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EDDY CURRENT HEATING OF BOOSTER DIPOLE VACUUM CHAMBER

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Collider Accelerator Department

Brookhaven National Laboratory

U.S. Department of Energy

USDOE Office of Science (SC)

DISCLAIMER

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AD

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B. McDOWELL

JANUARY 21, 1987

ACCELERATOR DEVELOPMENT DEPARTMENT

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INTRODUCTION:

This report covers two experiments performed to determine the magnitude of eddy current heating of the Booster dipole vacuum chamber. Results are presented for insulated and uninsulated chambers.

In the results section graphs of temperatures vs. time illustrate thermal gradients and terminal temperatures encountered. Also included are the calculated values of heat generation, convection and conduction.

Raw data and sample calculations are included so the reader may verify the assumptions made.

BACKGROUND:

The vacuum chamber used for the tests was manufactured from 14Ga. (.075") Gr 316L stainless steel. The dimensions of the chamber are shown in Figure 1.

Two separate experiments were performed to the vacuum chamber section described above. In the first experiment the exterior of the chamber was uninsulated. In the second run the chamber was insulated with three layers of "Ultra Insulation K" (Oike Industrial Co., Ltd). Figure 3 gives a detail of the insulation. In both cases the interior of the chamber was tightly packed with fiberglass insulation to simulate vacuum.

Thermocouples were used to measure temperatures during the tests. Location of the thermocouples for both cases are shown in Figure 2.

The test specimen was loaded into the dipole test magnet and the magnet powered with the current excitation shown in Figure 4.

During the test, temperatures were recorded at five minute intervals for 120 minutes and 285 minutes respectively.

After powering the insulated sample for 285 minutes power to the magnet was terminated and the specimen allowed to cool in place. During cooling, temperatures were measured at one minute intervals.

The data collected during cooling of the insulated chamber was used to calculate convection and conduction coefficients in the absence of the unknown heat generation.

The calculated convection and conduction parameters were then applied to the powered data to determine the heat generated by eddy currents.

RESULTS:

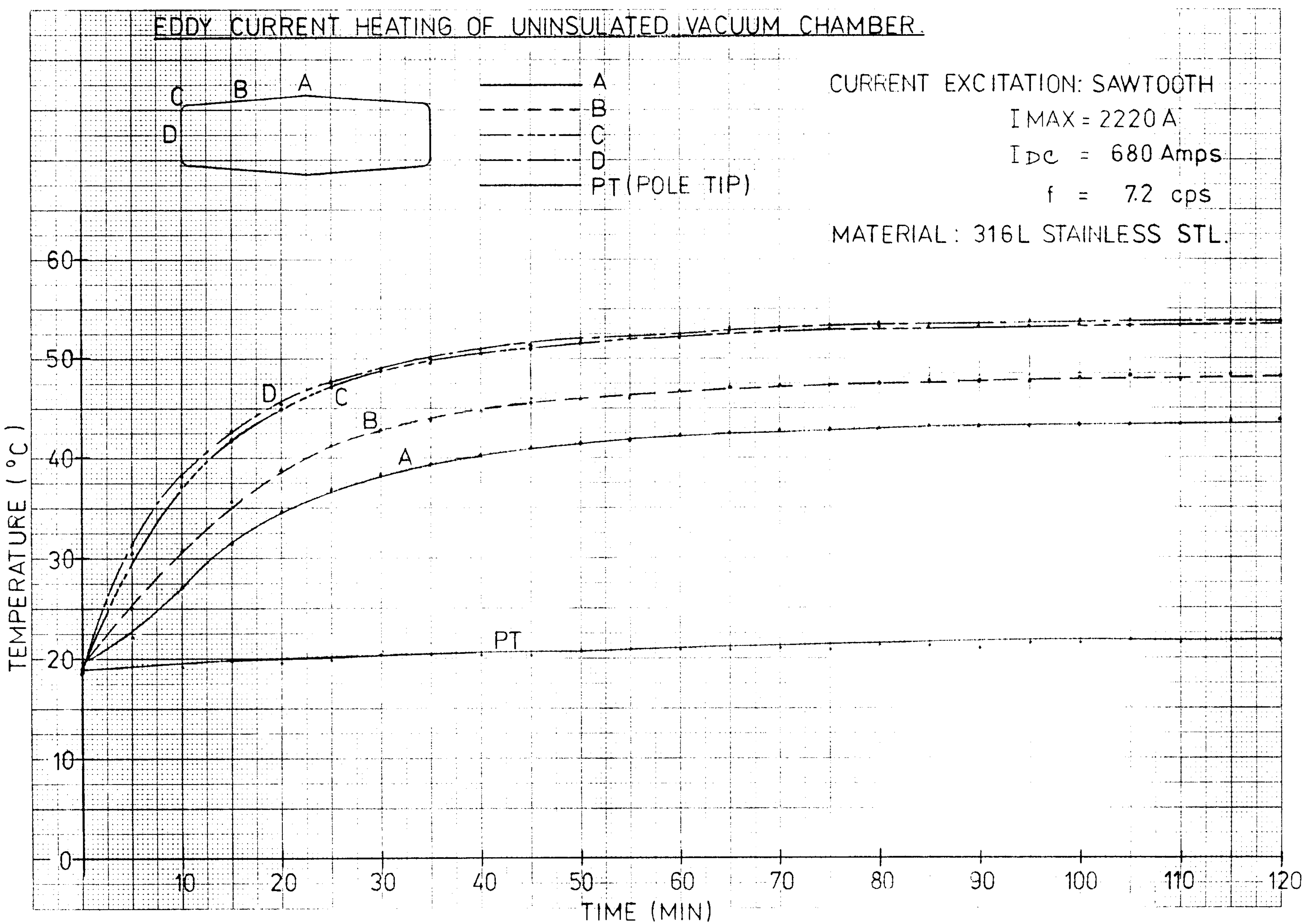
Measured temperatures around the chamber ¼ circumference are presented graphically as a function of time for both insulated and uninsulated data. Circumferential thermal gradients and terminal temperatures are of particular interest.

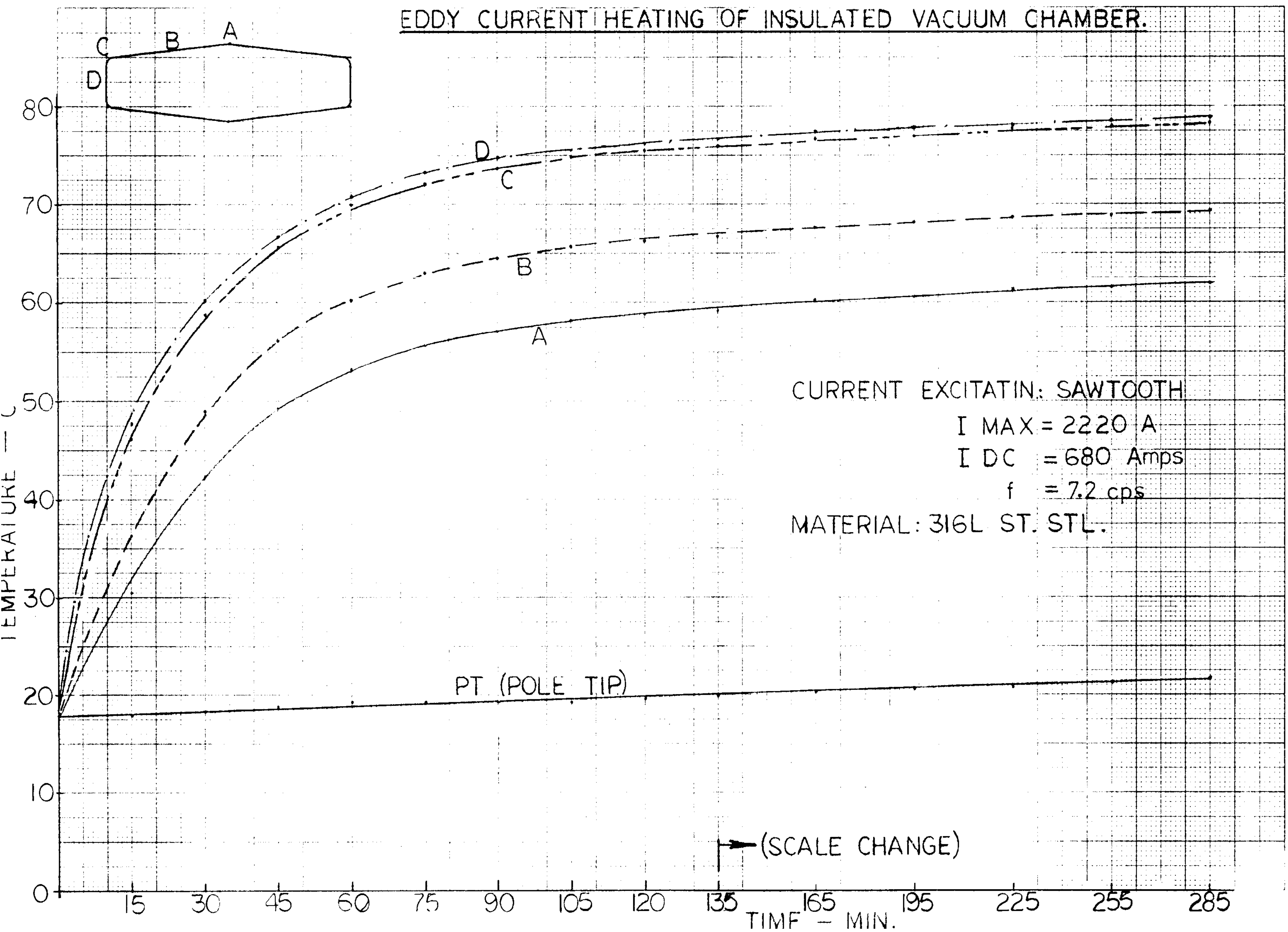
At the given excitation, power dissipation for the vacuum chamber is 32 watts/linear ft. of chamber.

Power dissipation was calculated for 32 different time intervals between the insulated and uninsulated data. Repeatability over a wide range of temperatures was excellent (see Tables 2 and 3, calculations section).

The conductive resistance of the insulation (R_K) was found to be 0.776 ^{o}K/watt-linear ft.

The mean convective resistance ($\bar{R}_{hc}$) within the magnet aperture is 0.890 ^{o}K/watt-linear ft. Convective resistance is assumed constant for a surface temperature range of 30-55°C.


EDDY CURRENT HEATING OF UNINSULATED VACUUM CHAMBER.
A
B
C
D
PT (POLE TIP)
CURRENT EXCITATION: SAWTOOTH
I MAX = 2220 A
I DC = 680 Amps
f = 7.2 cps
MATERIAL : 316L STAINLESS STL.
TEMPERATURE (°C)
TIME (MIN)
0
10
20
30
40
50
60
70
80
90
100
110
120
PT


EDDY CURRENT HEATING OF INSULATED VACUUM CHAMBER.
A
B
C
D
CURRENT EXCITATIN: SAWTOOTH
I MAX = 2220 A
I DC = 680 Amps
f = 7.2 cps
MATERIAL: 316L ST. STL.
PT (POLE TIP)
(SCALE CHANGE)
TEMPERATURE — C
TIME — MIN.
0
10
20
30
40
50
60
70
80
15
30
45
60
75
90
105
120
135
165
195
225
255
285

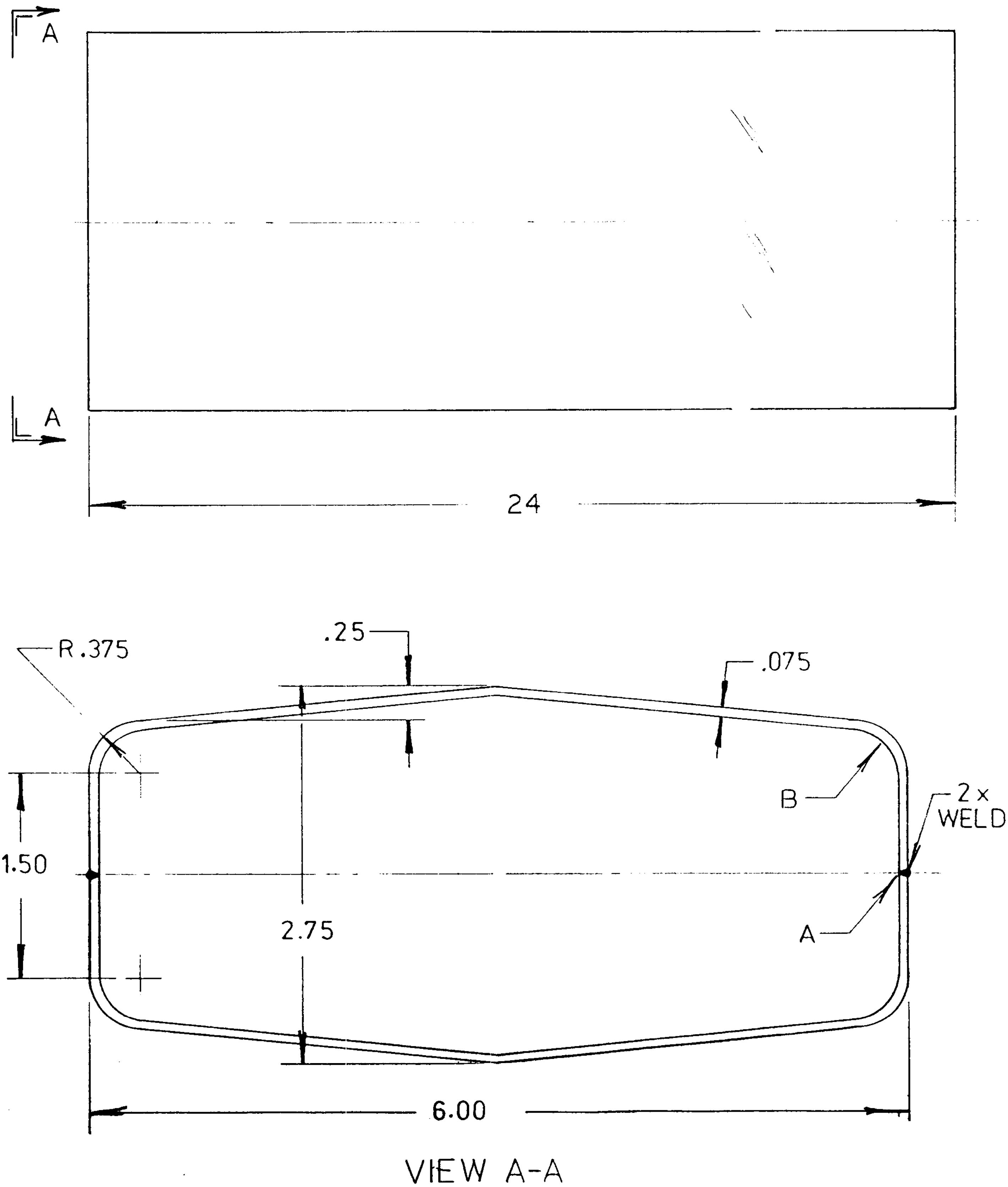
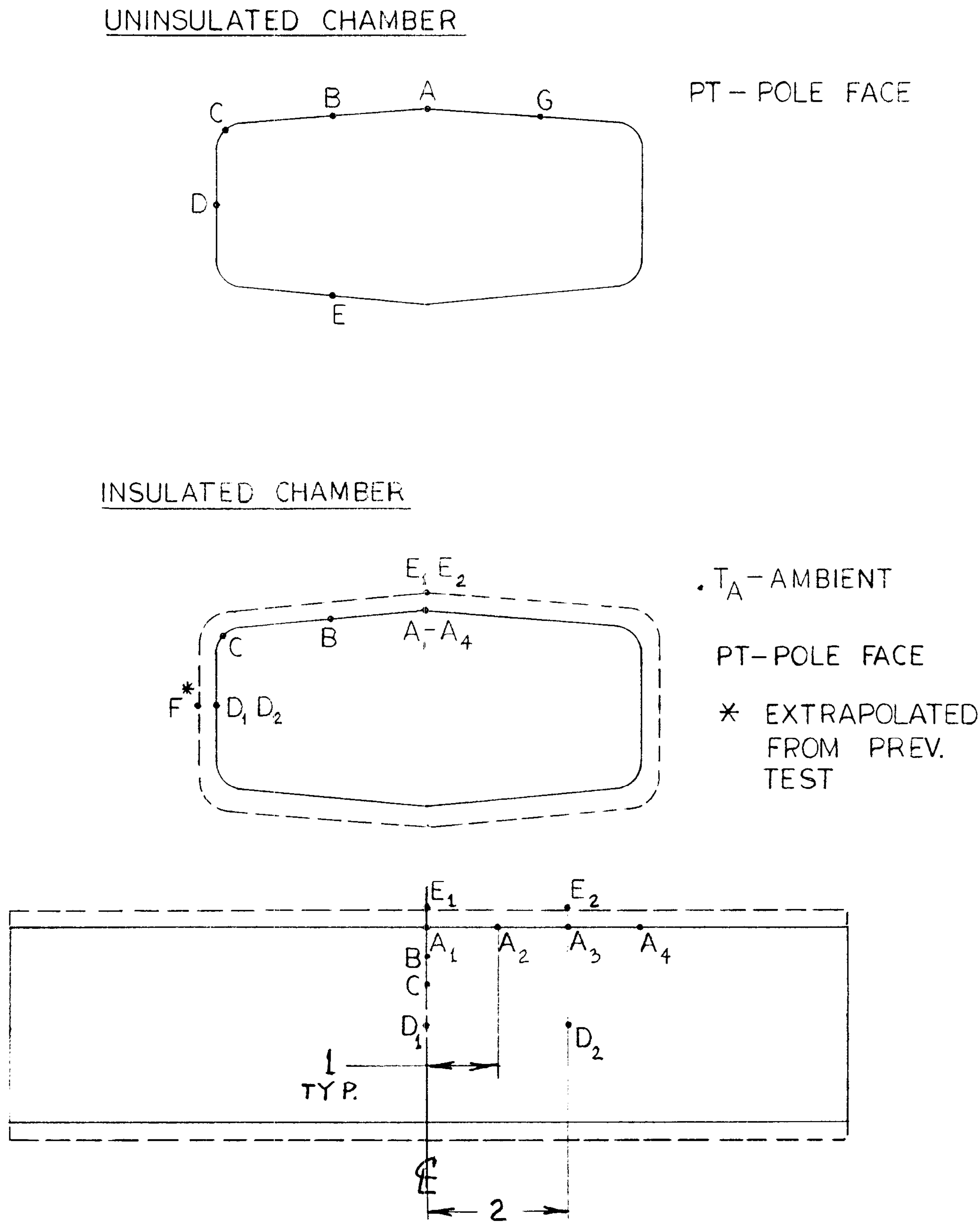


FIG. 1



THERMOCOUPLE PLACEMENT

FIG. 2

INSULATION OF CHAMBER

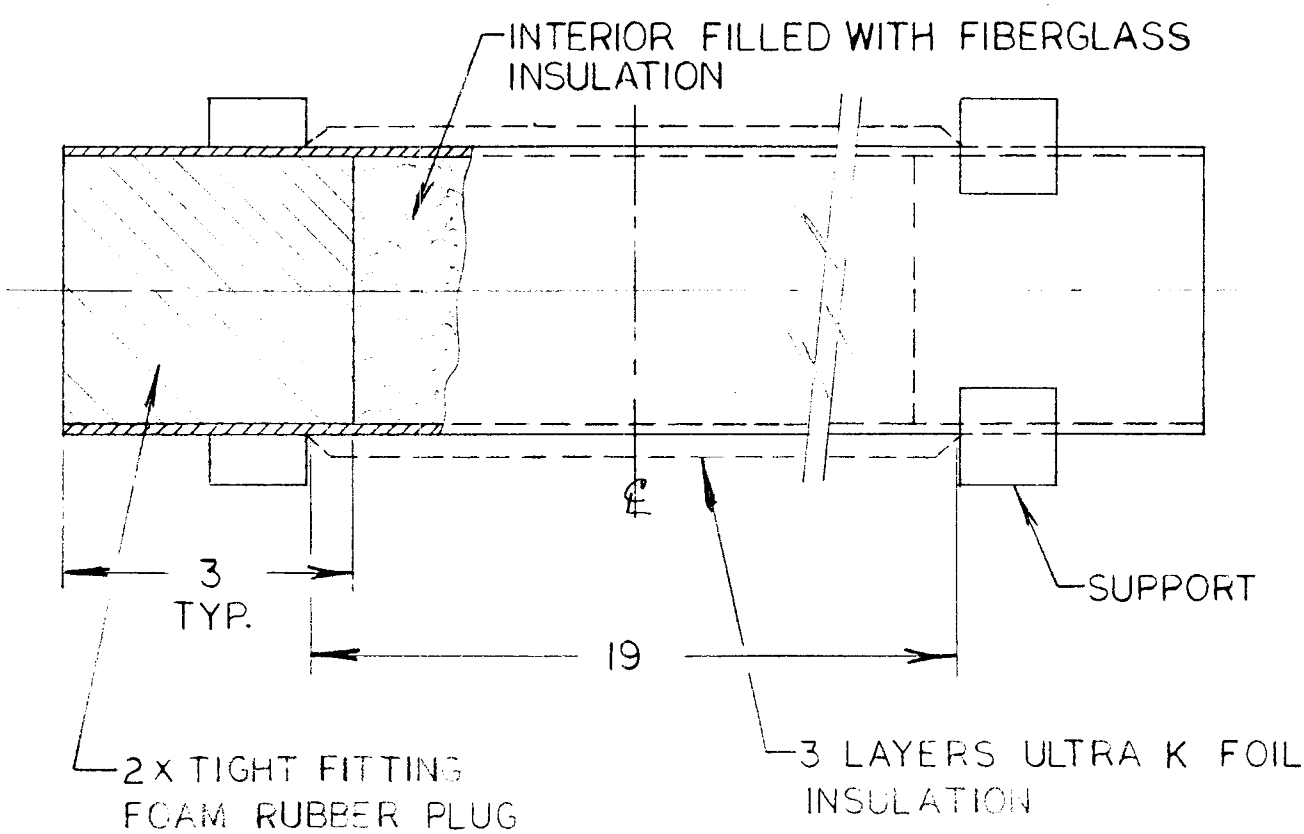


FIG. 3

CURRENT EXCITATION

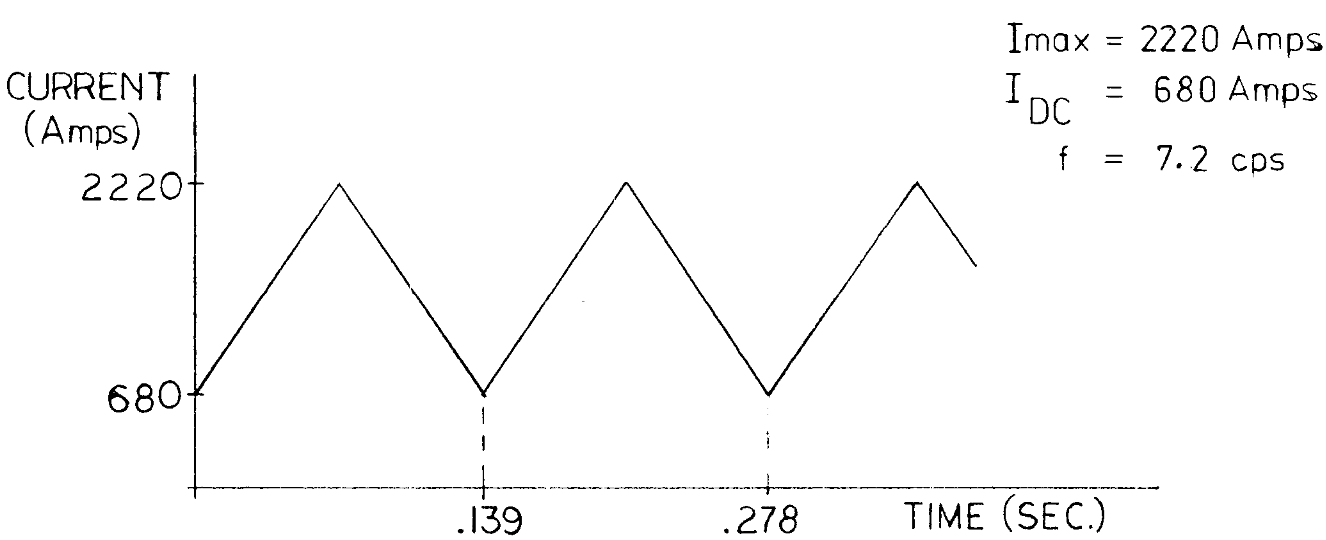


FIG. 4

CALCULATIONS:

Based upon temperature gradients observed and chamber geometry the average chamber temperature $\bar{T}_{ss}$ is taken as;

$$\bar{T}_{ss} = \bar{T}_D\ (.2) + T_B\ (.8)$$

During cool down of the chamber;

$$Qout = \frac{\rho V C\rho\ \Delta\bar{T}_{ss}}{\Delta t}$$

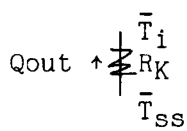
V - Volume of 1 foot section of chamber = $2.7867\text{x}10^{-4}m^3$

ρ - Density of stainless steel = 7817 $^{Kg}/m^3$

$C\rho$ - Stainless steel specific heat = 461 $^{J}/Kg°k$

Δt - Time increment = 60 sec.

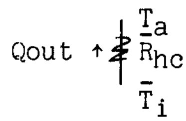
Conductive Resistance (R_K)



$$R_K = \frac{\bar{T}_{ss} - \bar{T}_i}{Qout}\ (°K/\text{watt - linear ft})$$

$\bar{T}i$ - average insulation temperatuare = $\frac{\bar{T}_E + T_F}{2}$

Convective Resistance ($\bar{R}_{hc}$)



$$\bar{R}_{hc} = \frac{\bar{T}_i - T_a}{Qout} \quad (^{\circ}K/\text{watt - linear ft})$$

T_a - ambient temperature within magnet aperture.

TABLE 1

CALCULATION OF R_K AND $\bar{R}_{hc}$
From Cool Down Data

Time (Min)	$\bar{T}_D$ (°C)	T_B (°C)	$\bar{T}_E$ (°C)	T_F* (°C)	T_a (°C)	$\bar{T}_{ss}$ (°C)	$\Delta\bar{T}_{ss}$ (°C)	$\bar{T}_i$ (°C)	Qout ($\frac{Watts}{ft}$)	R_K ($\frac{°K}{W}$)	$\bar{R}_{hc}$ ($\frac{°K}{W}$)
0	74.3	68.3	41.1	54.3	22.0	69.5	---	47.7	---	---	---
1	71.5	67.1	40.9	52.8	22.3	68.0	1.5	46.85	25.1	.843	.978
2	68.7	65.9	40.5	51.3	22.3	66.5	1.5	45.9	25.1	.821	.940
3	66.3	64.4	40.1	49.9	22.5	64.8	1.7	45.0	28.5	.695	.789
4	64.1	43.2	39.6	48.7	22.0	63.4	1.4	44.15	23.4	.823	.947
5	62.3	62.0	39.4	47.6	22.3	62.1	1.3	43.5	21.8	.853	.972
6	60.5	60.8	38.9	46.6	22.3	60.7	1.4	42.75	23.4	.767	.874
7	58.8	59.3	38.4	45.6	22.5	59.2	1.5	42.0	25.1	.685	.777
8	57.2	58.1	37.9	44.6	22.0	57.9	1.3	41.25	21.8	.764	.883
9	55.9	56.8	37.5	43.6	22.0	56.6	1.3	40.55	21.8	.736	.851
10	54.5	55.6	37.0	42.9	22.0	55.4	1.2	39.95	20.1	.769	.893

* $\bar{T}_F$ extrapolaited from previous test

R_K = .780 °K/watt - ft

$\bar{R}_{hc}$ = .890 °K/watt - ft

$\bar{R}_T$ = 1.67 °K/watt - ft

During operation heat generation (Qgen) is given by:

$$Qgen = \frac{\rho V C p \Delta \bar{T}_{ss}}{\Delta t} + \frac{\bar{T}_{ss} - \bar{T}_a}{R_T}$$

$\bar{T}_{ss}$ and $\bar{T}_a$ defined previously are averaged over the measurement interval.

TABLE 2
Qgen FOR INSULATED CHAMBER

Time (min)	$\bar{T}_{ss}$ (°C)	$\Delta\bar{T}_{ss}$ °C	Δt (sec)	Average during Δt $\bar{T}_{ss}$	$\bar{T}_a$	$\bar{T}_{ss}-\bar{T}_a$	Qgen $\left(\frac{watts}{ft}\right)$
5	30.0						
10	38.96	8.96	300	34.48	16.8	7.68	40.6*
20	50.34						
25	54.54	4.2	300	52.44	18.0	34.44	34.7*
40	62.86						
45	64.6	1.74	300	63.73	19.3	44.43	32.4
60	68.64						
65	69.64	1.00	300	69.14	19.85	49.29	32.9
80	71.64						
85	72.18	.54	300	71.91	20.45	51.46	32.6
100	73.18						
105	73.48	.30	300	73.33	20.7	52.63	32.5
130	74.52						
135	74.52	.00	300	74.52	20.9	53.62	32.1
175	75.34						
185	75.56	.22	600	75.45	21.65	53.80	32.9
225	76.10						
235	76.30	.20	600	76.2	22.15	54.05	33.0
275	76.82						
285	76.82	.00	600	76.82	22.75	54.07	32.4

$\bar{Q}$ = 32.6 watts/ft

* Excluded as transient data

TABLE 3 Qgen FOR UNINSULATED CHAMBER									
Time (min)	T_D (°C)	T_B (°C)	$\bar{T}_{ss}$ (°C)	$\Delta\bar{T}_{ss}$ (°C)	T_a °C)	Average over 5 min. $\bar{T}_{ss}$	T_a	$\bar{T}_{ss}-T_a$	Qgen $(\frac{watts}{ft})$
0	18.6	19.5	19.3	---	19.1				
5	31.4	25.1	26.4	7.1	19.3	22.85	19.2	3.65	27.9*
10	38.1	30.9	32.3	5.9	19.3	29.35	19.3	10.05	31.0
15	42.6	35.6	37.0	4.7	19.8	34.65	19.55	15.1	32.7
20	45.3	38.8	40.1	3.1	19.6	38.55	19.7	18.85	31.6
25	47.5	41.1	42.1	2.3	19.8	41.25	19.7	21.55	31.9
30	48.9	42.8	44.0	1.6	20.3	43.2	20.05	23.15	31.4
35	49.9	43.9	45.1	1.1	20.3	44.55	20.3	24.25	30.9
40	50.8	44.7	45.9	.8	20.3	45.5	20.3	25.2	31.0
45	51.4	45.5	46.7	.8	20.3	46.3	20.3	26.0	31.9
50	51.7	45.9	47.1	.4	20.6	46.9	20.45	26.45	31.1
55	52.3	46.2	47.4	.3	20.8	47.25	20.7	26.55	30.8
60	52.5	46.7	47.1	.5	20.8	47.65	20.8	26.85	31.8
65	53.1	47.0	48.2	.3	20.8	48.05	20.8	27.25	31.6
70	53.1	47.2	48.1	.2	21.0	48.3	20.9	27.4	31.5
75	53.4	47.3	48.5	.1	20.8	48.45	20.9	27.55	31.3
80	53.6	47.5	48.7	.2	21.3	48.6	21.05	27.55	31.6
85	53.4	47.7	48.8	.1	21.3	48.75	21.3	27.45	31.2
90	53.3	47.7	48.8	0	21.0	48.8	21.15	27.65	31.0
95	53.8	47.7	48.9	.1	21.5	48.85	21.25	28.6	32.5
100	53.8	48.0	49.1	.2	21.5	49.0	21.5	27.5	31.6
105	53.9	48.2	49.3	.2	21.8	49.2	21.65	27.55	31.6
110	53.4	47.8	48.9	0	21.5	49.1	21.65	27.45	30.8
115	53.8	48.1	49.2	0	21.8	49.15	21.65	27.5	30.9
120	53.8	48.1	49.2	0	21.8	49.2	21.8	27.4	30.8

$\boxed{\text{Qgen} = 31.4}$

*excluded as transient data

DATA INSULATED CHAMBER POWERED FOR 285 MIN TEMPERATURE °C												
TIME (IN)	A1	A2	A3	A4	B	C	D1	D2	E1	E2	PT	TA
0	17.9	18.1	18.1	17.9	18.1	18.1	18.1	17.9	17.9	17.9	17.7	17.7
5	20.1	20.3	20.1	20.1	23.5	30.3	31.5	31.7	18.6	19.1	17.7	16.7
10	25.2	25.7	25.4	25.7	30.3	39.5	41.0	41.2	20.6	22.0	17.9	16.9
15	30.5	31.0	30.8	31.3	36.4	46.1	47.6	47.6	22.5	25.0	17.9	17.2
20	35.1	35.6	35.1	35.9	41.2	51.2	52.5	52.7	24.2	27.6	18.1	17.9
25	39.3	39.5	39.0	40.0	45.6	55.4	56.6	56.9	25.9	29.8	18.4	18.1
30	42.4	42.7	42.2	43.2	49.0	58.8	60.1	60.1	26.9	31.5	18.4	18.6
35	45.1	45.4	44.9	45.9	51.7	61.5	62.5	62.7	28.1	33.0	18.6	18.9
40	47.3	47.6	47.1	48.1	54.2	64.0	65.0	65.0	29.1	34.2	18.9	19.3
45	49.3	49.5	48.8	50.0	56.1	65.7	66.7	66.7	29.8	35.1	18.9	19.3
50	50.8	51.0	50.3	51.5	57.9	67.4	68.4	68.1	30.5	36.1	19.1	19.6
55	52.0	52.5	51.7	52.7	59.1	68.9	69.6	69.6	31.0	36.9	19.1	19.8
60	53.2	53.4	52.7	53.4	60.3	69.9	70.8	70.6	31.7	37.6	19.3	19.6
65	54.2	54.4	53.7	54.7	61.3	70.8	71.8	71.6	32.0	38.1	19.3	20.1
70	55.0	55.2	54.2	55.6	62.3	71.6	72.6	72.3	32.5	38.6	19.3	19.8
75	55.6	55.9	55.0	56.1	63.0	72.3	73.3	73.0	32.7	39.0	19.3	20.3
80	56.4	56.4	55.4	56.6	63.5	73.0	73.8	73.5	33.0	39.3	19.6	20.3
85	56.6	56.9	56.1	57.4	64.2	73.5	74.3	74.0	33.4	39.5	19.1	20.6
90	57.1	57.4	56.3	57.6	64.5	73.8	74.8	74.5	33.7	40.0	19.3	20.6
95	57.6	57.6	56.6	57.9	65.0	74.3	75.0	74.5	33.7	40.3	19.3	20.8
100	57.9	58.1	56.9	58.3	65.2	74.5	75.3	75.0	34.0	40.5	19.6	20.8
105	58.1	58.3	57.1	58.3	65.7	74.8	75.5	75.3	34.2	40.5	19.3	20.6
110	58.3	58.6	57.6	58.8	66.0	75.0	75.7	75.5	34.3	40.8	19.6	21.0
115	58.6	58.8	57.9	58.8	66.0	75.3	76.0	75.5	34.4	41.0	19.6	21.0
120	58.8	59.1	57.9	59.1	66.2	75.5	76.2	75.7	34.7	41.0	19.6	21.0
130	59.3	59.3	58.1	59.6	66.7	75.7	76.7	76.2	34.9	41.5	19.8	21.0
135	59.3	59.6	58.3	59.6	66.7	76.0	76.7	76.3	34.9	41.5	19.8	20.8
145	59.6	59.8	58.8	59.8	66.9	76.2	77.0	76.5	35.4	41.7	20.1	20.8
155	59.8	60.1	58.8	60.1	67.4	76.5	77.2	76.7	35.6	42.0	20.3	21.3
165	60.1	60.3	59.3	60.3	67.6	76.7	77.5	77.0	35.6	42.2	20.3	21.5
175	60.3	60.3	59.3	60.5	67.6	77.0	77.5	77.0	36.1	42.5	20.3	21.5
185	60.5	60.5	59.6	60.8	67.9	77.0	77.7	77.2	36.1	42.7	20.3	21.5
195	60.5	60.8	59.8	60.8	68.1	77.0	77.7	77.2	36.4	42.7	20.6	21.8
205	60.8	60.8	59.8	61.0	68.1	77.2	78.0	77.5	36.6	42.9	20.8	21.8
215	61.0	61.0	60.1	61.3	68.4	77.5	78.0	77.7	36.6	43.2	20.6	22.0
225	61.3	61.3	60.3	61.5	68.6	77.7	78.2	77.7	36.9	43.4	20.8	22.0
235	61.3	61.5	60.5	61.5	68.6	77.7	78.4	78.0	37.1	43.4	21.0	22.3
245	61.5	61.5	60.5	61.5	68.9	78.0	78.4	78.0	37.1	43.7	21.3	22.0
255	61.5	61.8	60.5	61.8	68.9	78.0	78.7	78.2	37.3	43.9	21.3	22.0
265	61.8	61.8	60.8	62.0	69.1	78.2	78.9	78.4	37.6	44.2	21.5	22.3
275	62.0	62.0	61.0	62.3	69.4	78.4	78.9	78.4	37.8	44.2	21.5	22.5
285	62.0	62.0	61.0	62.3	69.4	78.4	78.9	78.4	37.8	44.4	21.8	23.0

INSULATED CHAMBER COOL DOWN TEMPERATURE °C												
TIME (IN)	A1	A2	A3	A4	B	C	D1	D2	E1	E2	PT	TA
0	61.8	62.0	60.8	62.0	68.4	74.5	74.8	74.0	37.8	44.4	21.5	22.0
1	61.5	61.5	60.5	61.5	67.2	72.1	72.1	71.1	37.6	44.2	21.3	22.3
2	60.8	61.0	59.8	61.0	66.0	69.6	69.1	68.4	37.3	43.7	21.0	22.3
3	60.1	60.1	59.1	60.1	64.5	67.2	66.7	66.0	36.9	43.4	21.0	22.5
4	59.3	59.3	58.1	59.1	63.2	65.2	64.5	63.7	36.6	42.7	21.0	22.0
5	58.6	58.3	57.4	58.3	62.0	63.5	62.7	62.0	36.4	42.5	20.6	22.3
6	57.6	57.4	56.3	57.4	60.8	61.8	61.0	60.1	35.9	42.0	20.6	22.3
7	56.6	56.4	55.2	56.4	59.3	60.1	59.3	58.3	35.6	41.2	20.6	22.5
8	55.4	55.2	54.2	55.2	58.1	58.6	57.6	56.9	35.1	40.8	20.6	22.0
9	54.4	54.2	53.0	53.4	56.9	57.1	56.4	55.4	34.9	40.0	20.3	22.0
10	53.2	53.2	52.0	53.0	55.6	55.9	54.9	54.2	34.4	39.5	20.3	22.0
11	52.2	52.2	51.0	52.0	54.4	54.7	53.7	53.0	34.2	39.0	20.6	22.0
12	51.2	51.2	50.3	51.0	53.4	53.4	52.7	51.7	33.7	38.6	20.3	22.5
13	50.5	50.3	49.3	50.0	52.5	52.2	51.5	50.8	33.4	37.8	20.1	22.3
14	49.5	49.3	48.3	48.8	51.5	51.3	50.5	49.5	33.0	37.3	20.3	22.0
15	48.6	48.3	47.3	48.1	50.3	50.0	49.3	48.6	32.7	36.9	20.3	21.5
16	47.6	47.3	46.6	47.1	49.3	49.3	48.6	47.6	32.5	36.4	20.3	21.8
17	46.9	46.6	45.6	46.4	48.6	48.3	47.6	46.7	32.0	35.9	20.3	21.3
18	46.1	45.9	44.9	45.4	47.6	47.3	46.6	45.9	31.7	35.6	20.3	21.5
19	45.4	44.9	44.2	44.7	46.9	46.6	45.9	45.1	31.5	35.1	20.3	21.0
20	44.4	44.2	43.4	43.9	45.9	45.6	44.9	44.2	31.3	34.7	20.1	21.0
22	43.2	43.0	42.0	42.4	44.4	44.2	43.4	42.7	30.8	34.0	20.3	20.8
24	41.7	41.5	40.8	41.0	43.0	42.7	42.0	41.5	30.3	33.2	20.1	20.1
26	40.5	40.3	39.5	39.8	41.7	41.2	40.8	40.0	29.8	32.5	20.3	21.3
28	39.3	39.0	38.3	38.6	40.3	40.0	39.5	38.8	29.3	31.7	20.1	20.6
30	38.3	38.1	37.3	37.6	39.3	39.0	38.3	37.8	29.1	31.3	20.3	20.6
35	35.9	35.6	34.9	35.1	36.6	36.4	35.9	35.4	28.1	30.0	19.8	20.6
40	33.9	33.7	33.2	33.2	34.7	34.2	33.9	33.2	27.4	28.8	20.1	20.8
45	32.2	32.0	31.5	31.5	32.7	32.5	32.0	31.5	26.6	27.8	20.1	19.6
50	30.8	30.5	30.0	30.0	31.3	31.0	30.5	30.0	26.1	27.1	20.1	19.8

TEMPERATURE (°C) UNINSULATED CASE								
Elapsed Time (Min)	A	B	C	D	E	F	G	Pole Tip Temp
0	19.6	19.5	19.0	18.6	16.9	-	19.3	19.1
5	22.1	25.1	30.5	31.4	22.7	-	27.1	19.3
10	27.2	30.9	37.3	38.1	30.0	-	33.4	19.3
15	31.5	35.6	41.7	42.6	36.4	-	38.3	19.8
20	34.7	38.8	44.9	45.3	35.9	-	41.5	19.6
25	36.9	41.1	47.1	47.5	39.8	-	44.2	19.8
30	38.4	42.8	48.7	48.9	41.2	-	45.9	20.3
35	39.4	43.9	49.7	49.9	44.7	-	46.9	20.3
40	40.3	44.7	50.5	50.8	46.6	-	47.6	20.3
45	41.0	45.5	51.0	51.4	48.3	-	48.6	20.3
50	41.5	45.9	51.5	51.7	44.2	-	49.0	20.6
55	41.8	46.2	51.9	52.3	46.9	-	49.3	20.8
60	42.2	46.7	52.2	52.5	44.7	-	49.8	20.8
65	42.5	47.0	52.7	53.1	51.2	-	50.0	20.8
70	42.7	47.2	52.8	53.1	45.1	-	50.3	21.0
75	42.8	47.3	53.0	53.4	50.8	-	50.5	20.8
80	42.9	47.5	53.2	53.6	49.8	-	50.5	21.3
85	43.2	47.7	53.2	53.4	49.5	-	50.5	21.3
90	43.3	47.7	53.2	53.3	49.8	-	50.8	21.0
95	43.3	47.7	53.2	53.8	49.3	-	50.8	21.5
100	43.4	48.0	53.4	53.8	46.6	-	50.8	21.5
105	43.4	48.2	53.4	53.9	47.3	-	51.0	21.8
110	43.4	47.8	53.3	53.4	52.2	-	50.8	21.5
115	43.6	48.1	53.6	53.8	49.3	-	51.0	21.8
120	43.7	48.1	53.6	53.8	49.0	45.1	51.0	21.8