BNL-101433-2014-TECH

RHIC/RF- 14;BNL-101433-2013-IR

Thermal analysis of RHIC PoP cavity

K. R. Vail

August 1993

Collider Accelerator Department

Brookhaven National Laboratory

U.S. Department of Energy

USDOE Office of Science (SC)

DISCLAIMER

RHIC/RF-14

RHIC Project
BROOKHAVEN NATIONAL LABORATORY

RHIC/RF Technical Note No. 14

Thermal Analysis of RHIC PoP Cavity

K. R. Vail
R. B. McKenzie-Wilson

August 1993

THERMAL ANALYSIS OF RHIC PoP CAVITY

Kimberly R. Vail
Raven B. McKenzie-Wilson

Brookhaven National Laboratory
August 1993

ABSTRACT

The Relativistic Heavy Ion Collider (RHIC) to be constructed at Brookhaven National Laboratory (BNL) is designed to accelerate, store and collide ion species ranging from protons to gold nuclei. The collision of these ions will form a quark-gluon plasma. Physicists will then study the structure of quark matter and conditions that are believed to have occurred at the time of the "Big Bang." The RHIC facility consists of two rings of superconducting dipole and quadropole magnets approximately 3.8 km in circumference contained in a common tunnel structure. Six experimental stations are located around the ring circumference to allow the construction of experimental equipment. Each ring of magnets is filled with an ion species from various pre-acceleration stages. The direction of motion of particles in each ring is such that the particle beams are contra-rotating. The particles are made to collide at the experimental locations. Two different RF systems perform the operations of beam acceleration and storage while a third system will take care of beam bunching errors. Beam acceleration will be carried out by two RF cavities in each ring which will be run in a CW mode during the acceleration cycle. As part of the development program, a Proof of Principle (PoP) accelerating cavity has been constructed with the primary purpose of studying RF problems. The problems include cavity multipactoring, power coupling, cavity tuning and higher order mode suppression. The initial cavity design was developed to be constructed at minimum cost and included only limited, best guess, cooling. This paper will discuss the cooling of the cavity to improve the CW performance. The computer code ALGOR has been used to design a "quick fix" approach to the cooling of the outer surfaces and also to analyze the cooling of the interior members with the currently installed cooling capacity.

INTRODUCTION

The 26.7 MHz Proof of Principle (PoP) accelerating cavity was built to study RF problems such are multipactoring, tuning, power coupling and higher order mode suppression. This PoP cavity will not carry a beam, it is for preliminary work only. A cross section is shown in figure 1, the cavity has circular symmetry about the axis. The acceleration process is vitally dependent on the resonant frequency of the cavity. The cavity itself is a component in a resonant circuit. This "resonant frequency" is analogous to the resonance of an RLC circuit. The cavity is "excited" by an RF power source to produce a voltage across the accelerating gap of the cavity. This voltage varies in time at 26.7 MHz and is made to coincide with the beam pulse such that acceleration of the beam takes place.

The PoP cavity was originally built without water cooling and with heat transfer and power dissipation to be calculated at a later time. Power densities have been calculated to vary greatly within the cavity. Cooling is needed to reduce the temperature gradient within the cavity. This is important because changes in temperature will expand or contract the metal and therefore alter the geometry. If the shape is changed, the resonant frequency will change also. This can not be allowed to happen if the beam is to reach the desired energy.

Since this is a prototype, cost is to be kept to an absolute minimum. Considering the outer wall of the cavity, the most practical solution is for the outer surface to have copper refrigeration tubing epoxyed onto it. Refrigeration tubing is readily available from industry, and is inexpensive. A thermally conducting epoxy would reduce cost and time from a labor standpoint. Epoxy is preferred over soldering because soldering a tube onto a copper plated AISI 1015 steel cavity is neither easy nor cost effective. The cavity inner members, on the other hand, already contain channels for water flow (see figure 1).

The heat transfer analysis was conducted using ALGOR, a finite elements analysis software package. In an RF cavity, power is dissipated in the walls by resistive losses. At resonance, the currents are large and flow in the top surface of the material only. Current penetration is a function of the operating frequency and at 26.7 MHz is approximately .05 mm. For the PoP cavity the power loss was calculated using the computer code SUPERFISH[1] and are shown in figure 2 as a function of surface position. To implement these sources into ALGOR, equivalent temperatures for a radiating black body with the given power density were calculated. Film coefficients were also calculated for surfaces in contact

26.7 MHz ACCELERATING RF CAVITY

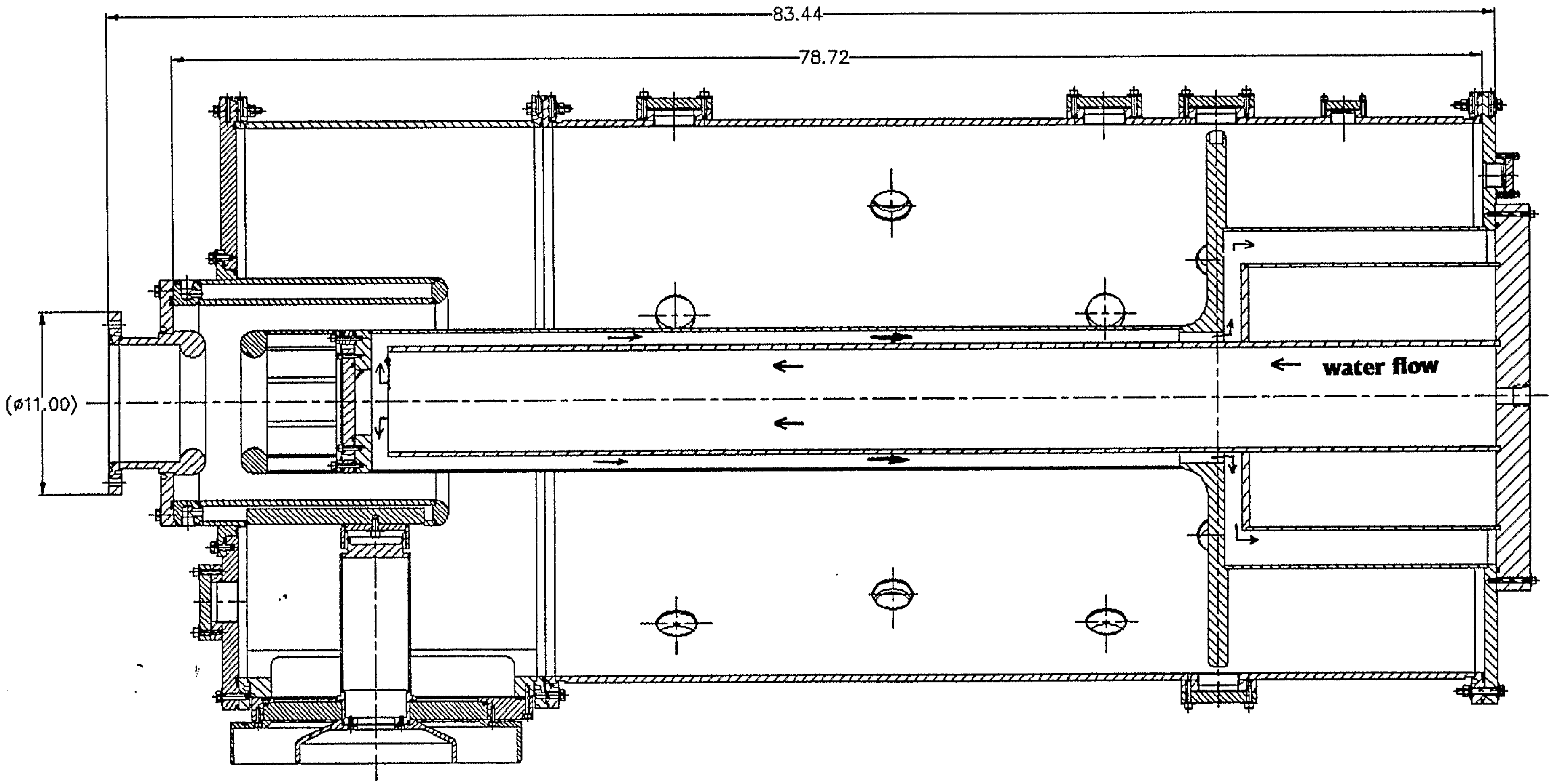


Figure 1

POWER DENSITIES CALCULATED BY SUPERFISH

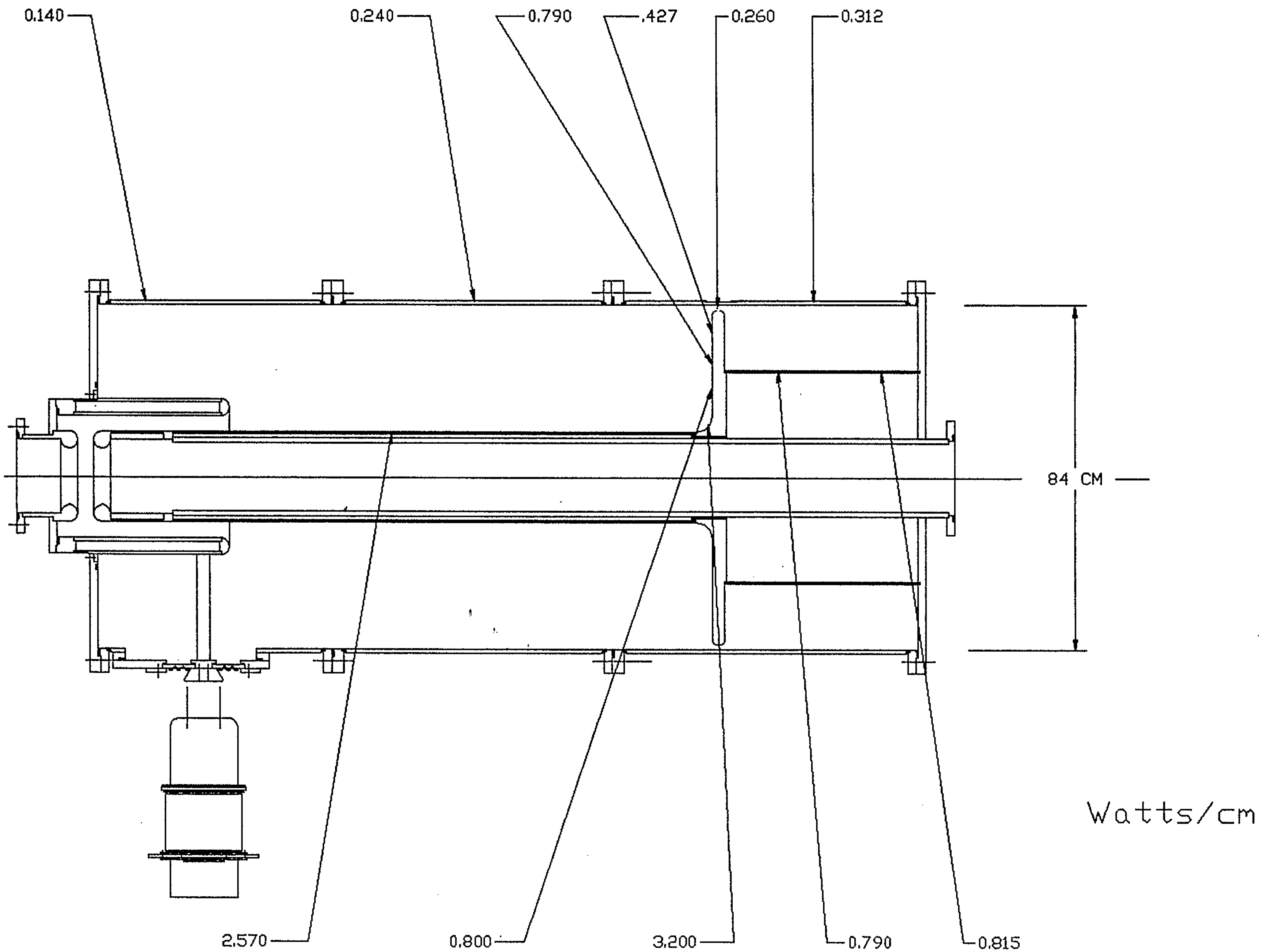


Figure 2

with a fluid (water or air).

PROCEDURE

As mentioned previously, ALGOR was used to conduct the heat transfer analysis. The cavity was broken down into six primary sections: three outside regions, and three inside. These sections are drawn with ALGOR's CAD package, Superdraw II, and then meshed to create the finite elements. The sections are shown below. Figure 3 is a cross section of the outside wall of the cavity with .5" O/D refrigeration tubing epoxyed onto it. The span between tubes is 8", the distance between the bottom outside edge of the tubing and the wall is 1/16" (epoxy thickness). The thickness of the copper tubing and the cavity wall are .032" and 3/8" respectively. The epoxy considered in this model is STYCAST 2850KT Epoxy Resin/Catalyst from Emerson and Cuming. The three regions of the outside surface are identical cross sections for three different power densities. Figures 4,5 and 6 are of the inner conductor of the cavity (not to scale). Figure 5 is the downward continuation of Figure 4.

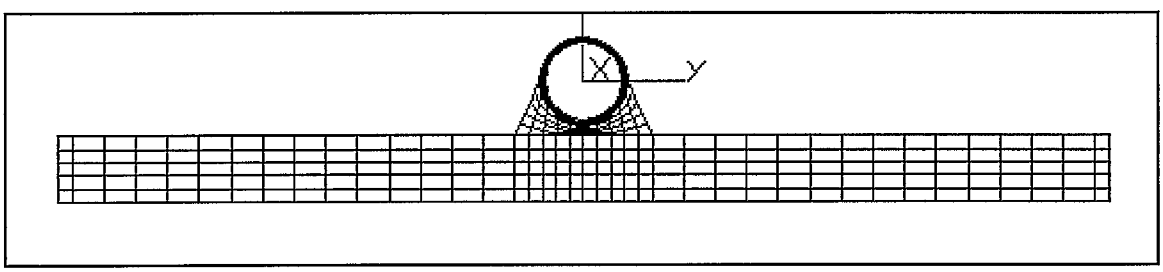


Figure 3

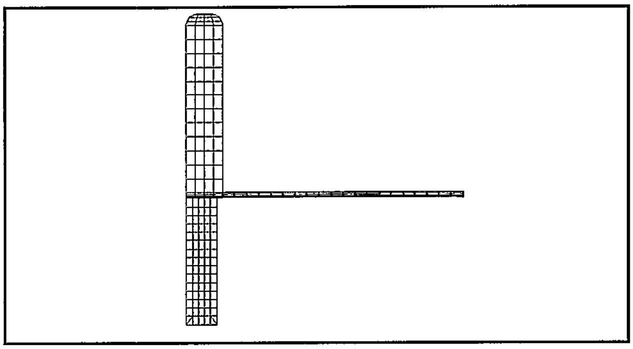


Figure 4

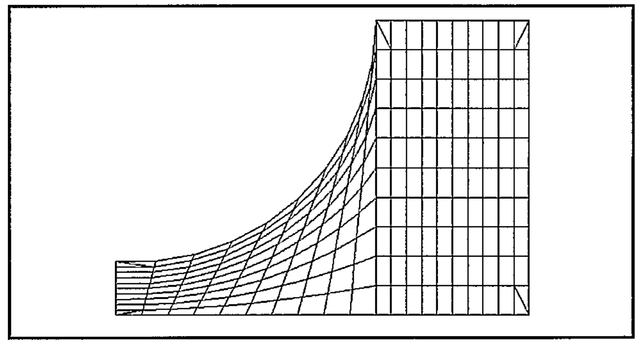


Figure 5

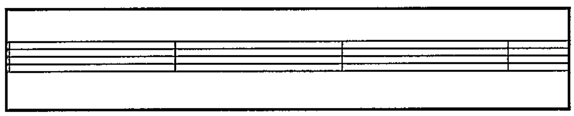


Figure 6

Figure 6 is a representative section of the leftward continuation of Figure 5.

Each section was further distinguished in Superdraw II with different colors. These different colors then had the appropriate power densities associated with them. (Refer to the engineering drawing, figure 1, for further component orientation.)

The Superdraw II file is then transferred to the thermal decoder "Decodit." In this file, the various thermal parameters and material properties are input into a spreadsheet type format (see appendix A). With these files created, a steady-state thermal analysis on the model can then be performed by the ALGOR program SSAP10H.

The criteria for sufficient cooling is approximately a 5°C gradient between the inside wall under the cooling tube and a similar point at the extreme distance from the cooling tube. For the inner members a larger gradient was allowed depending on the location.

CALCULATIONS

The film coefficient for the water flowing in the copper tube and for the air in contact with the cavity are calculated below. Equation 1[2] is valid for both cases. The differentiation between the two phenomena is in the Nusselt Number.

$$\frac{hD}{k} = Nu \tag{1}$$

where   *h = film coefficient*
D = the characteristic length of the system (the diameter of the cavity)
k = fluid thermal conductivity
Nu = overall Nusselt number

Cavity Exterior Surface

For free convective heat transfer the equation for the Nusselt Number is[2]:

$$Nu = C\ (Gr \times Pr)^{n}\ K \tag{2}$$

for a horizontal cylinder in a laminar flow of air[2]:

C	=	.47
n	=	.25
K	=	1

Grashof Number[2]:

$$Gr = \frac{\beta g \Delta\theta X^{3} \rho^{2}}{\mu^{2}} \tag{3}$$

Prandtl Number[2]:

$$Pr = \frac{\mu c_p}{k} \tag{4}$$

the values for the above variables are[2]:

Characteristic Length (D)	.859m
Fluid thermal Conductivity (k)	.02624 W/m-K
Fluid density (ρ)	1.1774 kg/m^3
Fluid viscosity (μ)	1.983x10^5 kg/m-s
Prandtl Number (Pr)	.708
Coeff. of volumetric expansion (β)	3.33x10^{-3}
Acceleration of gravity (g)	9.81 m/s^2
Temperature of fluid (T_f)	12.78°C
Temperature of cavity (T_w)	37.78°C
Temperature Difference (Δθ)	25.00°C

input these values into eqns. 2 & 3:

Grashof Number	1.8248x10^9
Nusselt Number	89.107

substituting into eqn. 1:

h = 2.722 W/m^2-K

Cooling tube

The water in the cooling tubing undergoes forced convective heat transfer of fluid flow through a cylindrical tube. The Nusselt Number for this process is as follows[2]:

$$Nu = C\ (Re^m Pr^n)\ K \tag{5}$$

for a circular tube with turbulent flow (see Reynold's Number Calculation below)[2]:

C	=.0225
m	=.8
n	=.4
K	= 1

Reynold's Number[2]:

$$Re = \frac{\rho v X}{\mu} = 2.5651 x 10^4 \tag{6}$$

since Re > 2,000, the flow is turbulent.

the values for the above variables are[2]:

Characteristic Length ($X=d_i$)	.0110744 m
Fluid density (ρ)	994.59 kg/m^3
Fluid viscosity (μ)	$6.5444x10^{-4}$ kg/m-s
Thermal conductivity (k)	.628 W/m-K
Prandtl Number (Pr)	4.34
Fluid temperature (T_f)	37.78°C
Fluid velocity (v)	1.524 m/s

substituting into eqns. 1 & 5:

h = 7730 W/m^2-K

Power Input

The heated surface temperature equivalence is calculated from the following equation[2]:

$$\frac{q}{A}=\epsilon\sigma T^4 \quad (7)$$

ALGOR uses the following equation for calculating radiation inputs[3]:

$$q'=F_{rad}\sigma\,(T_s^4-T_{rad}^4) \quad (8)$$

where q' = *heat per unit area*
σ = *Stefan-Boltzmann constant*
F_{rad} = *radiation function*
T_s = *unknown surface temperature*
T_{rad} = *temperature of the "radiating body"*

comparing eqns. 7 & 8, it can be seen that for all cases:

F_{rad} = .05

(the emissitivity of copper)

from eqn. 7[1]*:*

Power Density (W/cm^2)	T_{rad} (K)	T_{rad} (°C)
.14	838.3	565.15
.24	959.0	686.00
.312	1024.0	751.00

Cavity Interior

The calculations for the film coefficients of the inside surfaces are similar to that for the refrigeration tube. Calculations are based on assuming a water flow of .6096 m/s (2 ft/s) along the bottom edge of figure 4. Equation 1 is used to calculate

the film coefficients.

for all film coefficient calculations[2]*:*

Fluid density (ρ)	994.59 kg/m^3
Fluid viscosity (μ)	6.5444x10^{-4} kg/m-s
Prandtl Number (Pr)	4.34
Thermal conductivity (k)	.628 W/m-K
C	.0225
m	.8
n	.4
K	1

from conservation of mass flow, we know:

$$\rho_1 v_1 A_1 = \rho_2 v_2 A_2 \qquad (9)$$

from the geometry of the cavity and eqn 9:

Location of Surface	Diameter	Fluid Velocity	Reynold's #
Bottom Edge of Figure 5	.0200025 m	0.6096 m/s (2 ft/s)	18,531.20
Right Edge of Figure 5	.0535940 m	0.0849 m/s	6,916.26
Bottom Edge of Figure 6	.0248285 m	0.396 m/s	14,942.38
Bottom-right Edge of Fig. 4	.0515620 m	0.0917 m/s	7,188.92

substituting these values into eqns. 1 & 5:

Location of Surface	Film Coefficient
Bottom Edge of Figure 5	3298.96 W/m^2-K
Right Edge of Figure 5	559.65 W/m^2-K
Bottom Edge of Figure 6	2237.30 W/m^2-K
Bottom-right edge of Figure 4	599.98 W/m^2-K

Power Input

The inside area of the cavity was analyzed for both cw and 20% duty cycle. As in the previous case, the radiation function is a constant, namely the emissivity of copper. The radiant temperatures are also calculated in the same manner and their values are given below.

CW power[1]:

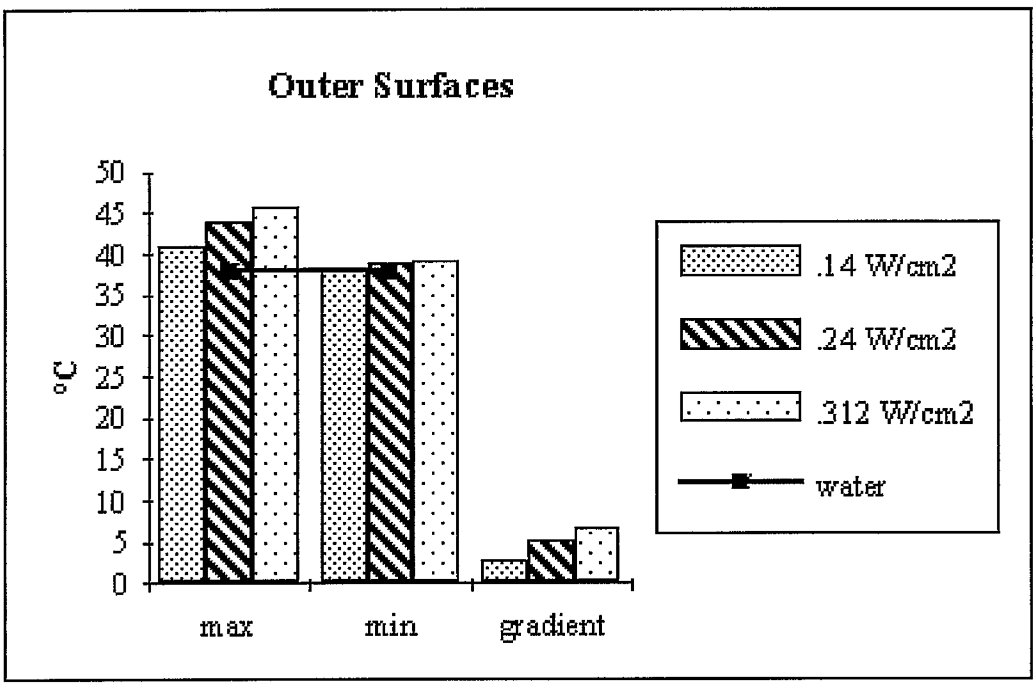
Power Density (W/cm^2)	T_{rad} (K)	T_{rad}(°C)
.26	978.63	705.48
.316	1027.55	754.40
.427	1107.86	834.71
.586	1199.11	925.96
.79	1292.08	1018.93
.598	1213.02	939.87
.8	1296.15	1023.00
1.13	1413.02	1139.87
3.2	1888.63	1615.48
2.7	1735.26	1462.11

20% Duty Cycle:

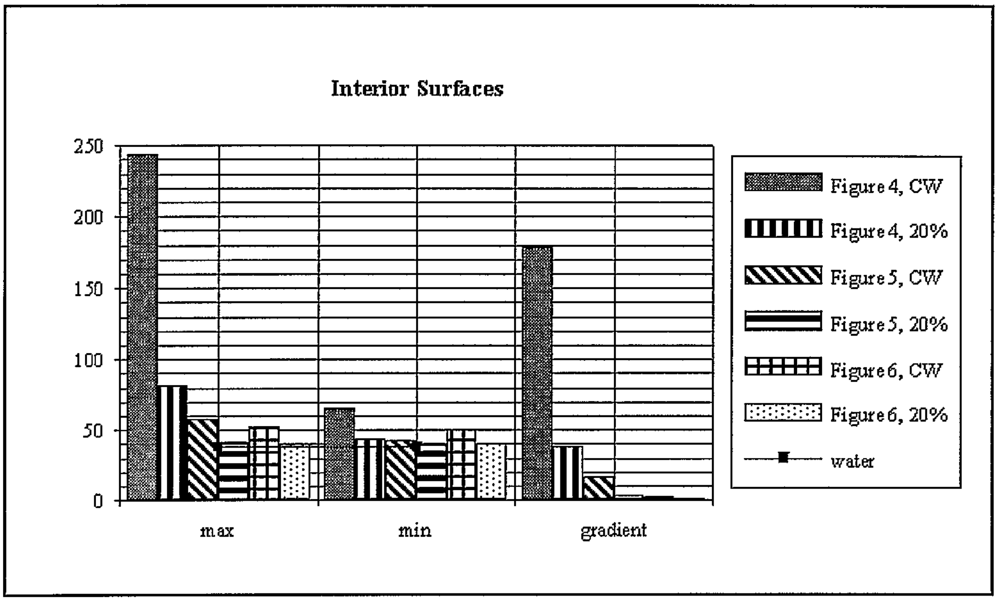
Power Density (W/cm2)	T_{rad} (K)	T_{rad} (°C)
.052	654.44	381.29
.0632	687.14	413.99
.0854	740.85	467.70
.1172	801.86	528.71
.158	864.04	590.89
.1196	805.94	532.79
.16	866.76	593.61
.226	944.92	671.77
.64	1225.78	952.63
.54	1174.81	901.66

RESULTS

After running the processors, the results can be viewed using ALGOR's Superview program. In this analysis, the primary concerns are the temperature gradients and the extremes reached. These critical data are given below. The "max" temperature is found midpoint between the cooling tubes in the wall of the cavity. The "min" is the temperature of the inner wall of the cooling tube itself. The "gradient" is the difference between these two values. The detailed output files are attached in appendix B.



For the inner surfaces, the maximum, minimum and difference there of are given below. The maximum occurs along the top portion of the tuning disk of figure 4, the upper left area of figure 5, and along the top surface of figure 6.



Additional studies were conducted on elliptical geometries for the cooling tube. Refrigeration tubing flattened to a .7 & .5 minor/major axis ratios were modeled for the three power densities of the outer surface cooling. It was found that a .7 vertical/horizontal ratio was most effective in cooling the cavity in these three cases. However, the labor requirements to fabricate the elliptical tube far outweighed the thermal gain. Decreasing the spacing between tubes more effectively improved cooling effectiveness. If modifications occur such that power densities are found to be higher than those calculated currently, and cooling is not sufficient, spacing should be reduced at .5" intervals until sufficient cooling is obtained. Elliptical shaping should be a last resort.

CONCLUSIONS

It has been determined that the outside of the cavity can be sufficiently cooled by using .5" refrigeration tubing spaced 8" apart attached by a 1/16" layer of STYCAST

2850KT Epoxy Resin/Catalyst and a water flow of 5 ft/s. The inside members are the critical areas, particularly in the area of the tuning disk. At 20% duty cycle, water flow of 2 ft/s* is sufficient to cool the inside surfaces to reasonable temperatures. However, when running cw the cavity reaches excessive temperatures. This is currently not of urgent concern since parallel investigations concerning the tuning of the cavity are indicating removal of this thermally critical area.

ACKNOWLEDGMENTS

The author would like to thank Ray McKenzie-Wilson for providing the opportunity to conduct this work and the entire RHIC/RF group for their support throughout my assignment here. I would also like to thank Mary Campbell for clerical assistance.

---

*This velocity is in reference to the water flow along the bottom edge of figure 5.

REFERENCES

1. Rose, Jim, "Power Dissipation and Power Densities in the PoP Cavity", RHIC/RF Memorandum Brookhaven National Laboratory, 1993.

2. Wong, H.Y., Heat Transfer for Engineers, Longman Group Limited, London, 1977.

3. ALGOR, Heat Transfer Analysis, Processor Reference Manual.

Appendix A:
Outside Surface - .14 W/cm^2

Name of material

40:2-DIM :Layer(1) Group

Gr	Name	Lib	Density	k-cond	Cp	S-Boltz	T-abs
1	Copper		.00893	3.98	386	5.6697e-12	273.15
2	Steel		.00784	.498	465	5.6697e-12	273.15
3	Epoxy			.026808		5.6697e-12	273.15
4	Copper		.00893	3.98	386	5.6697e-12	273.15
5	Steel		.00784	.498	465	5.6697e-12	273.15
6	Steel		.00784	.498	465	5.6697e-12	273.15
7							
8							
9							
10							
11							
12							
13							
14							
15							
16							
17							
18							

Esc-Escape F3-Edit F4-Delete /=Commands

thick: element thickness.

40:2-DIM :Layer(1) Color

Col	thick	Tconv	h conv	Trad	F rad	q/vol
1	1.0	12.77	.0002722			
2	1.0	12.77	.0002722			
3	1.0	12.77	.0002722			
4	1.0	37.78	.7730			
5	1.0			565	.05	.14
6	1.0					
7						
8						
9						
10						
11						
12						
13						
14						
15						
16						
17						
18						

Esc-Escape F3-Edit F4-Delete /=Commands

Name of material

Appendix A:
Outside Surface - .24 W/cm^2

40:2-DIM :Layer(1) Group

Gr	Name	Lib	Density	k-cond	Cp	S-Boltz	T-abs
1	Copper		.00893	3.98	386	5.6697e-12	273.15
2	Steel		.00784	.498	465	5.6697e-12	273.15
3	Epoxy			.026808		5.6697e-12	273.15
4	Copper		.00893	3.98	386	5.6697e-12	273.15
5	Steel		.00784	.498	465	5.6697e-12	273.15
6	Steel		.00784	.498	465	5.6697e-12	273.15
7							
8							
9							
10							
11							
12							
13							
14							
15							
16							
17							
18							

Esc-Escape F3-Edit F4-Delete /=Commands

thick: element thickness.

40:2-DIM :Layer(1) Color

Col	thick	Tconv	h conv	Trad	F rad	q/vol
1	1.0	12.77	.0002722			
2	1.0	12.77	.0002722			
3	1.0	12.77	.0002722			
4	1.0	37.78	.7730			
5	1.0			686	.05	.24
6	1.0					
7						
8						
9						
10						
11						
12						
13						
14						
15						
16						
17						
18						

Esc-Escape F3-Edit F4-Delete /=Commands

Name of material

Appendix A:
Outside Surface - .312 W/cm^2

40:2-DIM :Layer(1) Group

Gr	Name	Lib	Density	k-cond	Cp	S-Boltz	T-abs
1	Copper		.00893	3.98	386	5.6697e-12	273.15
2	Steel		.00784	.498	465	5.6697e-12	273.15
3	Epoxy			.026808		5.6697e-12	273.15
4	Copper		.00893	3.98	386	5.6697e-12	273.15
5	Steel		.00784	.498	465	5.6697e-12	273.15
6	Steel		.00784	.498	465	5.6697e-12	273.15
7							
8							
9							
10							
11							
12							
13							
14							
15							
16							
17							
18							

Esc-Escape F3-Edit F4-Delete /=Commands

thick: element thickness.

40:2-DIM :Layer(1) Color

Col	thick	Tconv	h conv	Trad	F rad	q/vol
1	1.0	12.77	.0002722			
2	1.0	12.77	.0002722			
3	1.0	12.77	.0002722			
4	1.0	37.78	.7730			
5	1.0			751	.05	.312
6	1.0					
7						
8						
9						
10						
11						
12						
13						
14						
15						
16						
17						
18						

Esc-Escape F3-Edit F4-Delete /=Commands

Appendix A:
Figure 4 - CW

Name of material

40:2-DIM :Layer(1) Group

Gr	Name	Lib	Density	k-cond	Cp	S-Boltz	T-abs
1	steel		.00784	.4980	465	5.6697e-12	273.15
2	Copper		.00893	3.98	386	5.6697e-12	273.15
3	Copper		.00893	3.98	386	5.6697e-12	273.15
4	Copper		.00893	3.98	386	5.6697e-12	273.15
5	Copper		.00893	3.98	386	5.6697e-12	273.15
6	Copper		.00893	3.98	386	5.6697e-12	273.15
7	Copper		.00893	3.98	386	5.6697e-12	273.15
8	Copper		.00893	3.98	386	5.6697e-12	273.15
9	Copper		.00893	3.98	386	5.6697e-12	273.15
10	Copper		.00893	3.98	386	5.6697e-12	273.15
11	Copper		.00893	3.98	386	5.6697e-12	273.15
12	Copper		.00893	3.98	386	5.6697e-12	273.15
13	Copper		.00893	3.98	386	5.6697e-12	273.15
14							
15							
16							
17							
18							

Esc-Escape F3-Edit F4-Delete /=Commands

thick: element thickness.

40:2-DIM :Layer(1) Color

Col	thick	Tconv	h conv	Trad	F rad	q/vol
1	1.0					
2	1.0			705.48	.05	.26
3	1.0			754.4	.05	.316
4	1.0			834.71	.05	.427
5	1.0			925.96	.05	.586
6	1.0			1018.93	.05	.79
7	1.0	37.78	.059998	1018.93	.05	.79
8	1.0	37.78	11.406	932.04	.05	.598
9	1.0			932.04	.05	.598
10	1.0	37.78	11.406	1023	.05	.8
11	1.0			1023	.05	.8
12	1.0	37.78	11.406	1139.87	.05	1.13
13	1.0			1139.87	.05	1.13
14						
15						
16						
17						
18						

Esc-Escape F3-Edit F4-Delete /=Commands

Appendix A:
Figure 4 - 20% Duty Cycle

Name of material

40:2-DIM :Layer(1) Group

Gr	Name	Lib	Density	k-cond	Cp	S-Boltz	T-abs
1	steel		.00784	.4980	465	5.6697e-12	273.15
2	Copper		.00893	3.98	386	5.6697e-12	273.15
3	Copper		.00893	3.98	386	5.6697e-12	273.15
4	Copper		.00893	3.98	386	5.6697e-12	273.15
5	Copper		.00893	3.98	386	5.6697e-12	273.15
6	Copper		.00893	3.98	386	5.6697e-12	273.15
7	Copper		.00893	3.98	386	5.6697e-12	273.15
8	Copper		.00893	3.98	386	5.6697e-12	273.15
9	Copper		.00893	3.98	386	5.6697e-12	273.15
10	Copper		.00893	3.98	386	5.6697e-12	273.15
11	Copper		.00893	3.98	386	5.6697e-12	273.15
12	Copper		.00893	3.98	386	5.6697e-12	273.15
13	Copper		.00893	3.98	386	5.6697e-12	273.15
14							
15							
16							
17							
18							

Esc-Escape F3-Edit F4-Delete /=Commands

thick: element thickness.

40:2-DIM :Layer(1) Color

Col	thick	Tconv	h conv	Trad	F rad	q/vol
1	1.0					
2	1.0			381.29	.05	.052
3	1.0			413.99	.05	.0632
4	1.0			467.7	.05	.0854
5	1.0			528.71	.05	.1172
6	1.0			590.84	.05	.158
7	1.0	37.78	.059998	590.84	.05	.158
8	1.0	37.78	11.406	532.79	.05	.1196
9	1.0			532.79	.05	.1196
10	1.0	37.78	11.406	593.61	.05	.16
11	1.0			593.61	.05	.16
12	1.0	37.78	11.406	671.77	.05	.226
13	1.0			671.77	.05	.226
14						
15						
16						
17						
18						

Esc-Escape F3-Edit F4-Delete /=Commands

Appendix A:
Figure 5 - CW

Name of material

40:2-DIM :Layer(1) Group

Gr	Name	Lib	Density	k-cond	Cp	S-Boltz	T-abs
1	Steel		.00784	.498	465	5.6697e-12	273.15
2	Copper		.00893	3.98	386	5.6697e-12	273.15
3	Copper		.00893	3.98	386	5.6697e-12	273.15
4	Copper		.00893	3.98	386	5.6697e-12	273.15
5							
6							
7							
8							
9							
10							
11							
12							
13							
14							
15							
16							
17							
18							

Esc-Escape F3-Edit F4-Delete /=Commands

thick: element thickness.

40:2-DIM :Layer(1) Color

Col	thick	Tconv	h conv	Trad	F rad	q/vol
1	1.0					
2	1.0			1559.82	.05	3.2
3	1.0	37.78	.3299			
4	1.0	37.78	11.406			
5						
6						
7						
8						
9						
10						
11						
12						
13						
14						
15						
16						
17						
18						

Esc-Escape F3-Edit F4-Delete /=Commands

Appendix A:
Figure 5 - 20% Duty Cycle

Name of material

40:2-DIM :Layer(1) Group

Gr	Name	Lib	Density	k-cond	Cp	S-Boltz	T-abs
1	Steel		.00784	.498	465	5.6697e-12	273.15
2	Copper		.00893	3.98	386	5.6697e-12	273.15
3	Copper		.00893	3.98	386	5.6697e-12	273.15
4	Copper		.00893	3.98	386	5.6697e-12	273.15
5							
6							
7							
8							
9							
10							
11							
12							
13							
14							
15							
16							
17							
18							

Esc-Escape F3-Edit F4-Delete /=Commands

Trad: Ambient Temperature for radiation

40:2-DIM :Layer(1) Color

Col	thick	Tconv	h conv	Trad	F rad	q/vol
1	1.0					
2	1.0			952.63	.05	.64
3	1.0	37.78	.3299			
4	1.0	37.78	11.406			
5						
6						
7						
8						
9						
10						
11						
12						
13						
14						
15						
16						
17						
18						

Esc-Escape F3-Edit F4-Delete /=Commands

Appendix A:
Figure 6 - CW

Name of material

40:2-DIM :Layer(1) Group

Gr	Name	Lib	Density	k-cond	Cp	S-Boltz	T-abs
1	Steel		.00784	.498	465	5.6697e-12	273.15
2	Copper		.00893	3.98	386	5.6697e-12	273.15
3	Copper		.00893	3.98	386	5.6697e-12	273.15
4							
5							
6							
7							
8							
9							
10							
11							
12							
13							
14							
15							
16							
17							
18							

Esc-Escape F3-Edit F4-Delete /=Commands

thick: element thickness.

40:2-DIM :Layer(1) Color

Col	thick	Tconv	h conv	Trad	F rad	q/vol
1	1.0					
2	1.0			1450.12	.05	2.5
3	1.0	37.78	.22373			
4						
5						
6						
7						
8						
9						
10						
11						
12						
13						
14						
15						
16						
17						
18						

Esc-Escape F3-Edit F4-Delete /=Commands

Appendix A:
Figure 6 - 20% Duty Cycle

Name of material

40:2-DIM :Layer(1) Group

Gr	Name	Lib	Density	k-cond	Cp	S-Boltz	T-abs
1	Steel		.00784	.498	465	5.6697e-12	273.15
2	Copper		.00893	3.98	386	5.6697e-12	273.15
3	Copper		.00893	3.98	386	5.6697e-12	273.15
4							
5							
6							
7							
8							
9							
10							
11							
12							
13							
14							
15							
16							
17							
18							

Esc-Escape F3-Edit F4-Delete /=Commands

thick: element thickness.

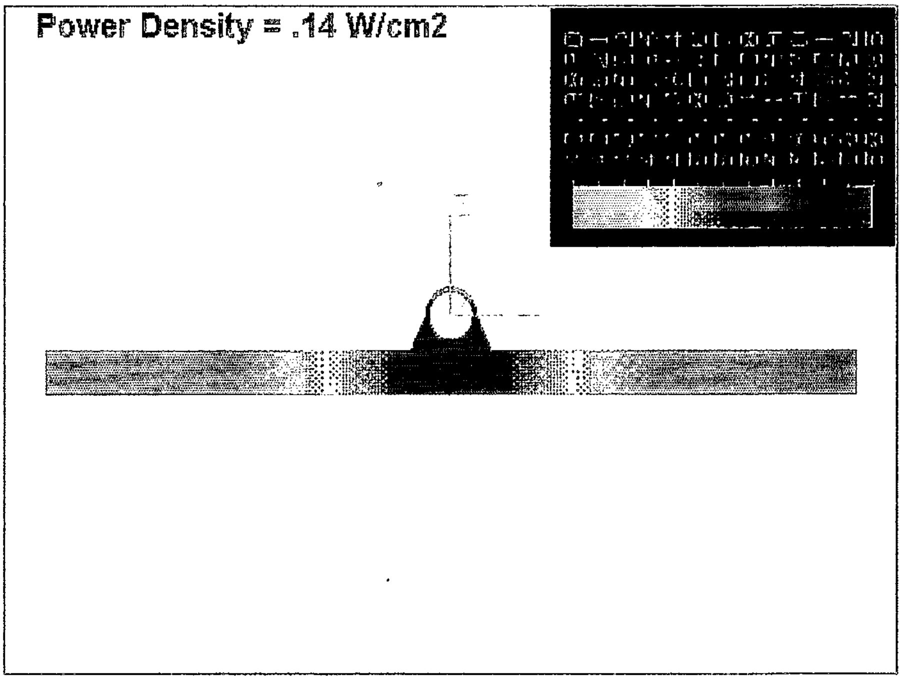
40:2-DIM :Layer(1) Color

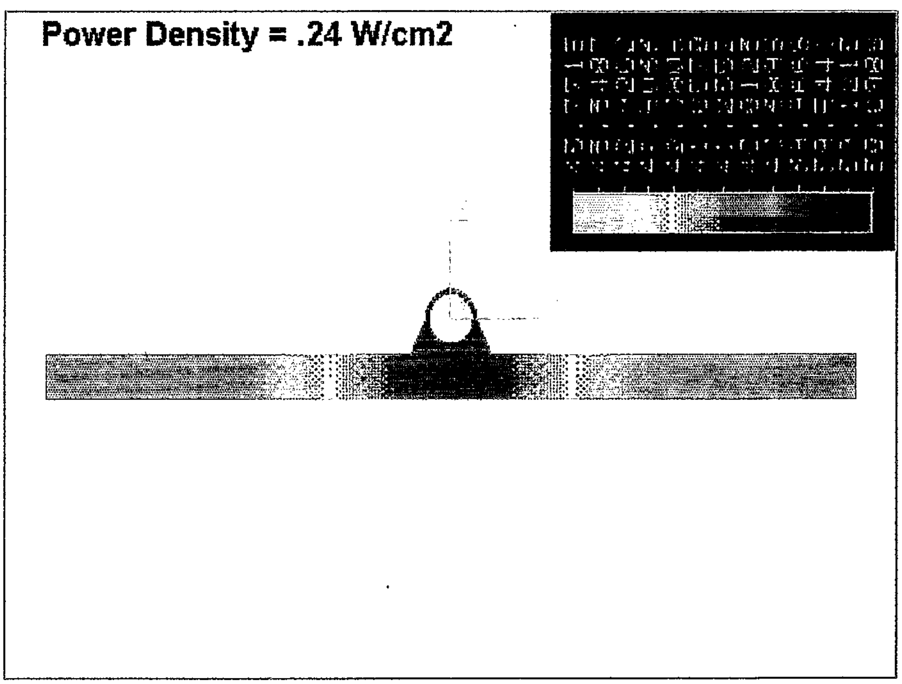
Col	thick	Tconv	h conv	Trad	F rad	q/vol
1	1.0					
2	1.0			879.27	.05	.5
3	1.0	37.78	.22373			
4						
5						
6						
7						
8						
9						
10						
11						
12						
13						
14						
15						
16						
17						
18						

Esc-Escape F3-Edit F4-Delete /=Commands

APPENDIX B

ALGOR Steady-State Thermal Analysis Outputs


Power Density = .14 W/cm2


Power Density = .24 W/cm2

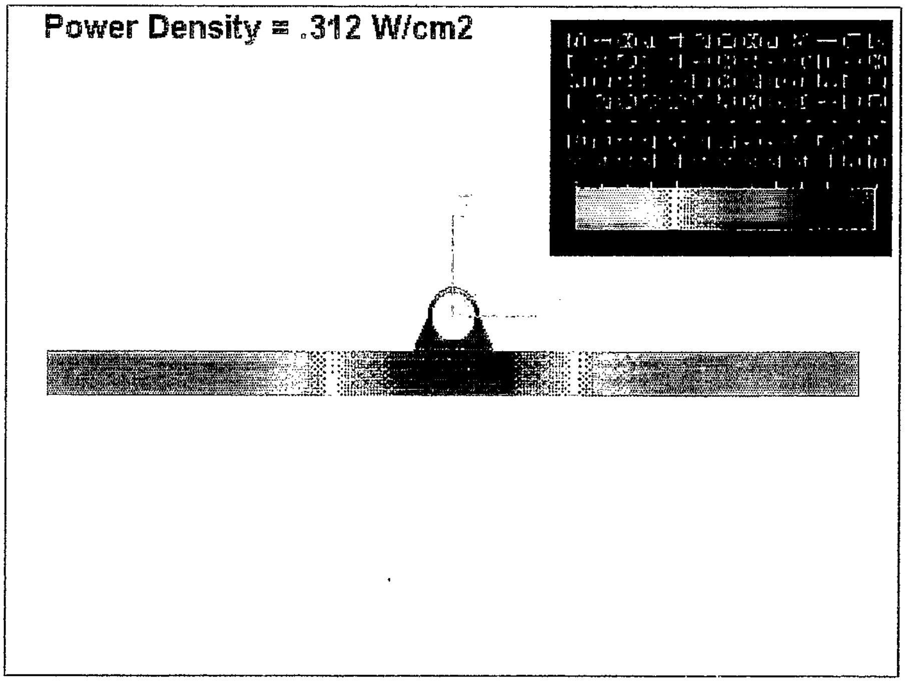
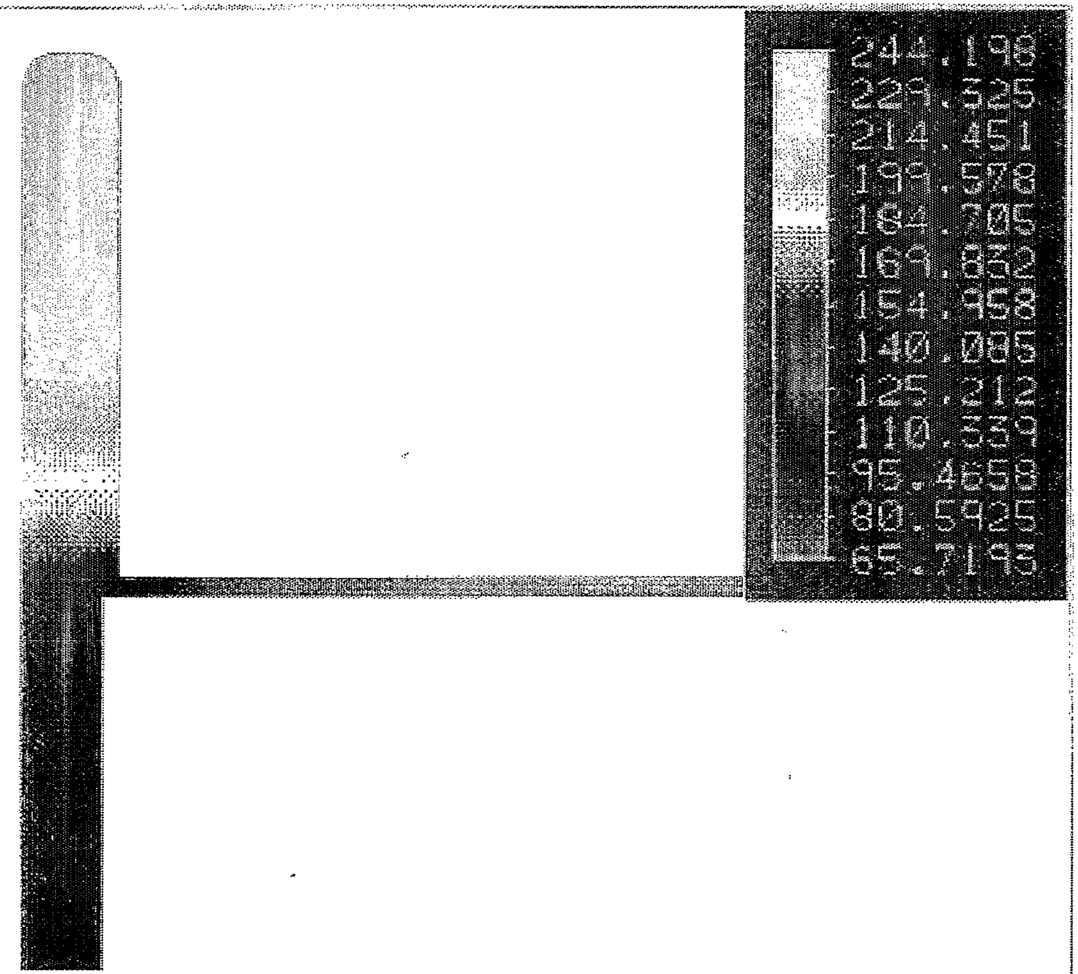

Power Density = .312 W/cm2

Figure 4
CW


244.198
229.325
214.451
199.578
184.705
169.832
154.958
140.085
125.212
110.339
95.4658
80.5925
65.7193

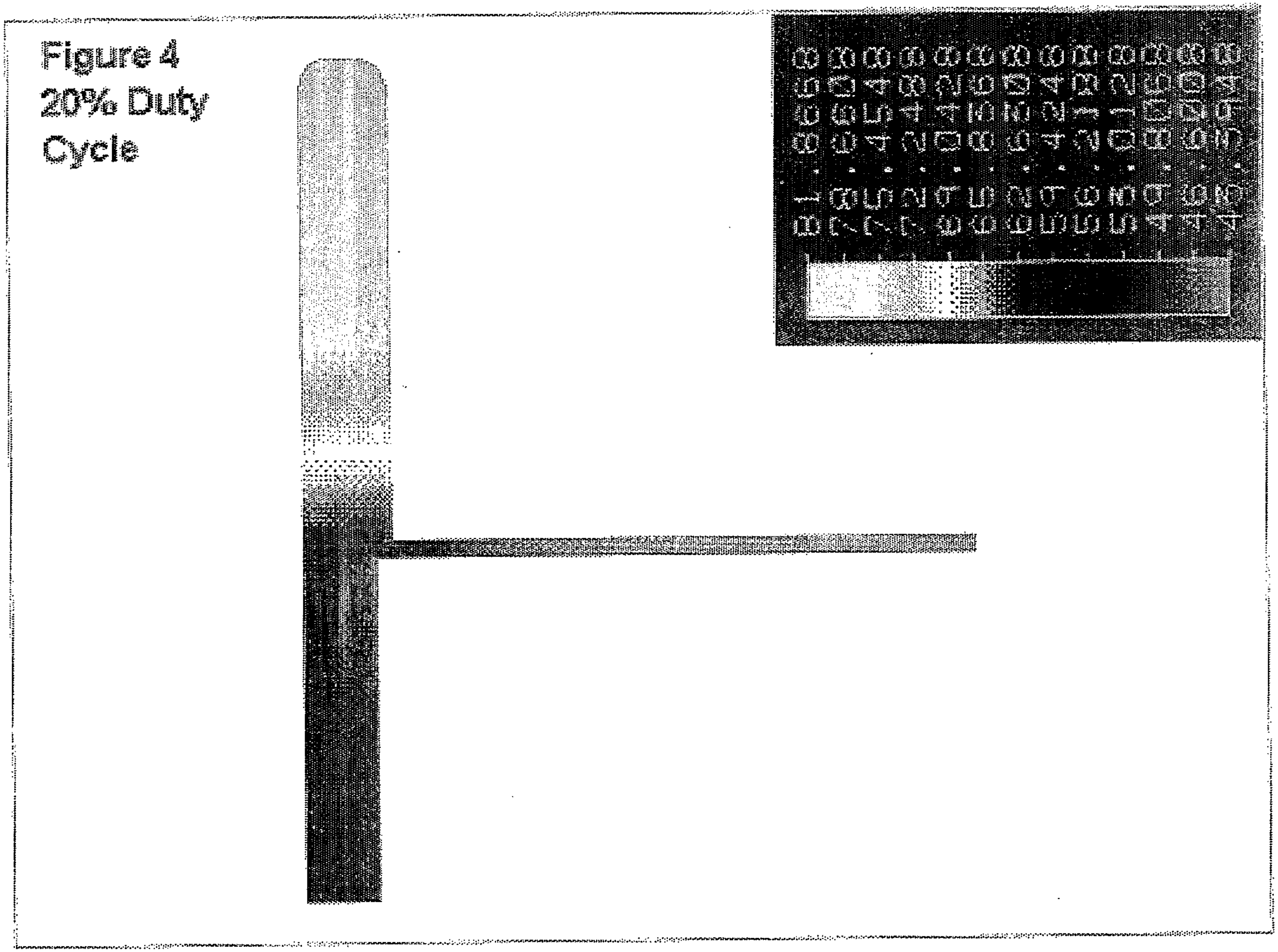


Figure 4
20% Duty Cycle

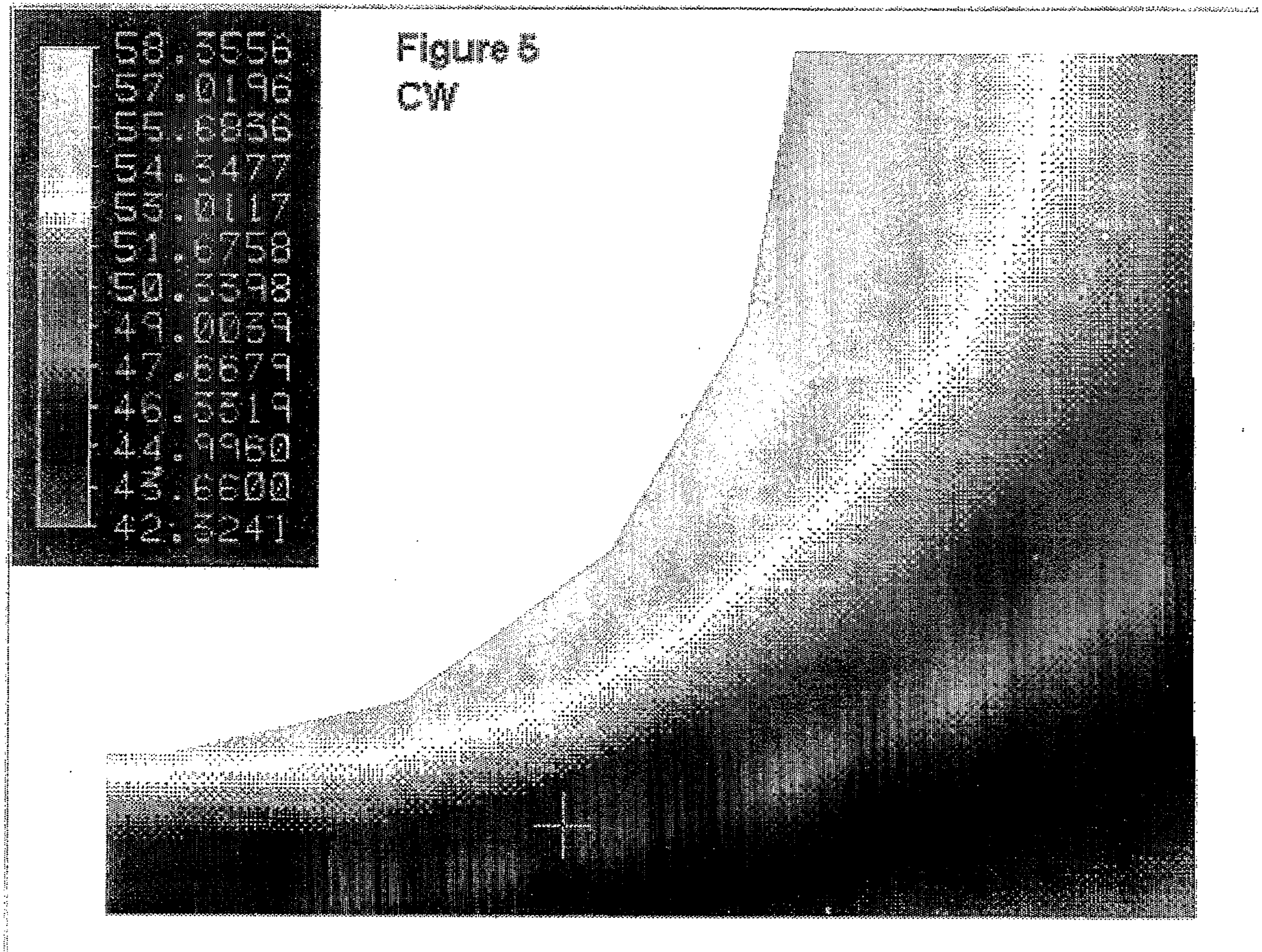

58.3556
57.0196
55.6836
54.3477
53.0117
51.6758
50.3398
49.0039
47.6679
46.3319
44.9960
43.6600
42.3241

Figure 5
CW

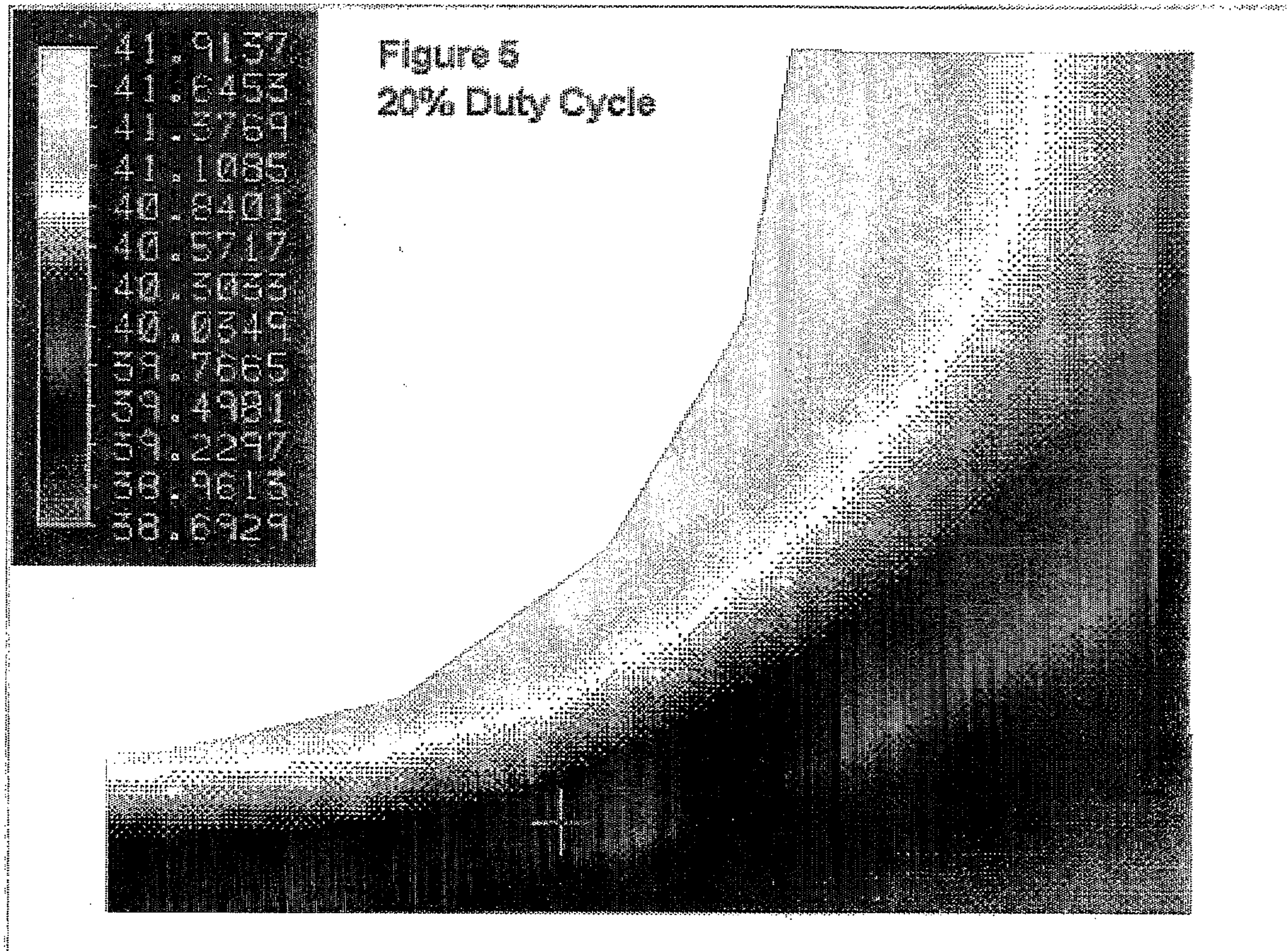


Figure 5
20% Duty Cycle

Figure 6
CW

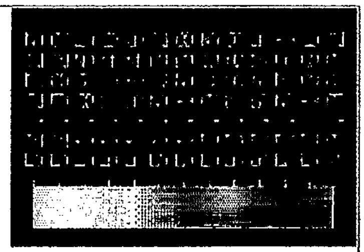


Figure 6
20% Duty Cycle