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TEMPERATURE DISTRIBUTION IN THE WINDINGS OF THE 3.4 MW POWER SUPPLY

SUMMARY

The temperature distribution in the high-voltage and low-voltage windings of the 3.4 MW power supply was calculated. The maximum temperature anywhere in the power supply was found to be approximately 330 °C; it occured in the inner winding of the high-voltage coil. The center winding of the same coil showed a temperature of 255 °C, and the outer winding one of 215 °C. Both the highest temperatures in the inner and in the center windings are in excess of the temperature rating of the adjacent insulating material. The latter is NOMEX, a nylon fiber paper which is rated at 220 °C, although operation at 250 °C is probably safe.

Several possible methods to reduce these excessive temperatures were investigated. An increase in the cooling air velocity as well as a reduction in the air inlet temperature proved to be not practical. On the other hand, a reduction of the operating current and thus the power by 10% would reduce the maximum temperatures to approximately 250 °C. In the long-term interest of the project and the groups concerned, a redesign of the high-voltage coil is suggested.

Both low-voltage coils (Δ and Y) were found to be properly designed for heat transfer purposes and showed moderate temperatures.

I. INTRODUCTION

Subject of this investigation is the SLAC 3.4 MW power supply. It is used to operate the magnets of the 40-inch and 82-inch bubble chamber and the magnet of the 54-inch spark chamber. The power supply is a silicon-controlled rectifier with a current rating of 10,000/5,000 A.

The unit has a long standing history of overheating which is cause for this detailed examination of the temperature distribution in the various windings.

In the second section of this note the high-voltage coil is examined in detail. Thermal resistances for the insulation layers are computed along with the electrical resistance of the conductors. The power dissipated in the conductors due to I^2R-heating allows calculation of the effective heat fluxes and temperature differences. Heat transfer by both natural and forced convection to air is used to determine the surface temperature and thus temperature distribution of the windings.

The third section evaluated the low-voltage coils. The windings are especially examined for cross-coupling, an often neglected phenomenon which can have disastrous consequences.

Finally, in the fourth section some suggested methods to reduce excessive temperatures in the windings are examined.

It is hoped that this note not only presents the important temperature data of the 3.4 MW power supply but also serves as a guide for future calculation, design, and examination of other power supplies.

II. TEMPERATURE DISTRIBUTION IN THE HIGH-VOLTAGE WINDINGS

1. Material Properties

Some properties of the materials used in the windings are as follows:

Thermal Conductivities	k Btu/(hr ft^2 ^oF/ft)
Copper	225 (at 80 ^oF)
Aluminum	140
Press Board	0.057
NOMEX*	0.065
Isomica	0.073
Air	0.015 (at 80 ^oF)
Varnish	0.05 (estimated)
Mixture of Air and Varnish	0.03 (estimated)

A schematic cross section of the high-voltage coil is shown in Fig. 1.

2. Thermal Resistances

The thermal resistance across a layer is defined as

$$R_{th} = \frac{\delta}{k} \qquad (1)$$

where δ = thickness of the layer

k = thermal conductivity of layer

*A trade-name of the DuPont Co.

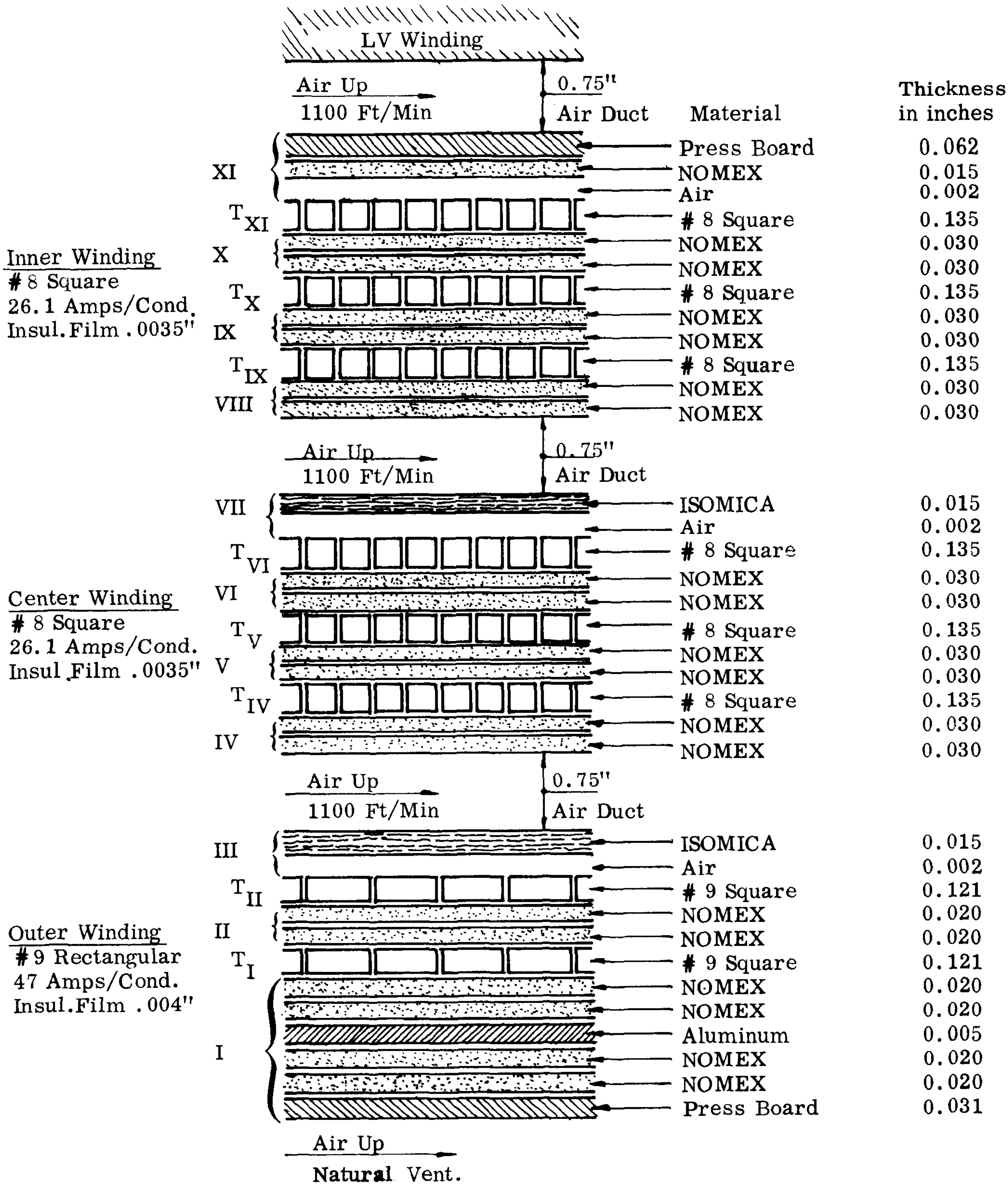

Fig. 1 Schematic Cross Section Through High-Voltage Coil

Note, the heat transfer problem is a one-dimensional problem only, since the lateral dimensions of the various layers are large compared to their thickness, and since power dissipation over lateral distances comparable to the thickness of the winding can be assumed to be constant.

It can be shown that the thermal resistance across the copper conductor is negligible compared to the other resistances.

It is assumed that each two adjacent layers are on the average separated by 0.003 inch, and that this space is filled by a mixture of varnish and air bubbles with an assumed thermal conductivity of 0.03 Btu/(hr ft^2 ^{o}F/ft). Measurements of the total thickness of some windings indicated that 0.003 inch is probably low.

The various insulation layers are designated by Roman numerals as shown in Fig. 1. The thermal resistance of the outer most layer is then

$$R_I = \frac{0.031}{0.057} + \frac{0.003}{0.03} + \frac{0.020}{0.065} + \frac{0.003}{0.03} + \frac{0.020}{0.065} + \frac{0.003}{0.03}$$

$$+ \frac{0.005}{140} + \frac{0.003}{0.03} + \frac{0.020}{0.065} + \frac{0.003}{0.03} + \frac{0.020}{0.065} + \frac{0.004}{0.03}$$

$$\approx 2.40 \text{ hr ft}^2 \, ^o\text{F/Btu}.$$

All other resistances are obtained likewise and are listed as follows:

R_{II}	$\approx$ 0.97 hr ft^2 ^{o}F/Btu	R_{VII}	$\approx$ 0.47 hr ft^2 ^{o}F/Btu
R_{III}	$\approx$ 0.47 hr ft^2 ^{0}F/Btu	R_{VIII}	$\approx$ 1.14 hr ft^2 ^{o}F/Btu
R_{IV}	$\approx$ 1.14 hr ft^2 ^{o}F/Btu	R_{IX}	$\approx$ 1.26 hr ft^2 ^{o}F/Btu
R_V	$\approx$ 1.26 hr ft^2 ^{o}F/Btu	R_X	$\approx$ 1.26 hr ft^2 ^{o}F/Btu
R_{VI}	$\approx$ 1.26 hr ft^2 ^{o}F/Btu	R_{XI}	$\approx$ 1.57 hr ft^2 ^{o}F/Btu

3. I^2R-Losses in the Conductors

(a) Conductors of Rectangular Cross Section

The conductor size is #9 with a cross-sectional area of $A_{\#9} \approx 0.026$ inch^2. The conductors are rated at 47 A/conductor giving a current density of 1810 A/inch^2. The electrical resistance per unit length is given by

$$R = \frac{\rho}{A} \tag{2}$$

For copper at room temperature, the resistivity is

$$\rho = 1.72 \times 10^{-6}\ \Omega\text{-cm} \equiv 0.675 \times 10^{-6}\ \Omega\text{-inch.}$$

The temperature coefficient of the electrical resistivity is $0.0068 \times 10^{-6}\ \Omega\text{-cm}/^{o}\text{C}$.

The electrical resistance of the #9 conductor is then

$$R = \frac{0.675 \times 10^{-6}}{0.026}$$

$$= 26 \times 10^{-6}\ \Omega/\text{inch} \equiv 3.12 \times 10^{-4}\ \Omega/\text{ft.}$$

The I^2R-loss per unit conductor length becomes

$$N' = I^2R = (47)^2 \times 3.12 \times 10^{-4}$$

$$= 0.69 \text{ Watts/ft.}$$

The conductor cross section has the dimensions 0.114×0.228 inch and the power dissipated per unit area of conductor (normal to the direction of heat transfer) is

$$N'' = \frac{0.69}{(0.228/12)} = 36 \text{ Watts/ft}^2 \equiv 123 \text{ Btu/(hr ft}^2\text{).}$$

Since there is an insulation film of $\delta = 0.004$ inch thickness (or 2%) separating adjacent conductors, the resulting effective power dissipated per unit area of conductor becomes

$$N''_{eff} = 0.98 \times 123 = 120 \text{ Btu/(hr ft}^2\text{)}.$$

(b) Square Conductors

The conductor size is #8 with a cross-sectional area of $A_{\#8} \approx 0.0157$ inch^2. The conductors are rated at 26.1 A/cond. resulting in a current density of 1560 A/inch^2. The electrical resistance per unit length is

$$R = \frac{0.675 \times 10^{-6}}{0.0157}$$

$$= 43 \times 10^{-6}\ \Omega/\text{inch} \equiv 5.15 \times 10^{-4}\ \Omega/\text{ft.}$$

The I^2R-loss per unit conductor length is

$$N' = I^2R = (26.1)^2 \times 5.15 \times 10^{-4}$$
$$= 0.35 \text{ Watts/ft} .$$

The conductor cross section has the dimensions 0.1285 × 0.1285 inch and the power dissipated per unit area of conductor is

$$N'' = \frac{0.35}{(0.1285/12)} = 32.6 \text{ Watts/ft}^2 \equiv 111 \text{ Btu/(hr ft}^2) .$$

The insulation film between the conductors is 0.0035 inch (or 2.7%) and the effective power dissipated per unit area becomes

$$N''_{eff} = 0.97 \times 111 = 108 \text{ Btu/(hr ft}^2).$$

4. <u>Effective Heat Fluxes and Resulting Temperature Differences</u>

(a) Winding with Conductors of Rectangular Cross Section

The total effective power dissipated per unit area in the outer winding is 120 + 120 = 240 Btu/(hr ft^2). On the outside of this winding heat transfer is by natural convection, on the inside by forced convection (air at 1100 ft/min). The two different modes of heat transfer on the surfaces and the rather large variation in the thermal resistance of the 3 insulation layers causes an effective heat flux across layer No. I of $q''_I \approx 50$ Btu/(hr ft^2), across layer No. II of $q''_{II} \approx 70$ Btu/(hr ft^2), and across layer No. III of $q''_{III} \approx 190$ Btu/(hr ft^2); (Note, these fluxes were estimated and the final temperatures are a check on the quality of the estimates).

The temperature difference across a layer is defined by the following equation:

$$q'' = \frac{\Delta T}{R_{tot}} \quad . \tag{3}$$

Thus, for layer No. I

$$\Delta T_I = q''_I R_I$$
$$= 50 \times 2.4 = 120\,^oF \equiv 67\,^oC .$$

In the same fashion the heat fluxes across layers No. II and III result in

$$\Delta T_{II} = 70 \times 0.97 = 68\,^oF \equiv 38\,^oC$$

and

$$\Delta T_{III} = 190 \times 0.47 = 89\,^oF \equiv 49.5\,^oC .$$

Heat transfer by natural convection to air from vertical walls with a height in excess of 30 cm is approximately given by[1]

$$q''_{nc} = 1.78 \times 10^{-3} (\Delta T)^{1.25} \qquad (4)$$

where the constant has the dimensions of a convective conductance, Watts/(cm^2 ^{o}C). For $q''_I = q''_{nc} = 50$ Btu/(hr ft^2) $\equiv$ 0.016 Watts/cm^2 the resulting film drop, i.e., the temperature difference between the surface and the bulk fluid, is

$$\Delta T = T_s - T_\infty = 37\ ^{o}C \equiv 67\ ^{o}F.$$

For an assumed air inlet temperature $T_\infty = 20\ ^{o}C$ the surface temperature of the insulation (press board) is $T_s = 20 + 37 = 57\ ^{o}C$, and the temperature of the outermost conductors will be

$$T_I = T_\infty + \Delta T_{film} + \Delta T_I$$

$$= 20 + 37 + 67 = \underline{\underline{124\ ^{o}C}} .$$

Insulation layer No. III is cooled by forced convection to air in the duct (formed by two adjacent windings), at V = 1100 ft/min $\equiv$18.4 ft/sec. The convective conductance h is defined by

$$q'' = h\,(T_s - T_\infty). \qquad (5)$$

The duct cross section is to first approximation rectangular with the short dimension b = 0.75 inch and the long dimension $L \gg b$. In order to calculate the Reynolds number, N_{Re}, for this flow, an equivalent diameter D_e of this duct can be defined as

$$D_e = \frac{4A}{p} = \frac{4bL}{2L + 2b} \qquad (6)$$

where A = cross-sectional area of the duct
p = wetted perimeter.

With b = 0.75 inch

$$D_e = \frac{4 \times 0.75 \times L}{2L + 2 \times 0.75}$$

and for $L \gg 0.75$

$$D_e \approx \frac{4 \times 0.75}{2} = 1.5 \text{ inch} \equiv 0.125 \text{ ft}.$$

The Reynolds number for the flow in this duct can be defined as

$$N_{Re} = \frac{D_e V}{\nu} .$$

For air at room temperature $\nu \approx 1.5 \times 10^{-5}$ ft^2/sec and the Prandtl number $N_{Pr} \approx 0.7$. Then

$$N_{Re} = \frac{0.125 \times 18.4}{15 \times 10^{-5}}$$

$$= 15,400 > N_{Re,\ crit} = 2300$$

which means the flow is highly turbulent (beyond the laminar entry length).

The heat transfer inside a tube (from the wall to the fluid)for fully developed turbulent flow is described by the empirical equation[2]

$$N_{Nu,D} = 0.0243\ N_{Re,D}^{0.8}\ N_{Pr}^{0.4} \qquad (8)$$

where $N_{Nu,D}$ is the Nusselt number, a dimensionless convective heat transfer coefficient based on the diameter of the duct. Numerical values:

$$N_{Nu,D_e} = 0.0243\ (15,400)^{0.8} \times (0.7)^{0.4}$$
$$= 46.5 .$$

Other sources confirm this number at $N_{Nu} \approx 50$. The Nusselt number is defined by

$$N_{Nu} = \frac{h D_e}{k}$$

and the convective conductance h is readily evaluated as

$$h = \frac{46.5 \times 0.015}{0.125} \approx 5.5 \text{ Btu/(hr ft}^2\ {}^{o}\text{F)} .$$

With Eq. 5 the film drop becomes

$$\Delta T_{film} = T_s - T_\infty = \frac{q''_{III}}{h}$$

$$= \frac{190}{5.5} = 34.5\ {}^{o}F \equiv 19\ {}^{o}C .$$

For an assumed air inlet temperature of $T_\infty = 20\ ^oC$, the surface temperature of the insulation is $T_s = 20 + 19 = 39\ ^oC$ and the temperature of the inner rectangular conductors is

$$T_{II} = T_\infty + \Delta T_{film} + \Delta T_{III}$$

$$= 20 + 19 + 49.5 \approx \underline{\underline{88\ ^oC}}$$

and the temperature of the outer rectangular conductors is

$$T_I = T_\infty + \Delta T_{film} + \Delta T_{III} + \Delta T_{II}$$

$$= 20 + 19 + 49.5 + 38 \approx \underline{\underline{126\ ^oC}}$$

Thus, $T_I = 124\ ^oC$ as calculated from the side where natural convection takes place is in close agreement with $T_I = 126\ ^oC$ as calculated from the surface cooled by forced convection, i.e., the respective heat fluxes were estimated correctly.

The highest temperature in this winding occurs as expected in the outer bank of conductors and is

$$T_I \approx 125\ ^oC \qquad \text{for} \qquad T_\infty = 20\ ^oC$$

and

$$T_I \approx 140\ ^oC \qquad \text{for} \qquad T_\infty = 35\ ^oC\ .$$

$T_\infty = 35\ ^oC$ is close to the air outlet and reflects a $15\ ^oC$ bulk temperature rise through the system.

Note, these temperatures were obtained using the value for the electrical resistivity at room temperature. If ρ is corrected with the temperature coefficient given above, the final maximum temperatures close to the air outlet (due to increased I^2R-losses) are expected to be

$$\underline{\underline{T_I = 215 \pm 5\ ^oC}}\ ; \qquad \underline{\underline{T_{s,I} = 95 \pm 3\ ^oC}}\ ;$$

$$\underline{\underline{T_{II} = 145 \pm 5\ ^oC}}\ ; \qquad \underline{\underline{T_{s,III} = 65 \pm 3\ ^oC}}\ .$$

(b) Center Winding with Square Conductors

Based on the magnitude of the thermal resistances of the various insulation layers, it is estimated that $q''_V = 30$ Btu/(hr ft^2) of the total of $q'' = 108$ Btu/(hr ft^2) generated in the center conductors flow across layer No. V, and the balance $q''_{VI} =$ 78 Btu/(hr ft^2) flow across layer No. VI.

Then

$$\Delta T_V = q''_V R_V$$

$$= 30 \times 1.26 = 38\ ^oF \equiv 21\ ^oC$$

$$\Delta T_{IV} = q''_{IV} R_{IV}$$

$$= (30 + 108)\ 1.14 = 158\ ^oF \equiv 88\ ^oC .$$

With $h = 5.5$ Btu/(hr ft^2 ^{o}F) the film drop at layer No. IV is

$$\Delta T_{film} = \frac{q''_{IV}}{h}$$

$$= \frac{30 + 108}{5.5} = 25\ ^oF \equiv 14\ ^oC .$$

For an inlet bulk temperature of $T_\infty = 20\ ^oC$ the temperature of the center conductors becomes

$$T_V = T_\infty + \Delta T_{film} + \Delta T_{IV} + \Delta T_V$$

$$= 20 + 14 + 88 + 21 = \underline{143\ ^oC} .$$

Furthermore,

$$\Delta T_{VI} = q''_{VI} R_{VI}$$

$$= 78 \times 1.26 = 98.5\ ^oF \equiv 55\ ^oC ,$$

$$\Delta T_{VII} = q''_{VII} R_{VII}$$

$$= (78 + 108)\ 0.47 = 87.5\ ^oF \equiv 49\ ^oC,$$

and the film drop at layer No. VII is

$$\Delta T_{film} = \frac{q''_{VII}}{h}$$

$$= \frac{78 + 108}{5.5} = 34\ ^{o}F \equiv 19\ ^{o}C .$$

For $T_{\infty} = 20\ ^{o}C$ the temperature of the center conductor becomes

$$T_{V} = T_{\infty} + \Delta T_{film} + \Delta T_{VII} + \Delta T_{VI}$$

$$= 20 + 19 + 49 + 55 = \underline{143\ ^{o}C}$$

which is in exact agreement with T_V as calculated above (i.e., the heat flux estimates were correct); in summary

$$T_V \approx 145\ ^{o}C \qquad \text{for} \qquad T_{\infty} = 20\ ^{o}C$$

$$T_V \approx 160\ ^{o}C \qquad \text{for} \qquad T_{\infty} = 35\ ^{o}C .$$

If the electrical resistivity is temperature corrected, the following final temperatures are expected:

$$\underline{\underline{T_{IV} = 215 \pm 5\ ^{o}C}} \; ; \qquad \underline{\underline{T_{s,IV} = 60 \pm 3\ ^{o}C}} \; ;$$

$$\underline{\underline{T_{V} = 255 \pm 5\ ^{o}C}} \; ;$$

$$\underline{\underline{T_{VI} = 155 \pm 5\ ^{o}C}} \; ; \qquad \underline{\underline{T_{s,VI} = 65 \pm 3\ ^{o}C}} .$$

(c) Inner Winding with Square Conductors

Based on the thermal resistances of the various insulation layers it is estimated that $q''_{IX} = 66$ Btu/(hr ft^2) and $q''_{X} = 42$ Btu/(hr ft^2). Then in similar fashion as above

$$\Delta T_{IX} = q''_{IX} R_{IX}$$

$$= 66 \times 1.26 = 83\ ^{o}F \equiv 46\ ^{o}C$$

and

$$\Delta T_{VIII} = q''_{VIII} R_{VIII}$$

$$= (66 + 108)\ 1.14 = 198\ ^{o}F \equiv 110\ ^{o}C.$$

For $h = 5.5$ Btu/(hr ft^2 ^oF) the film drop at layer No. VIII is

$$\Delta T_{film} = \frac{q''_{VIII}}{h}$$

$$= \frac{66 + 108}{5.5} = 32\ ^oF \equiv 18\ ^oC$$

and

$$T_X = T_\infty + \Delta T_{film} + \Delta T_{VIII} + \Delta T_{IX}$$

$$= 20 + 18 + 110 + 46 = \underline{\underline{194\ ^oC}}$$

Furthermore,

$$\Delta T_X = q''_X R_X$$

$$= 42 \times 1.26 = 53\ ^oF \equiv 29\ ^oC ,$$

$$\Delta T_{XI} = q''_{XI} R_{XI}$$

$$= (42 + 108)\ 1.57 = 235\ ^oF \equiv 131\ ^oC ,$$

and

$$\Delta T_{film} = \frac{q''_{XI}}{h}$$

$$= \frac{42 + 108}{5.5} = 27\ ^oF \equiv 15\ ^oC$$

which results in

$$T_X = T_\infty + \Delta T_{film} + \Delta T_{XI} + \Delta T_X$$

$$= 20 + 15 + 131 + 29 = \underline{\underline{195\ ^oC}} .$$

This result is in good agreement with T_X as calculated above. In summary,

$$T_X \approx 195\ ^oC \quad \text{for} \quad T_\infty = 20\ ^oC$$

and

$$T_X \approx 210\ ^oC \quad \text{for} \quad T_\infty = 35\ ^oC .$$

Correction of the electrical resistivity for the temperature increase in the conductors gives finally the following expected conductor and surface temperatures:

$$T_{IX} = 220 \pm 15\ ^{o}C; \qquad T_{s,IX} = 65 \pm 3\ ^{o}C;$$

$$T_{X} = 330 \pm 15\ ^{o}C;$$

$$T_{XI} = 260 \pm 15\ ^{o}C; \qquad T_{s,XI} = 60 \pm 3\ ^{o}C\ .$$

III. TEMPERATURE DISTRIBUTION IN THE LOW-VOLTAGE WINDINGS

A. ∇ - Coil

1. Thermal Resistance

The insulation between turns, i.e., two insulation films plus press board filler, has the following thermal resistance:

$$R_F = R_{film} + R_{PB} + R_{film}$$

$$= \frac{0.003}{0.03} + \frac{0.237}{0.057} + \frac{0.003}{0.03} = 4.35 \text{ hr ft}^2\ ^{o}F/\text{Btu}.$$

The insulation layer between two windings is

$$R_{XII} = \frac{0.003}{0.03} + \frac{0.031}{0.057} + \frac{0.003}{0.03} = 0.75 \text{ hr ft}^2\ ^{o}F/\text{Btu}\ .$$

A schematic cross section of the low-voltage coils is shown in Fig. 2.

2. I^2R-Losses in the Conductors

The conductors are of square cross section. They are #3 with a cross-sectional area of $A_{\#3} = 0.0493$ inch^2. The #3 water-cooled conductors are $A_{wc,\#3} = 0.015$ inch^2. A full turn (consisting of two water-cooled conductors and four solid conductors) is then $A_{turn} = 0.227$ inch^2. One turn is rated at 1177 A/turn giving a current density of 5180 A/inch^2. The electrical resistance per unit length of solid conductor is then (at room temperature)

$$R = \frac{\rho}{A_{turn}}$$

$$= \frac{0.675 \times 10^{-6}}{0.0493} = 13.7 \times 10^{-6}\Omega/\text{inch} = 1.64 \times 10^{-4}\Omega/\text{ft}.$$

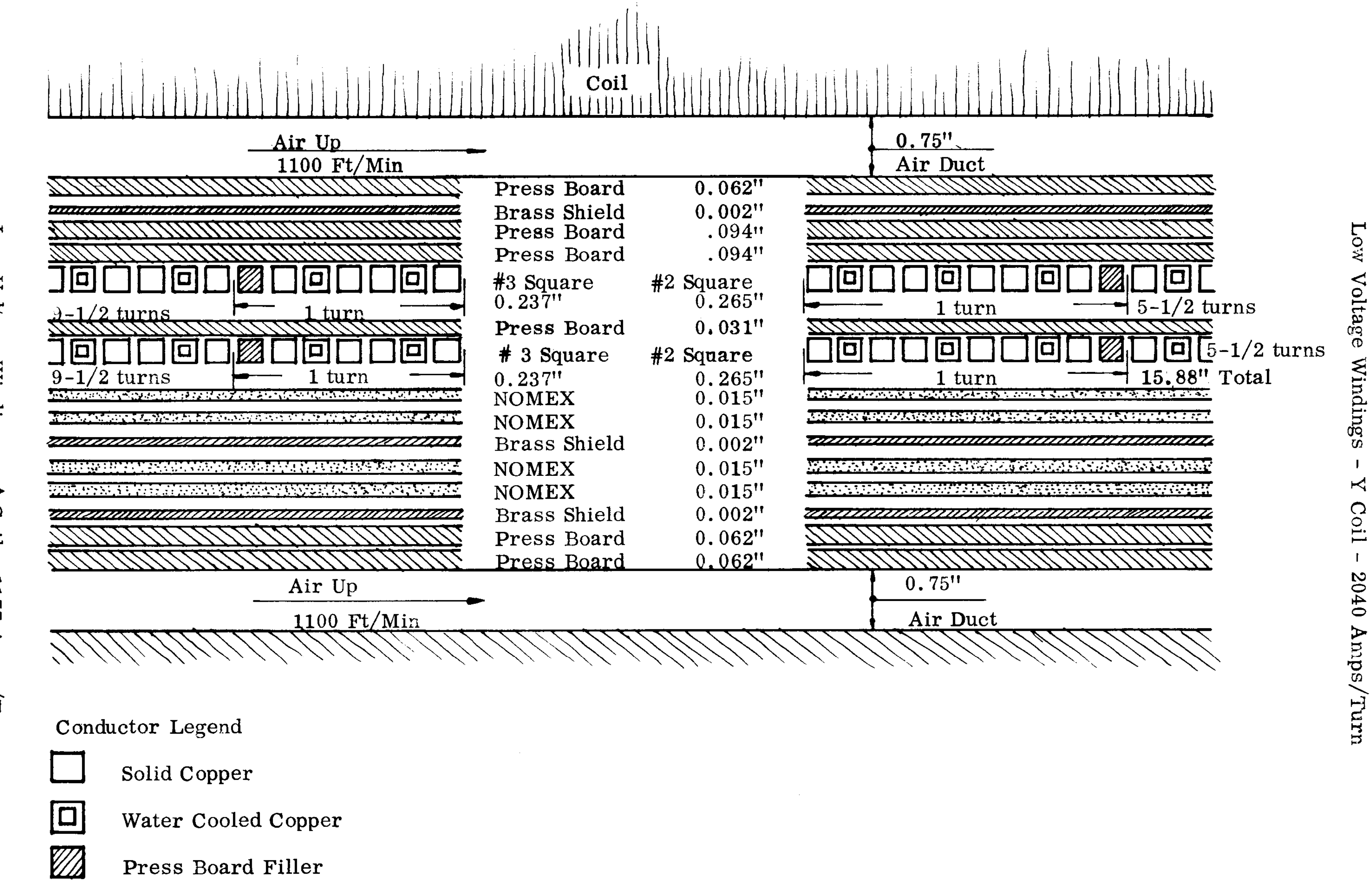

Fig. 2 Schematic Cross Section Through Low Voltage Coils

The I^2R-loss per unit conductor length is

$$N' = I^2R = (255)^2 \times 1.64 \times 10^{-4} = 10.6 \text{ Watts/ft.}$$

Similarly, the water-cooled conductor has an electrical resistance of

$$R = \frac{0.675 \times 10^{-6}}{0.015} = 45 \times 10^{-6}\ \Omega/\text{inch} = 5.4 \times 10^{-4}\ \Omega/\text{ft}$$

and its I^2R-loss is

$$N' = (77.7)^2 \times 5.4 \times 10^{-4} = 3.25 \text{ Watts/ft.}$$

The total power dissipated per unit length and per 1/2 turn, i.e. one water-cooled and two solid conductors, is

$$N'_{tot} = 24.45 \text{ Watts/ft} \equiv 0.8 \text{ Watts/cm.}$$

3. Effective Heat Fluxes and Resulting Temperature Differences

The flow cross section of the water-cooled conductor is

$$A_{flow} = 0.0493 - 0.015 = 0.0434 \text{ inch}^2$$

with an equivalent diameter of $d = 0.209$ inch $\equiv$ 0.53 cm. The heat flux across this surface into the water becomes approximately

$$q'' = \frac{N'_{tot}}{A_{flow}} = \frac{0.8}{\pi \times 0.53 \times 1} = \underline{\underline{0.48 \text{ Watts/cm}^2}}$$

which is very small for this mode of heat transfer, i.e., the copper conductors are essentially at the cooling water temperature.

A question which must be examined thoroughly in the case of any water-cooled coil is whether or not cross-coupling between successive turns or between supply and return exists. The importance of this examination cannot be stressed enough! Failure to do so can result in total destruction of an expensive coil due to internal hot spots, although an external calorimetric evaluation during operation shows everything in perfect shape.

The water flow is in series through a total of 19 turns (including return). The length of each turn is on the average 44 inch $\equiv$ 112 cm and the total length is thus

19 × 112 = 2/30 cm. The total power dissipated is

$$P_{av} = 0.8 \times 2130 = 1700 \text{ Watts} \equiv 407 \text{ cal/sec.}$$

If a water inlet temperature of 35 °C is assumed and a 15 °C temperature rise through the system is allowed, the required flow rate becomes

$$w = \frac{P_{av}}{c_p \times \Delta T} \tag{9}$$

$$= \frac{407}{1 \times 15} = 27 \text{ g/sec} \equiv \underline{\underline{0.43 \text{ gpm}}}.$$

The resulting water velocity is

$$V = \frac{w}{A_{flow}} = \frac{9.5 \times 10^{-4} \text{ ft}^3/\text{sec}}{0.0343/144 \text{ ft}^2} = \underline{\underline{4 \text{ ft/sec}}} \ .$$

The temperature rise from turn-to-turn is

$$\Delta T_{turn} = \frac{15}{19} = 0.8 \ ^{\circ}\text{C/turn.}$$

The possible heat flux across the press board insulation from turn-to-turn is then

$$q'' = \frac{\Delta T_{turn}}{R_F}$$

$$= \frac{0.8 \times 9/5}{4.35} = 0.33 \text{ Btu/(hr ft}^2) \equiv 1 \times 10^{-4} \text{Watts/cm}^2 \ .$$

This is negligible compared to the total possible heat flux, which is $2 \times 0.8/(0.237 \times 2.54) = 2.65$ Watts/cm^2. Thus, the insulation is adequate for thermal protection.

Next, the cross-coupling between the coil inlet and outlet must be examined. The copper conductors are at water temperature and a total temperature rise $\Delta T = 15$ °C was allowed. The maximum possible heat flux across the press board insulation between the two windings is then

$$q'' = \frac{\Delta T}{R_{XII}} = \frac{15 \times 9/5}{0.75} = 36 \text{ Btu/(hr ft}^2) = 0.0114 \text{ Watts/cm}^2$$

which is about 2-1/2% of the power dissipated locally (= 0.435 Watts/cm^2, a result of P_{av} = 0.8 Watts/cm and a width of 1.83 cm for 1/2 turn).

Thus, cross-coupling is negligible and the insulation is adequate for heat transfer purposes.

A closer examination of the inner and outer insulation layers (Fig. 2) shows readily that the thermal resistances are much larger than the local resistances to the water-cooled conductors. Thus, heat transfer to the air ducts is small and the coils are essentially at water temperature, varying from an assumed maximum inlet temperature of 35 ^{o}C up to 50 ^{o}C for a water velocity of 4 ft/sec or about 1/2 gpm.

B. Y-Coil

The Y-coil was examined in the same way as the Δ-coil. The results are similar to those of the Δ-coil and are thus omitted.

IV. DISCUSSION AND SUGGESTIONS

It has been shown that temperatures up to at least 330 ^{o}C are possible in the high-voltage coils. The most abundant material in the various insulation layers is NOMEX, a nylon fiber paper. It is adjacent to all conductors which show high temperatures. Although recognized by various agencies as a 220 ^{o}C insulating material, this author feels that operation at 250 ^{o}C in the center of a coil is safe for considerable length of time, probably several years. However, as demonstrated above, several of the conductor banks show temperatures even in excess of 250 ^{o}C. The useful lifetime of this insulation depends mainly on dielectric strength, tensile strength, and elongation properties and is inversely proportional to the operating temperature. Such data were published by the manufacturer of NOMEX. They indicate that at 330 ^{o}C a useful life of 100 to 300 hrs can be expected. Although the specific location inside the winding may delay failure significantly, the coil will suffer destruction in the long run.

It should be mentioned at this point that C. H. Harris has measured some resistances in the coils after an extended operation at 100% current rating. From these and other data he computed a hot spot temperature of at least 311 ^{o}C, which is close to the 330 ^{o}C as predicted above.

In the following a few methods to reduce the temperature inside the coil are examined.

1. Surface Temperature Reduction

Objective: To lower the surface temperature of the windings (i.e., at the air-insulation interface) by 50 °C. This is probably all that is needed since the additional reduction in the electrical resistivity results in an even lower power dissipation N' and therefore lower heat flux q'' and lower ΔT.

Two methods appear readily available:

(a) an increase of the gas flow rate and therefore velocity over the coil surface.

(b) a decrease in the gas inlet temperature by 50 °C.

The first method is not feasible, since the maximum film temperature drop observed on any surface cooled by forced convection is less than 35 °C. Even if a film drop in excess of 50 °C existed this method would not be practical. Equation 8 describes heat transfer by forced convection in the turbulent flow range. The only real variable in this equation is the Reynolds number and therefore implicitly the gas velocity. The heat transfer coefficient is proportional to the 0.8 power of the Reynolds number. Very high velocities would be required, exceeding the limits of structural integrity of the coils and practically available pumping horsepower.

The second method warrants further investigation. The air inlet temperature was assumed to be $T_\infty = 20\,^oC$ and an average bulk temperature rise of 15 °C was measured. The presently available air flow rate is $w = 5000\ ft^3/min = 400\ lb/min$. The objective is to lower the air inlet temperature by 50 °C (≡ 90 °F) to $T_\infty = -30\,^oC$. Liquid nitrogen could be used (with a boiling point of -196 °C ≡ -322 °F); it would evaporate, mix with the 20 °C inlet air, and result in an effective inlet temperature of -30 °C. The available temperature increase for the nitrogen would be 166 °C (≡300 °F). The total power associated with a 90 °F temperature decrease of 400 lbs/min of air is

$$P_{av} = w\ c_p\ \Delta T$$

$$\approx 400 \times 0.25 \times 90 = 9000\ \text{Btu/min}\ .$$

The required nitrogen flow rate would be

$$w = \frac{P_{av}}{c_p \Delta T}$$

$$\approx \frac{9000}{0.25 \times 300} = \underline{\underline{120\ \text{lbs/min}}}\ .$$

This would require a good-size refrigeration plant and represents a very costly solution. If helium were used instead of nitrogen (it has a much higher specfic heat) the flow rate would be reduced, but costs for gas and refrigeration system are still excessive. The method is not practical!

2. Reduction of Operating Power

The temperature rise is proportional to the heat flux q'' which in turn is proportional to N'' and N'. The latter varies as I^2. To arrive at a maximum temperature of 250 °C the power dissipated in the conductors would have to be reduced by 20%. Since N is proportional to I^2 the current and thus the rating of the power supply would have to be reduced by approximately 10%. This does not look too attractive in view of the requirements for proper operation of the bubble chamber and spark chamber magnets.

3. Redesign of the High-Voltage Coil

From the foregoing it is evident that the high-voltage coil of the 3.4 MW power supply has rather severe shortcomings. The coil should be redesigned, using direct cooling of the conductors, as in the low-voltage coils. Both, gas- and liquid-cooled conductors appear feasible. This author believes that the problems associated with the electrical insulation of such directly-cooled conductors in a high-voltage application can be overcome.

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