

$$B = \int_{4.2}^{T} K(T) \, dT \Big/ \int_{4.2}^{T_{LN2}} K(T) \, dT$$

then

$$\gamma = \frac{1+C\ (T-4.2)B}{1+C\ (T-4.2)} \qquad C = \frac{\text{specific heat per unit mass}}{\Delta H_{fg} \text{ per unit mass}}$$

$$\frac{\ell_1}{L} = \frac{\ell_1}{\ell_1+\ell_2} = \frac{B}{\gamma}$$

Cp was chosen to be 5.2 j/gm°K
5.49 j/gm°K would have been a better choice.

$$m = \frac{\gamma Q_0}{\Delta H_{fg}}$$

Curves are given for γ and ℓ_1/L for both Inconel 718 and Randolite rods for self sufficient boiloff rates. For expample, using the axial Randolite post between 4.2 and 77°K, we get:

$\gamma = .24$

$\ell_1/L = .44$

$T_{optimum} = 25°K$

$$\int_{4.2}^{77} K\ dT = .15 \text{ w/cm}$$

$$Q_{4.2} = Q_1 = \gamma \frac{A}{L} \int_{4.2}^{77} = .24 \times \frac{25.65}{17.5} \times .15 = .052 \text{ watt}$$

=minimum heat leak for a post between 4.2 and 77

Our supports, however, have a LN2 intercept temperature of ~ 100°K, and the optimum location was not always chosen due to construction constraints. Non-optimum locations present only small increases in heat load because of the broad minimum in γ.

Self Sufficient Boiloff

Support	(Optimum 4.2 to 77) γ	T °K	ℓ_1/L	Q watts	(As built 4.2 to 100°K) γ	T °K	ℓ_1/L	Q watts
Axial Randolite	.24	25	.44	.052	.21	31	.49	.062
Axial Inconel	.27	24	.40	.022	.23	35	.58	.026
Horz. Randolite	.24	25	.44	.051	.21	31	.47	.060

Adding up the heat leaks to 4.2K,

Q (optimum; 4.2-77) = .97 watts

Q (actual; 4.2-100) = 1.15 watts = 1.65 liter/hr

*NOTE: There is a very small penalty for a 100°K LN2 intercept and slightly off optimum intercept location.

Without gas cooling the 4.2K heat leak would be $\frac{1.15}{.22}$ =5.2 watt This gas cooling saves ~ 8x1.4 = 11 liter/hr for the complete magnet system.

Gas Cooled Axial and Horizontal Supports Non-Optimum Flow Conditions:

Heat leaks into 4.2 for gas flow rates other than self-sufficient boiloff can also be easily calculated.

From an energy balance;

$$Q_2 = Q_1 + Q \text{ gas}$$

$$\dot{m} = \frac{Q_2 - Q_1}{Cp(T-4.2)} = \frac{\frac{A}{\ell_1}\int_T^{100} K\,dT - \frac{A}{\ell_2}\int_{4.2}^{T} K\,dT}{5.2(T-4.2)}$$

1) Pick an intercept temperature T

2) Calculate $\dot{m}$ and plot T vs $\dot{m}$

3) Calculate equivalent heat leak to produce

$Q\ \dot{m}_{o\ He} = \dot{m}\ \Delta\ h_v = 20.42\ \dot{m}$

4) Calculate the heat leak from the support into 4.2K (Q_1) from the thermal conductivity integral.

5) $Q_{He} - Q_1 = Q_{external}$ = the heat from other sources.

6) $Q_{additional} = Q_{He} - Q_{self\ sufficient}$. This equals the heat into the helium in excess of the self-sufficient flow. Q_{add}/Q_{ext} is the fraction of external heat load actually added to the helium.

The following curves have been plotted for both the axial Inconel 718 and Randolite supports:

1) T vs $\dot{m}$

2) $Q_{support}$ (Q_1) vs. $\dot{m}$

3) $Q_{additional}$ vs $Q_{external}$

4) Q_{add}/Q_{ext} vs Q_{ext}

Conclusions:

1) For small external heat inputs the actual penalty is ~ .47 watts per watt.

Conclusions:

1) For small external heat inputs the actual penalty is ~ .47 watts per watt.

2) Both the Randolite and Inconel 718 supports have very similar efficiency characteristics for flows greater than self-sufficient. It can be assumed the horizontal posts also behave the same.

3) We presently flow 120 SCFH = 4.5 liter/hr or $\frac{4.5}{1.65} = 2.7$ times the self-sufficient flow.

$Q_{add} = 4.5 - 1.65 = 2.85$ liter/hr = 2.0 watt

$Q_{self\text{-}sufficient} = Q_{ss} = 1.15$ watt = 1.65 liter/hr

$Q_{add}/Q_{ss} = 2.0/1.15 = 1.74$

Using either the Inconel or Randolite chart,

$Q_{add} = 1.74\ Q_{ss}$; find Q_{ext}/Q_{ss}

Then, $Q_{add}/Q_{ext} = .73$

$Q_{external} = 2.0/.73 = 2.74$ watts

A 2.74 watt external heat load + 1.15 support heat load = 3.89 watt is reduced to 2.0 + 1.15 = 3.15 watt.

4) The exit temperature of the gas after intercepting all the supports is ~ 16°K.

Gas Cooled Radial Arms:

After thermally intercepting all axial and horizontal supports, the gas stream is equally divided to both vertical stainless steel arms. The gas stream flows in a serpentine fashion up through 38 threaded holes. The holes were sized for optimum heat exchange. We will assume perfect heat transfer.

Heat exchange length = 14" = 35.6 cm

Area = 42.3 cm^2

L/A = .84 cm^{-1}

The LN2 intercept is assumed to be at 100°K. The gas entering the arm is assumed to be at 15°K. The previous section demonstrated that the temperature was ~ 16°K.

This problem is solved using Scott's eq. 7.9. I have plotted his equation for end temperatures of 15°K and 100°K.

The self sufficient boiloff case has a cold end heat leak of .58 watts per arm. For comparison, the ideal case with 4.2K and 77K ends has a self- sufficient heat flux of .35 watts. Without any cooling the heat load would be.

Q_0 = 3.15 A/L = 3.75 watts 4.2 to 77K

5.2 A/L = 6.2 watts 15 to 100K

For either case the improvement factor is ~ 10.5. At present, we have 60 SCFH or .078 gm/sec. From the chart we see that this mass flow rate is greater that that required for no heat leak. In fact, for L/A = .84 any mass flow rate greater than ~ .05 gm/sec = 1.44 liter/hr = 38 SCFH (70°F) is wasted.

However, we have roughly a 5" (12.7cm) uncooled path length between 4.2K and 15°K.

$$Q = \frac{42.3}{12.7}\int_{4.2}^{15} K\,(T)\,dT = .28 \text{ watts per arm}$$

Thus, the minimum heat leak to 4.2K = .56 watts for both arms.

In retrospect, this path should have been longer and the gas cooled portion shorter.

LHe Dewar Neck:

The stainless steel connection to 4.2K is gas cooled through a set of spirals in a close fitting G-10 tube. As with the LN2 boiloff estimates, the bottom of the bellows (or the top of the gas cooled tubes) can be assumed to be at 100°K. The gas comes from the dewar and starts out at 4.2K.

$L/A = 30.5/25.9 = 1.18 \text{ cm}^{-1}$

The self-sufficient heat leak is:

Q_{ss} = .32 watts= .45 liter/hr= .0156 gm/sec= 12 SCFH (70°F).

Without any gas cooling

$Q_{4.2} = 4.4$ watts

Improvement factor = 13.8

It is found from the chart that the dewar neck adds no additional heat if the mass flow rate is greater than .02 gm/sec= 15.3 SCFH (70°F). Theoretically, any more flow than this is wasted cooling.

*NOTE: A flow of at least 12 SCFH is very important. For .01 gm/sec =

7.6 SCFH, the heat flux into the helium is 1.5 watts which equals 56 SCFH = 2.1 liter/ hr

Thermal Radiation:

Total area = 25,000 in^2 = 174 ft^2

Use 15 mW/m^2 ~ 5 layers of superinsulation plus aluminim tape

= 1.4 x 10^{-3} watt/ft^2

Q radiation = .24 watt

Blackbody radiation from 4.2 to 293°K = .27 watt/in^2

Assume 1 in^2 of blackbody radiation form dewar neck, light cracks etc. Note, however, the top of the LHe dewar has a LN2 intercept. Still there is no perfect seal around transfer lines, LHe probes etc.

Total thermal radiation = .51 watt per half system.

Current Leads:

Presently set at 40 SCFH = 1.5 liter/hr per lead

= 3.0 liter/hr per coil

= 2.1 watt per coil

AMI values

I amps	liter/hr	SCFH
1000	2.8	37
700	2.2	29
0	1.8	24

Standoffs:

LN2/LHe standoffs exist only in the interconnecting line and the LHe dewar.

Assume 10 G-10 interconnecting line standoffs with an A/L = .5/5 = .1 cm. Also assume ten 3/4" long 1/4-20 standoffs touch in the dewar (A/L = .168 cm).

$$\int_{4.2}^{90} K\,dT = .25 \text{ w/cm}$$

Q standoffs = .25 (10x.1 + 10x.168)

= .67 watts

4.2K HEAT LEAK SUMMARY

Measured Boiloff:

Based on liquid level probes ~ 9.5 liter/hr per coil

Based on flow meters ~ 205 SCFH (70°F)

$$\frac{\nu \text{ gas, } 4.2}{\nu \text{ liquid}} = 7.4$$

1 cm^3 of liquid helium vaporizes then,

6.4 cm^3 of gas is expelled and 1 cm^3 of gas remains

$$\frac{\text{gas vented}}{\text{gas vaporized}} = \frac{6.4}{7.4} = .865$$

9.0 liter per x 26.6 SCF/liter x .865 = 207 SCFH (70°F)

Self-Sufficient Flow

	4.2 Heat Leak (watts)	Gas Flow Required SCFH (70°F)
Combined Axial & Horz. Supports	1.15	43
2 Stainless Arms	1.16	43.5
Dewar Neck	.32	12
Radiation	.51	-
Standoff	.67	-
2 Current Leads		
I = 700 Amps	2.1	79
I = 0 Amps	1.28	48
TOTAL		
700 Amps	7.1	178
0 Amps	6.2	147

7.1 watt = 10.0 liter/hr = 266 SCFH x .865 = 230 SCFH

266 SCFH warm gas equivalent would be generated; only 230 SCFH will leave the system. This remaining gas is "wasted" during the next fill cycle. Compare this to the 178 SCFH of required flow.

Adding up all the heat leaks for non self-sufficient flow is difficult. For example, at 79 SCFH per lead pair what is the actual 4.2K heat leak which then further cools the supports? The following recommendations should be used.

1) Set current leads to 40 SCFH end (80 SCFH per coil).

2) Set dewar neck flow to 15 SCFH. At this flow rate the dewar neck adds no heat leak.

3) Flow through each radial arm should be at least 40 SCFH. This means that 80 SCFH or 2 times the self-sufficient flow rate is established for axial and horizontal supports. With 40 SCFH per arm, the minimum 4.2K heat leak for both arms is .56 watts. At the present time our flow rate is ~ 120 SCFH. All extra flow should be sent through the support system.

Total minimum recommended gas flow = 80 + 15 + 80 = 175 SCFH.

Now add up heat leaks.

Axial & Horizontal = 1.15 watt

Current Leads = 2.1 watt

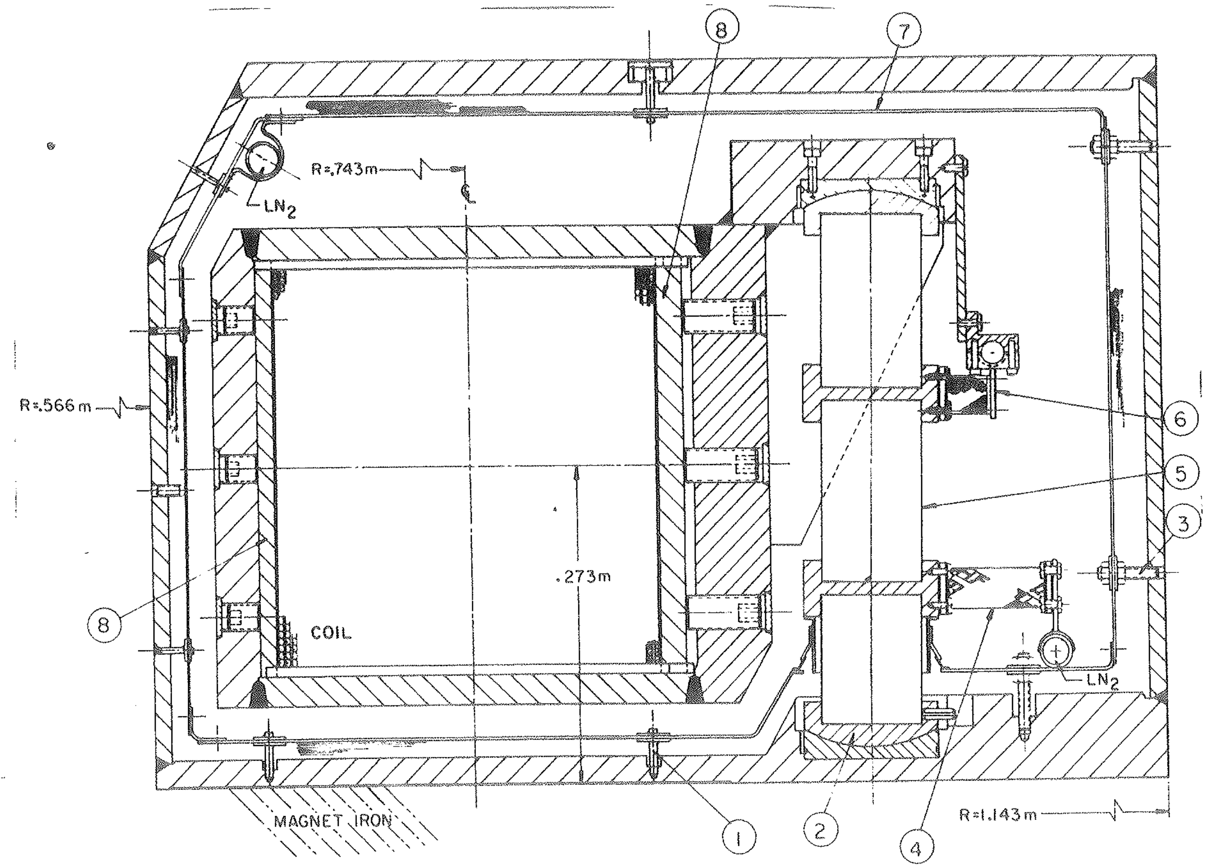
Stainless Arms = .56 watt

Dewar Neck = .40 watt

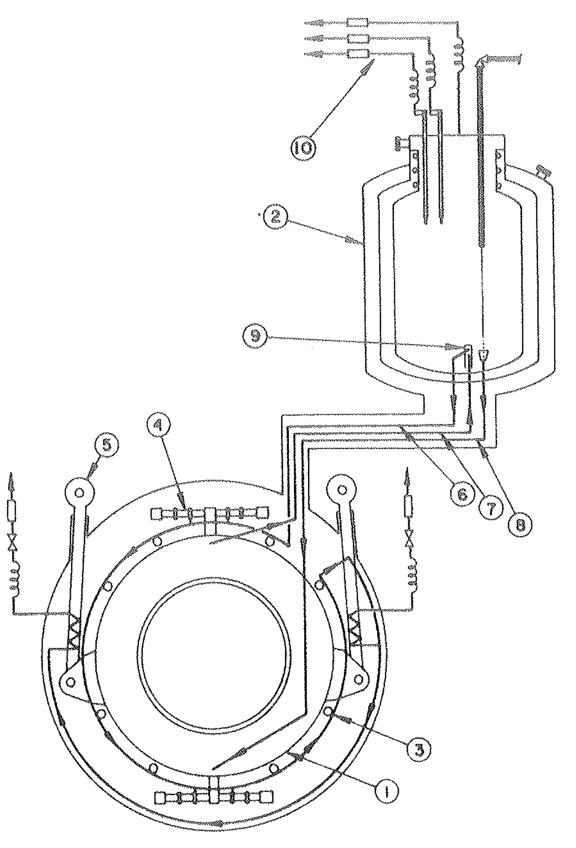
Radiation & Standoffs = 1.18x.69 = (.69 is Q add/Q ext from the charts)

Total = 5.0 watt = 188 SCFH of generated gas

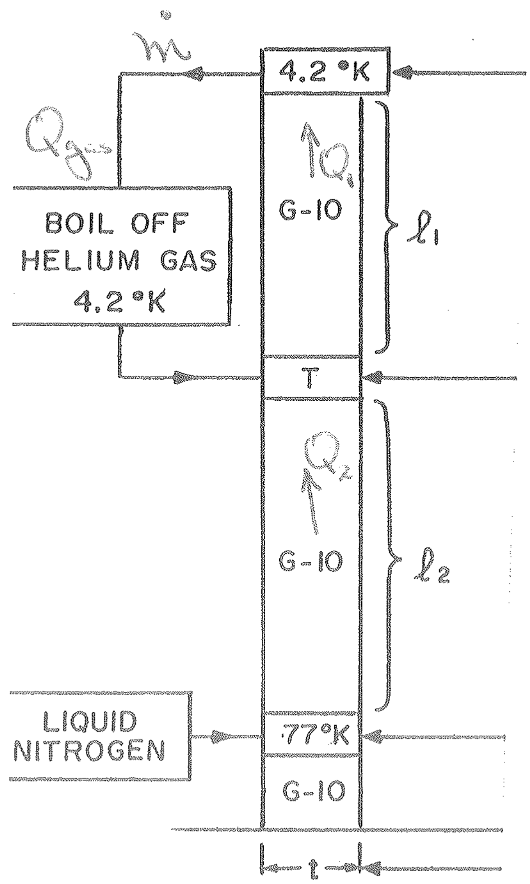
188 x 865 = 162 SCFH = measured boiloff flow. Obviously the solution has not fully converged, but theoretically we should expect to see ~ 170 SCFH gas flow through the flow meter instead of the ~ 207 SCFH.



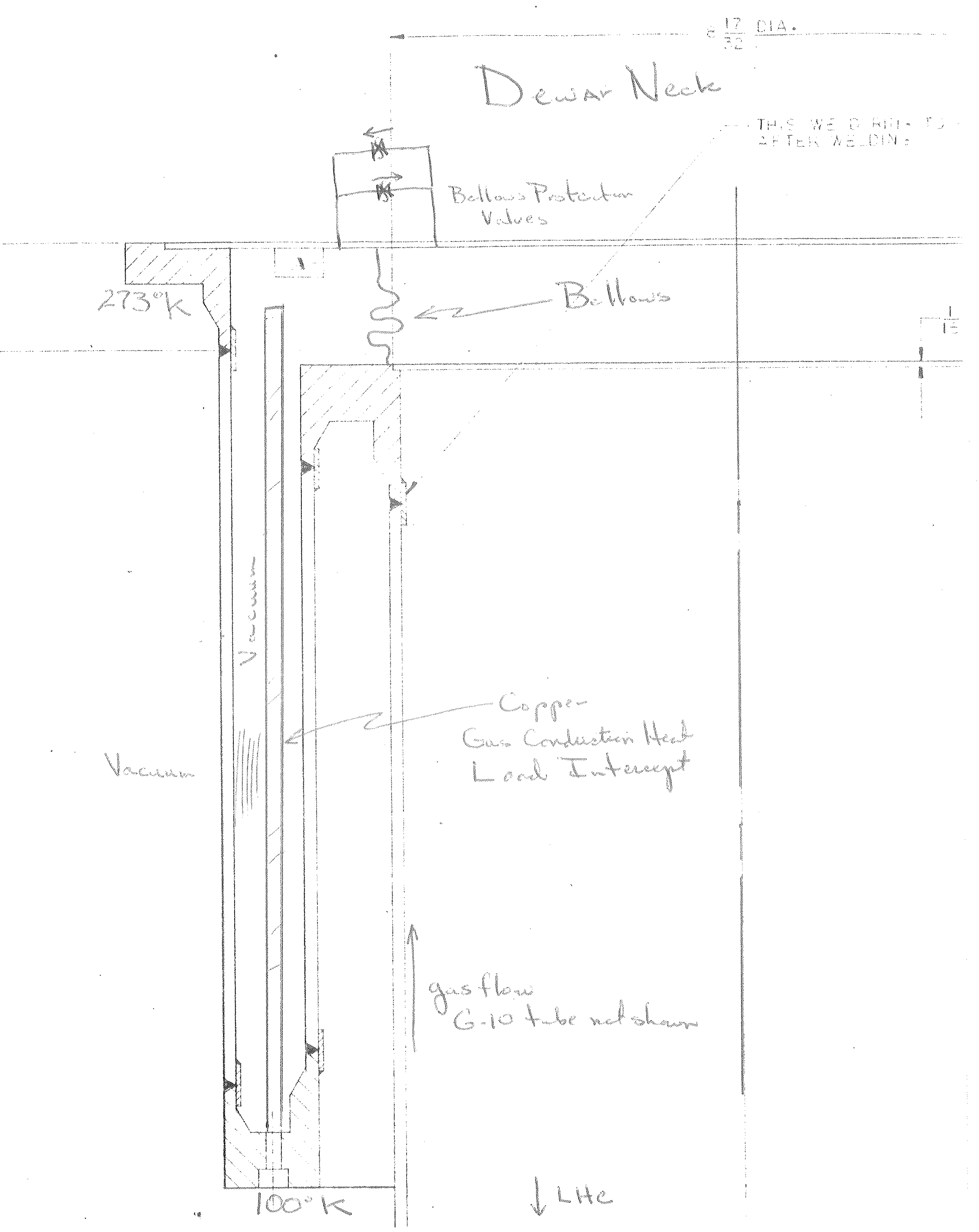
Coil cross section through an axial support post. LEGEND: (1) Ti6Al4V standoff; (2) 7075-T6 aluminum spherical bearing surface; (3) G-10 standoff; (4) copper braid; (5) Randolite fiberglass epoxy axial support; (6) ∿10 K He gas intercept; (7) LN_2 shield; (8) coil preload bars.

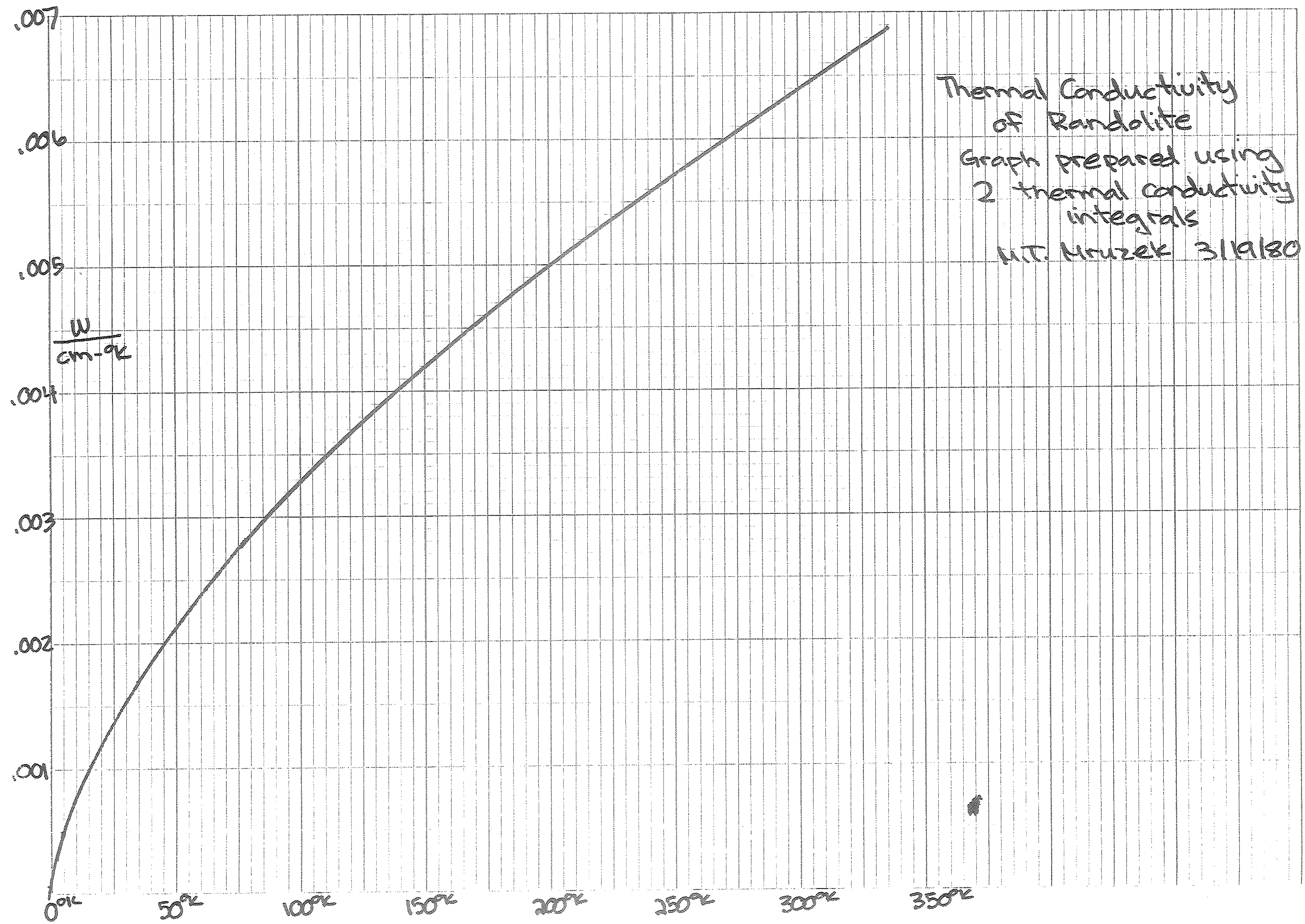


Helium flow schematic for one coil. LEGEND: (1) coil; (2) LHe storage dewar; (3) fiberglass epoxy axial support; not shown are two small Inconel 718 preload rods; (4) fiberglass horizontal support; (5) vertical tension links; (6) helium boiloff gas to supports; (8) LHe cooldown line and normal supply line; (9) gas collection can; (10) helium cooling vent lines for current leads and dewar neck.



Support cooled by He boiloff gas.


8 17/32 DIA.
Dewar Neck
AFTER WELDING
Bellows Protection Valves
273°K
Bellows
Vacuum
Copper
Gas Conduction Heat Load Intercept
Vacuum
gas flow
G-10 tube not shown
100°K
LHe


Thermal Conductivity
of Randolite
Graph prepared using
2 thermal conductivity
integrals
M.T. Mruzek 3/19/80
W / cm-°K
.007
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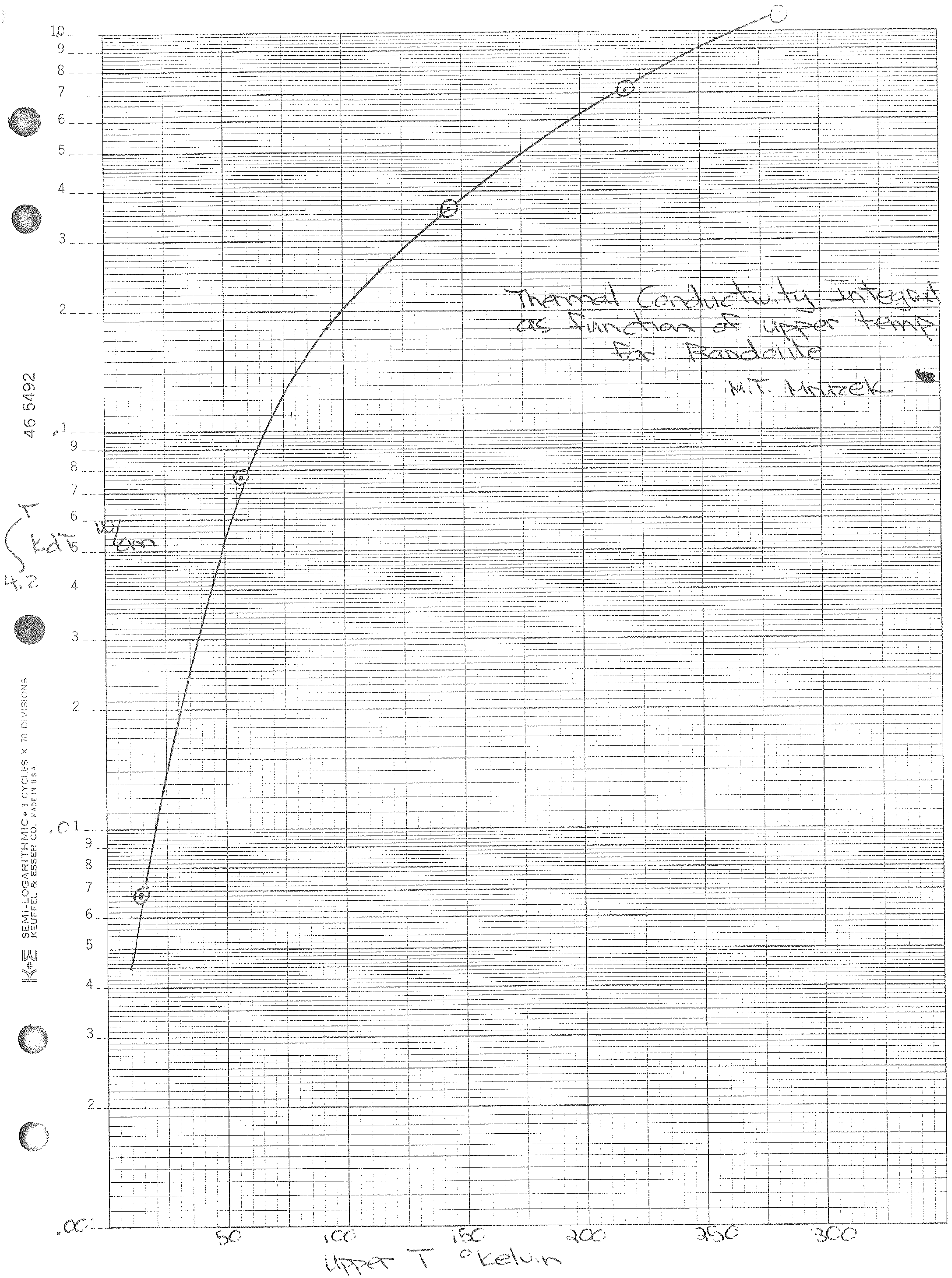
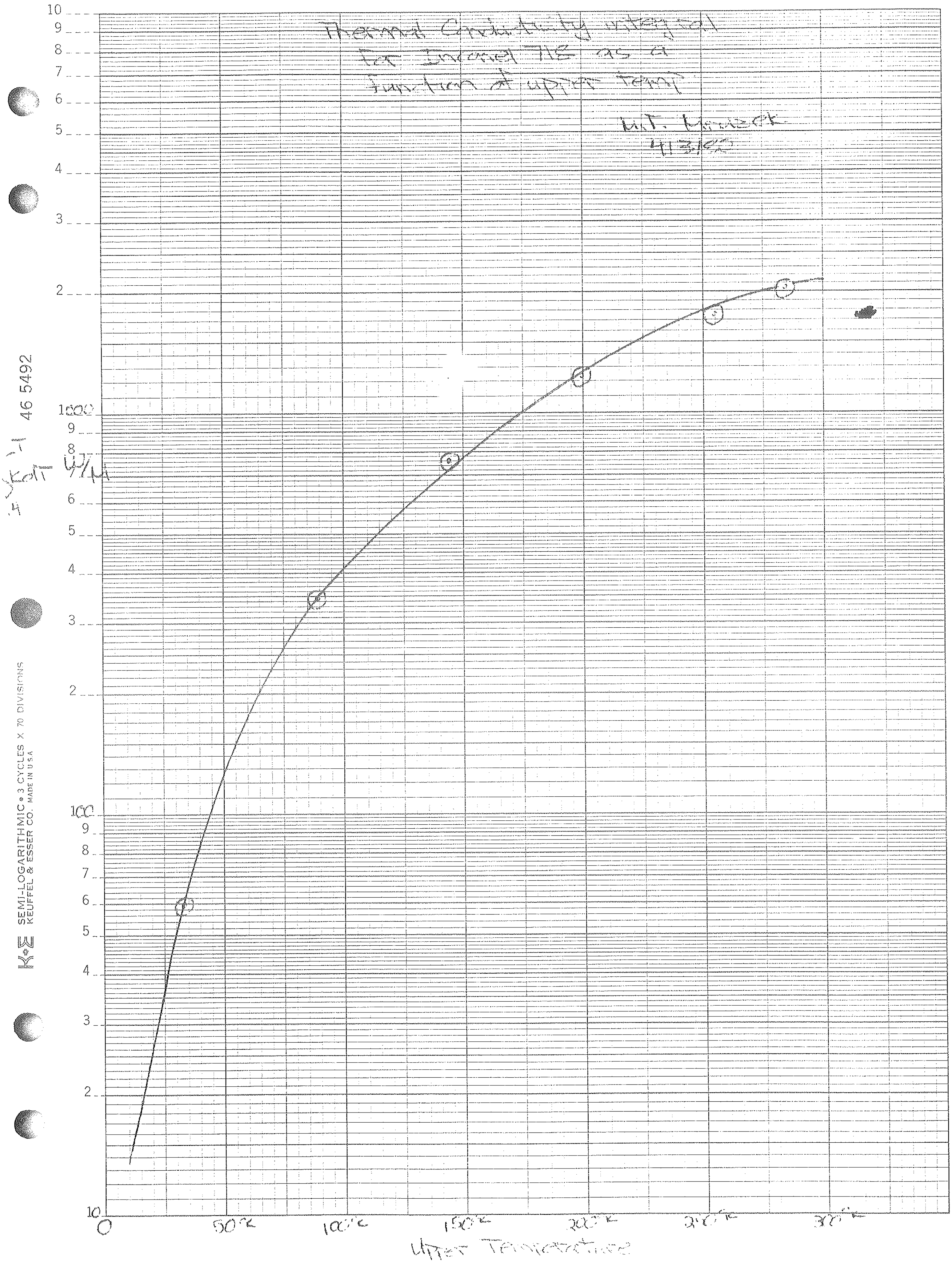

Thermal Conductivity Integral
as function of upper temp.
for Randalite
M.T. Mrazek
$\int_{4.2}^{T} k\,dT$ W/cm
Upper T °Kelvin
10
1
.1
.01
.001
50
100
150
200
250
300
46 5492
K&E SEMI-LOGARITHMIC • 3 CYCLES X 70 DIVISIONS
KEUFFEL & ESSER CO. MADE IN U.S.A.


Thermal Conductivity integral for Inconel 718 as a function of upper Temp
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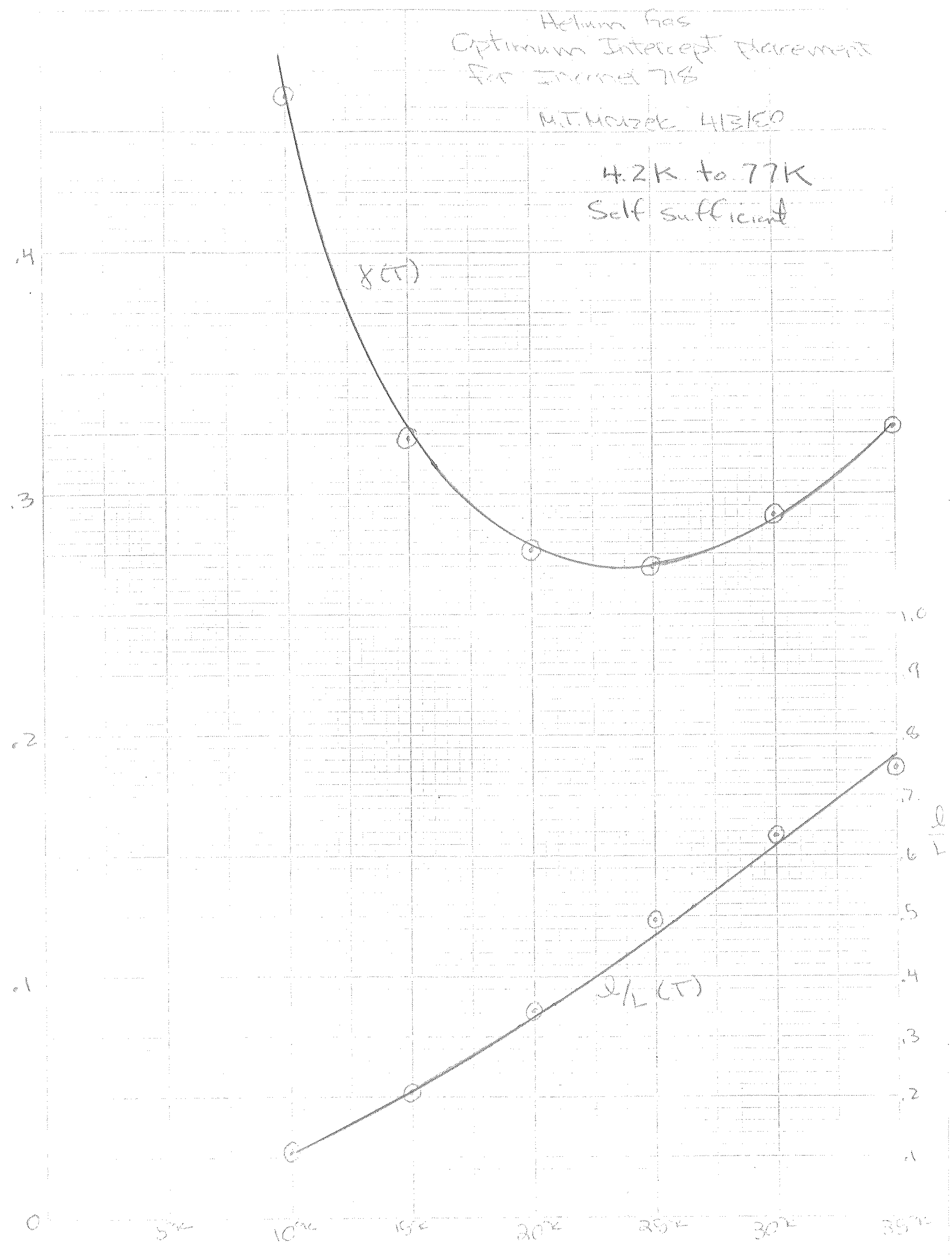
Upper Temperature


Helium Gas
Optimum Intercept Placement
for Inconel 718
M.T. Mruzek 4/3/80
4.2K to 77K
Self sufficient
γ(T)
l/L(T)
γ
.4
.3
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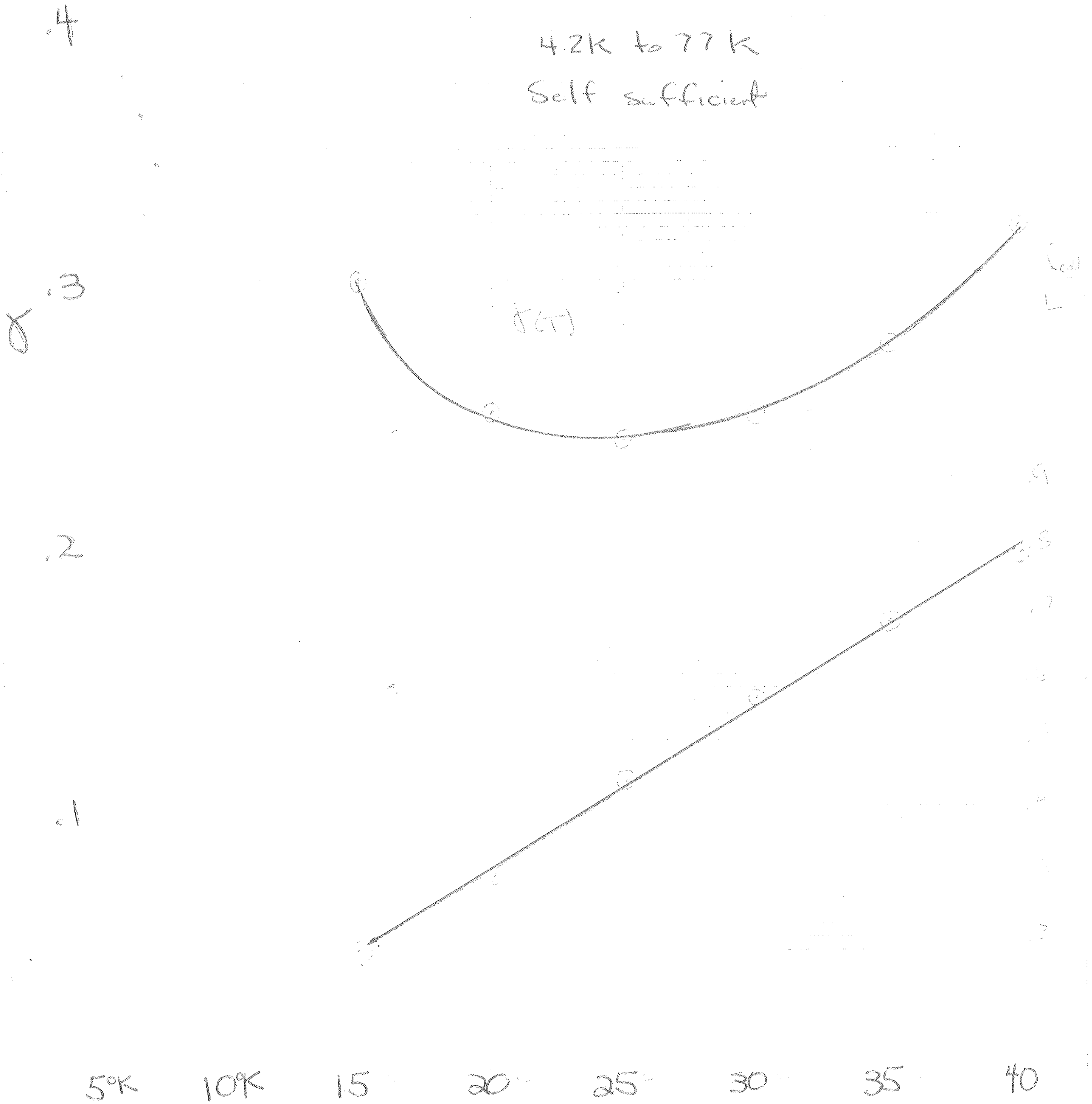
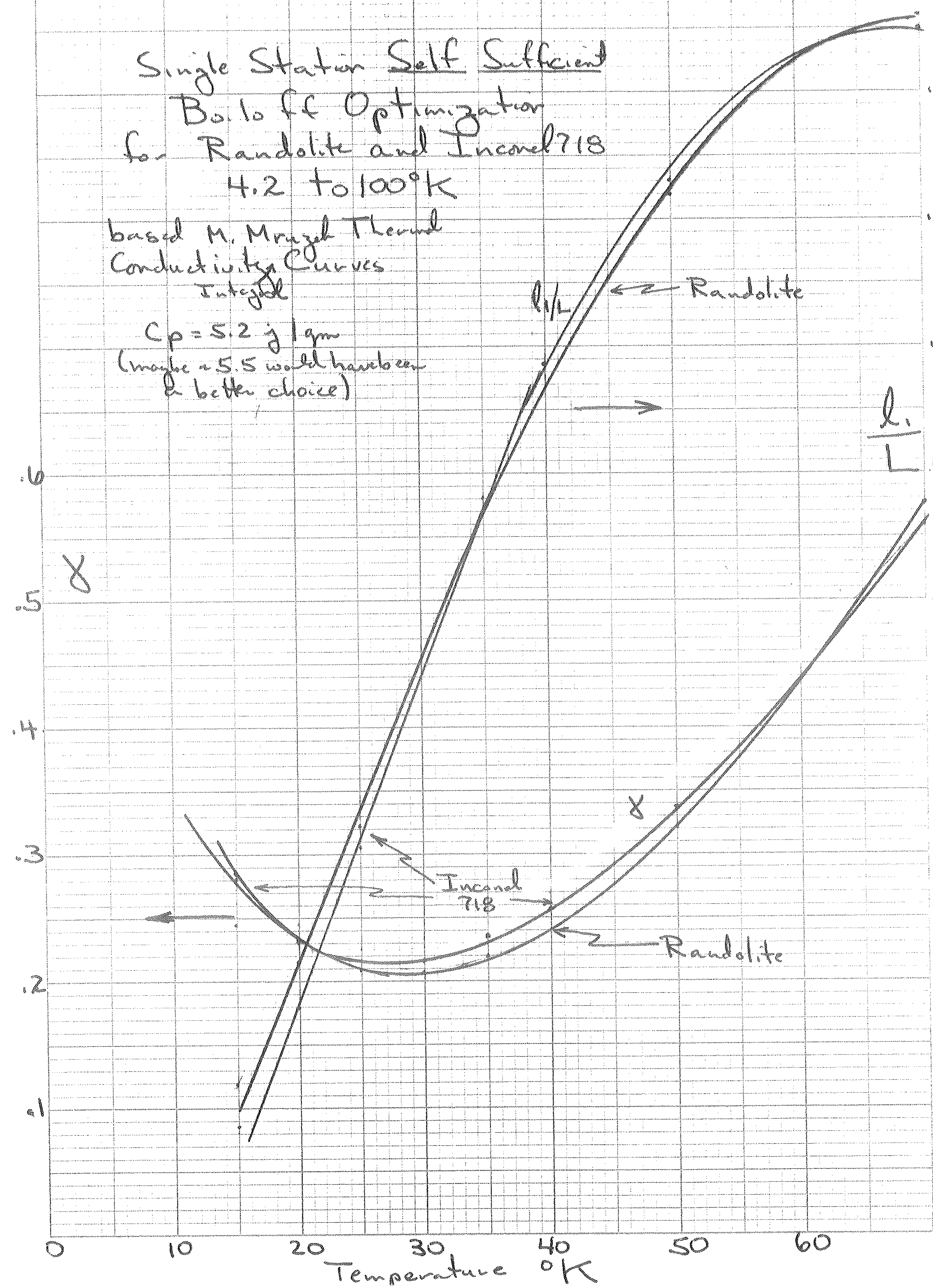
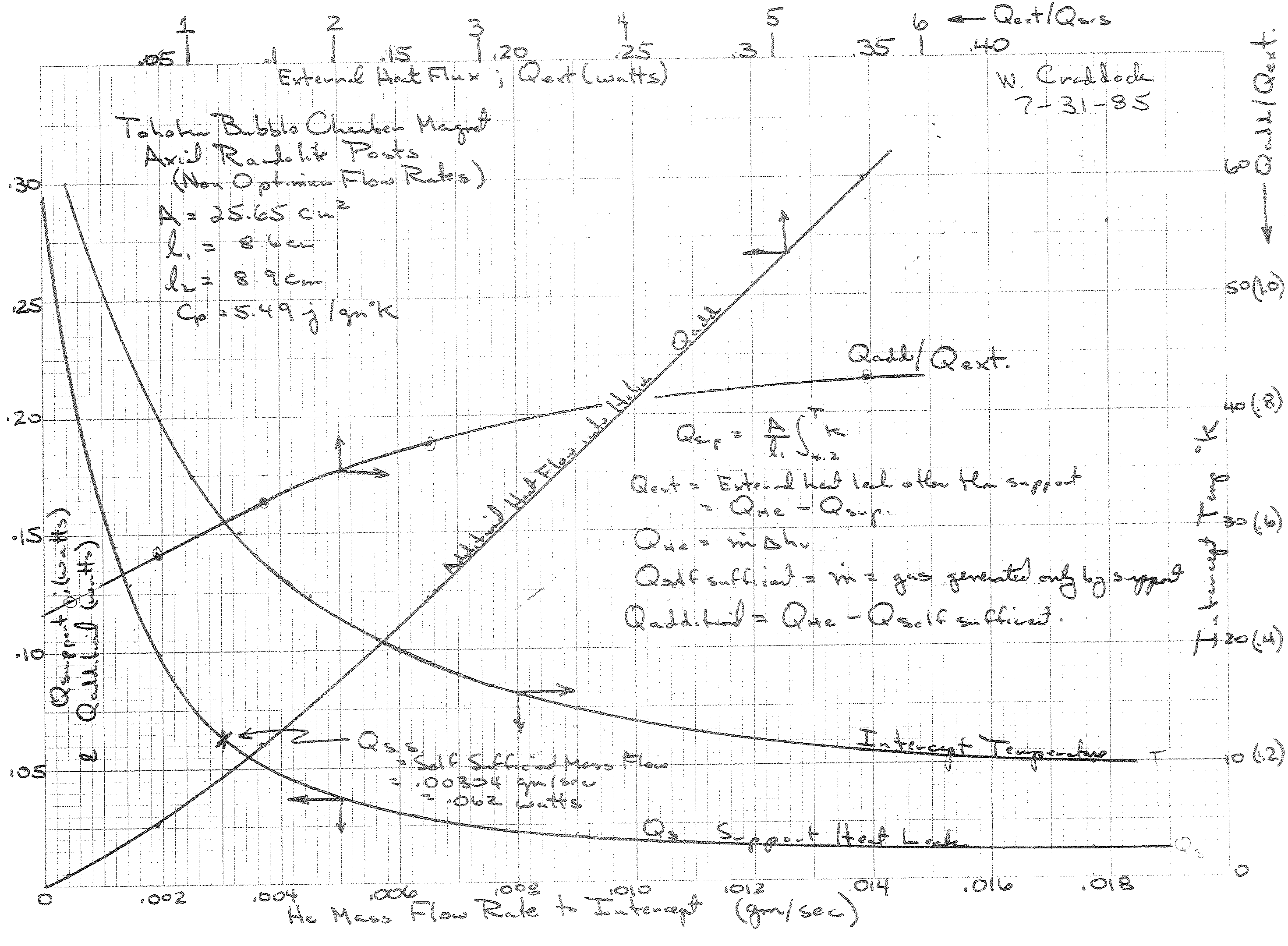
RANDOLITE



W. Craddock
7-31-85




Qext/Qss
External Heat Flux ; Qext (watts)
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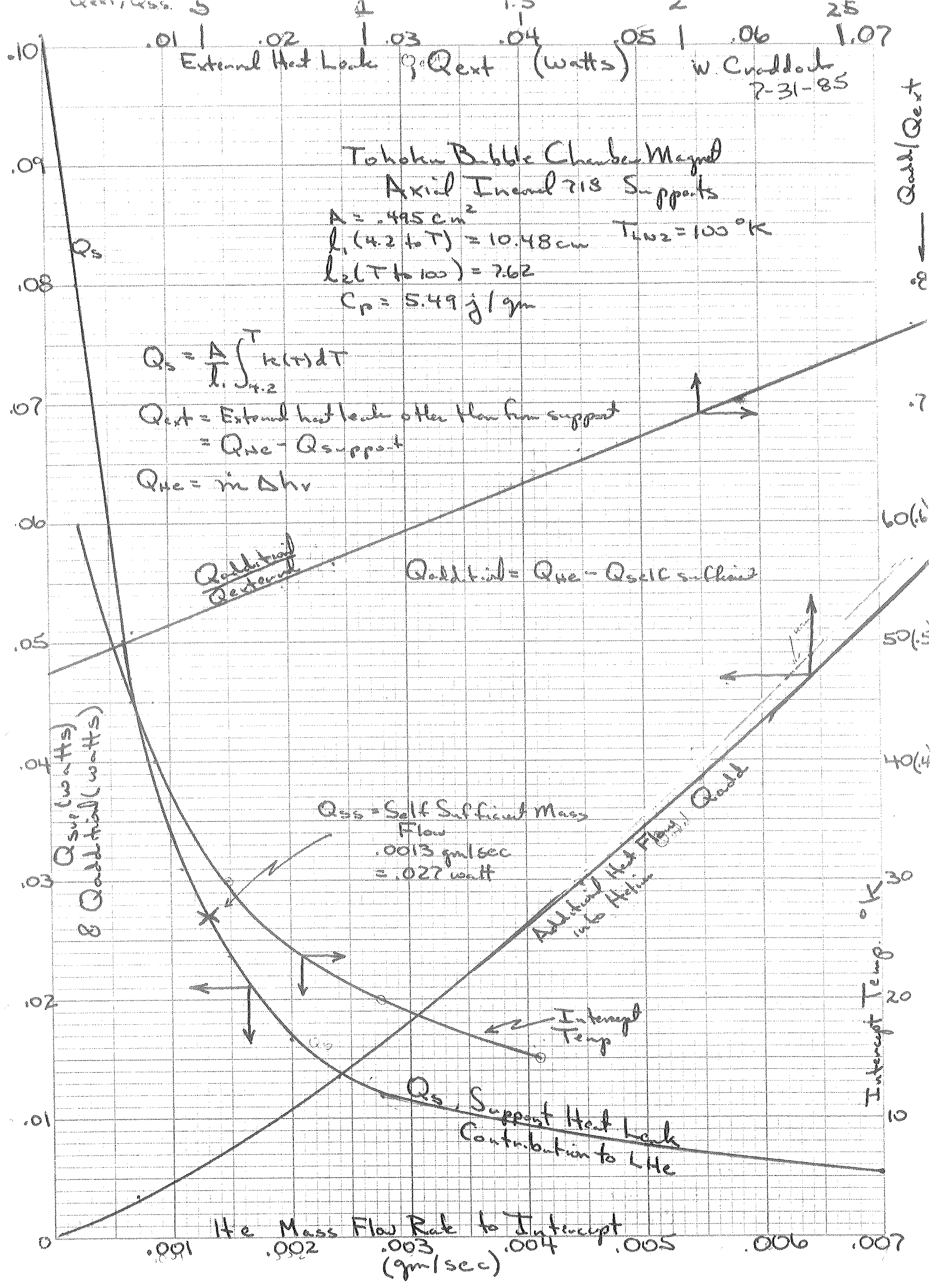
Tokohu Bubble Chamber Magnet
Axial Randolite Posts
(Non Optimized Flow Rates)
A = 25.65 cm²
l₁ = 8.6 cm
l₂ = 8.9 cm
Cp = 5.49 j/gm°K
Additional Heat Flow into Helium Qadd
Qadd/Qext.
Qsup = A/l₁ ∫ k
Qext = External heat load other than support
= QHe - Qsup.
QHe = ṁ Δhv
Qself sufficient = ṁ = gas generated only by support
Qadditional = QHe - Qself sufficient.
Qsupport (watts)
Qadditional (watts)
Qs.s.
= Self Sufficient Mass Flow
= .00354 gm/sec
= .062 watts
Intercept Temperature
Qs Support Heat Leak
Intercept Temp °K
Qadd/Qext
He Mass Flow Rate to Intercept (gm/sec)



External Heat Leak q: Qext (watts)
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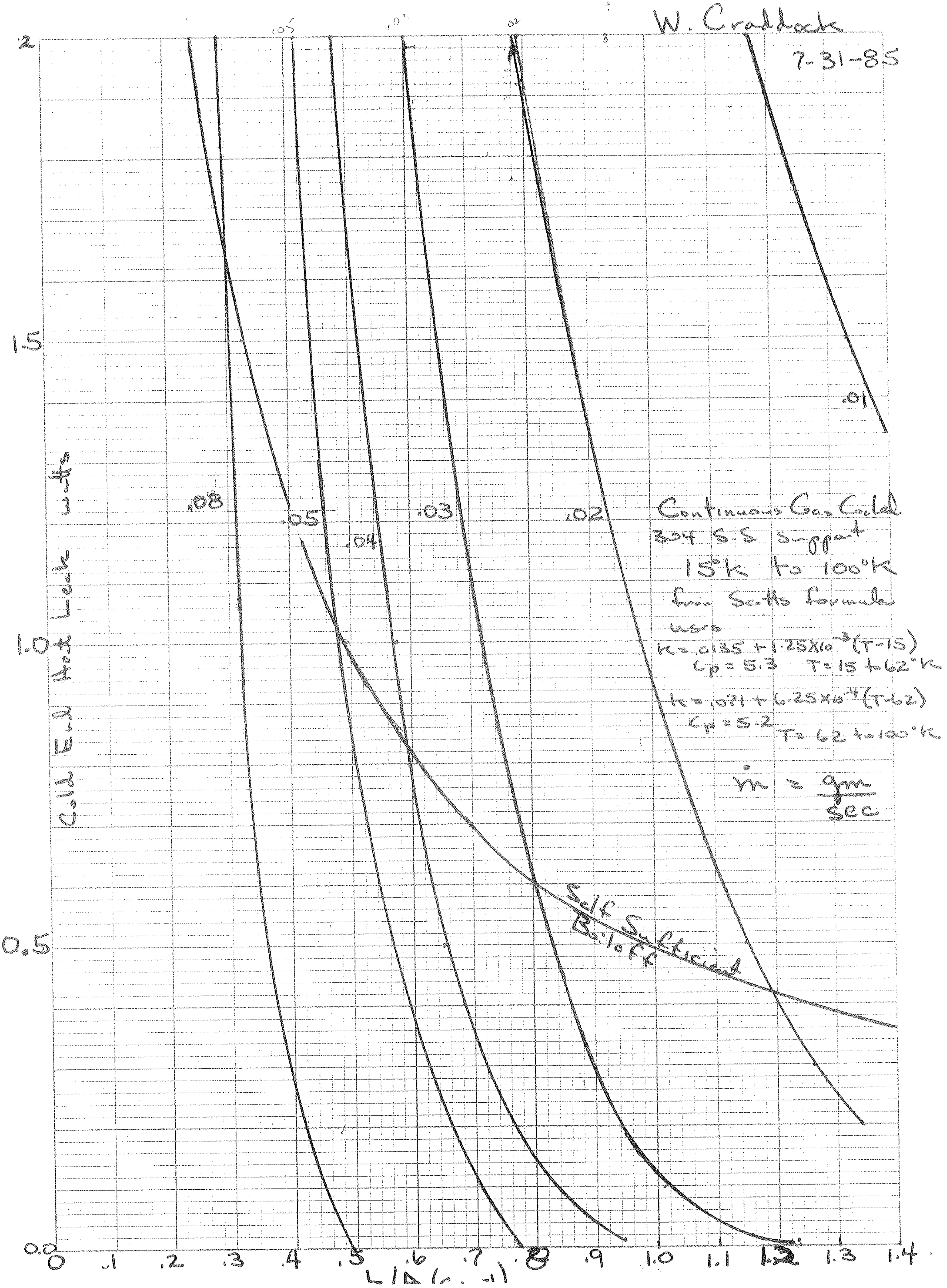
Tohoku Bubble Chamber Magnet
Axial Inconel 718 Supports
A = .495 cm²
l₁ (4.2 to T) = 10.48 cm
l₂ (T to 100) = 7.62
Cp = 5.49 j/gm
T_LN2 = 100 °K
Qs = A/l₁ ∫ k(T)dT
Qext = External heat leak other than from support
= QHe − Qsupport
QHe = ṁ Δhv
Qadditional / Qexternal
Qadditional = QHe − Qself sufficient
Qadd/Qext
Qs
Qss = Self Sufficient Mass Flow
.0013 gm/sec
= .027 watt
Qsupport (watts) & Qadditional (watts)
Additional Heat Flow into Helium
Qadd
Intercept Temp
Qs, Support Heat Leak Contribution to LHe
Intercept Temp °K
He Mass Flow Rate to Intercept (gm/sec)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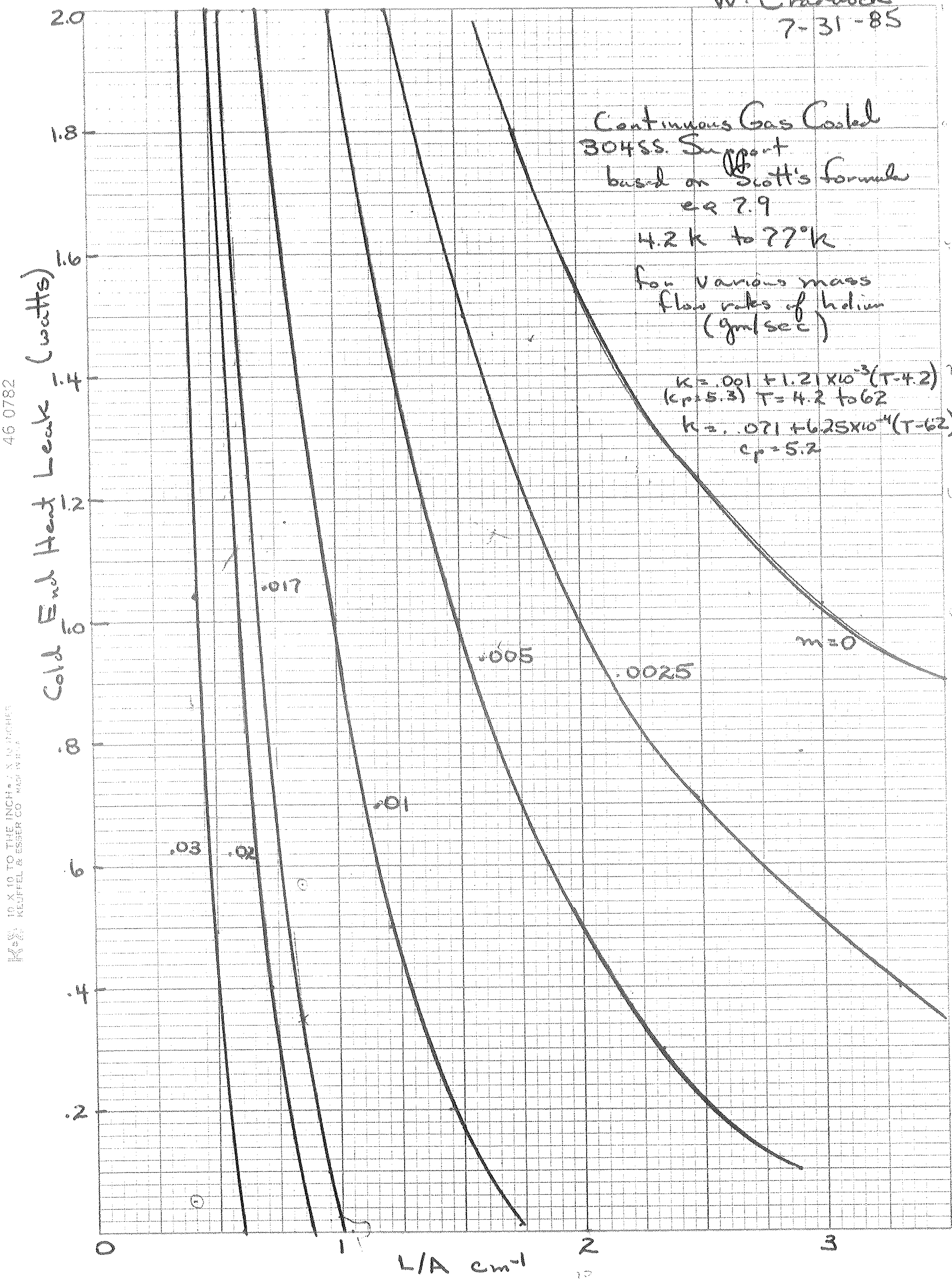
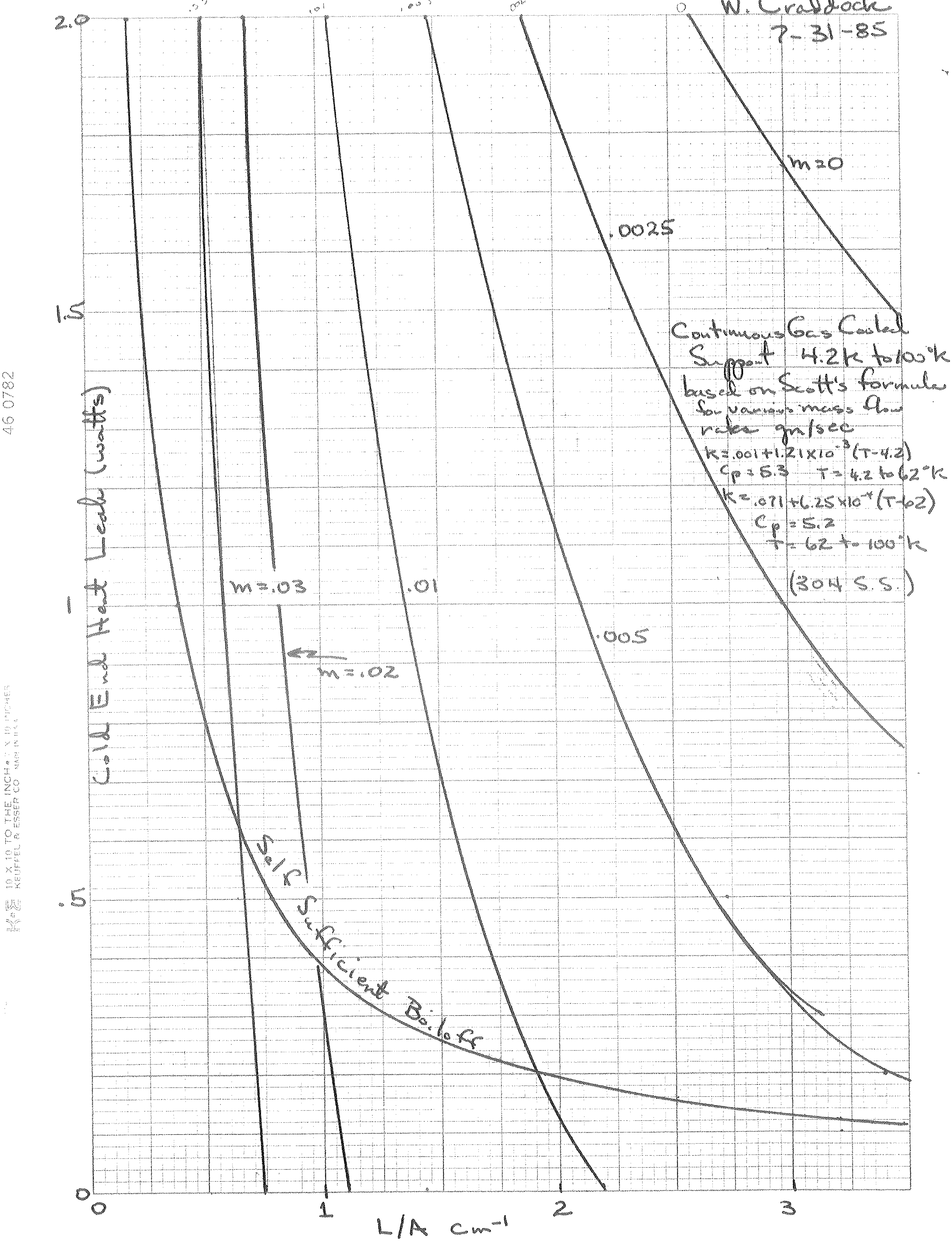
Continuous Gas Cooled
304 S.S Support
15°K to 100°K
from Scotts formula
using
k = .0135 + 1.25×10⁻³ (T-15)
Cp = 5.3 T = 15 to 62°K
k = .071 + 6.25×10⁻⁴ (T-62)
Cp = 5.2 T = 62 to 100°K
ṁ = gm/sec
Self Sufficient
Cold End Hot Leak watts
L/A (cm⁻¹)
.08
.05
.04
.03
.02
.01
Self Sufficient
0.0
0.5
1.0
1.5
2
0
.1
.2
.3
.4
.5
.6
.7
.8
.9
1.0
1.1
1.2
1.3
1.4

W. Craddock
7-31-85




W. Craddock
7-31-85
m=0
.0025
.005
.01
m=.03
m=.02
Self Sufficient Boiloff
Continuous Gas Cooled Support 4.2K to 100°K
based on Scott's formula for various mass flow rates gm/sec
K=.001+1.21x10^-3 (T-4.2)
Cp=5.3 T=4.2 to 62°K
K=.071+6.25x10^-4 (T-62)
Cp=5.2
T=62 to 100°K
(304 S.S.)
Cold End Heat Leak (watts)
L/A cm-1
0
.5
1
1.5
2.0
2
3
46 0782
10 X 10 TO THE INCH 7 X 10 INCHES
KEUFFEL & ESSER CO. MADE IN U.S.A.