Rick Hance

Engineering Note

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Project: Solenoid Energization, Control, Interlocks and Quench Protection
Doc. No: H960917B

Subject: Dump Resistor Review

Introduction

This note details a review of the solenoid dump resistor as designed by Walter Jaskierny[1]. The dump resistor is to be located in room 511 of the DZERO Assembly Building and cooled by free convection. The resistor will be permanently connected across the input of the DC bus. During normal operation, the dump resistor dissipates considerable heat due to its permanent connection across the bus. When the dump switch is opened, the solenoid power supply is disconnected from the dump resistor/solenoid circuit and the dump resistor (with help from the dc resistance of the water cooled bus) dissipates the solenoid energy in the form of heat. This note will examine the dump resistor resistance and temperature rise during normal and fast dump operation. This review is to determine if the resistor design is adequate for the purpose and whether the design contains any obvious flaws.

Regarding Numerical Accuracy

All calculations will be performed and all results recorded to three significant digits of precision except as necessary to accommodate intermediate steps. Normal rules of rounding apply.

Pertinent Parameters:

- Maximum power supply voltage - 15 Volts[2]
- Solenoid Operating Current - 4825 Amps[2]
- Solenoid Inductance - 0.48 Henry[3]
- Length of Water Cooled DC bus - 150 feet assumed (gives worst case situation).
- Resistance of Water Cooled DC Bus - 4.44 micro-Ohms per foot @ 20 °C per conductor[4].
- Resistance Temperature Coefficient of type 304 Stainless Steel: 0.00094 per °C (unverified).
- Resistivity of type 304 Stainless Steel - 72 microOhms-cm (28.35 microOhms-in).[5]
- Density of type 304 Stainless Steel - 0.290 lb/cu in.[6] (Note WJ has used 0.283 lb/cu in)
- Specific Heat of type 304 Stainless Steel - 0.12 BTU/lb/°F.[7]

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[1]Rick Hance Engineering Note (By Walter Jaskierny) H960814A

[2]Fermilab-TM-1886 Conceptual Design of a 2 Tesla Superconducting Solenoid for the Fermilab D0 Detector Upgrade - May 13, 1994.

[3]Same as above.

[4]Per Anaconda Copper literature for 1.9" OD, 1.1" ID double extra strong copper bus tubes.

[5]CRC Handbook of Chemistry & Physics 59th edition

[6]Handbook of Engineering fundamentals - Eshbach 3rd Edition

Resistance

There are 12 pieces of 1/4" X 4" X 144" steel. The 12 pieces are connected in series in a switch back topography to minimize inductance. Each piece is connected to the next across the inside of the end with a piece of 1/2" X 4" X 1 1/2" steel. these pieces are welded in position such that their resistance is in series with the 144" pieces they connect . There are a total of 11 interconnecting pieces.

- The 12 pieces of 1/4" X 4" X 144" have a series resistance at 20 centigrade of approximately:

$$R = \rho \frac{L}{A} = 28.35 \times 10^{-6}\,\Omega in \times \frac{12 \times 144 in}{4 in \times 0.25 in} = 49.0 \times 10^{-3}\,\Omega$$

R = Resistance in Ohms
ρ = Resistivity in Ohms X inches (actually Ohms per square inch per inch)
L = Length in inches
A = Area in inches

- The 11 pieces of 1/2" X 4" X 1 1/2" have a total series resistance of approximately:

$$R = \rho \frac{L}{A} = 28.35 \times 10^{-6}\,\Omega in \times \frac{11 X 1.5 in}{4 in \times 0.5 in} = 0.2339 \times 10^{-3}\,\Omega$$

- Thus the total resistance of the dump resistor at 20 centigrade is the total series resistance of the 12 long pieces and the 11 short pieces (neglecting anomalies due to the welds) which is approximately:

$$49.0 \times 10^{-3} + 0.2339 \times 10^{-3} = 49.23 \times 10^{-3}\,\Omega$$

Which agrees with WJ's calculation.

- Several iterations of this dump resistor analysis, to determine convection coefficients, show the dump resistor to operate at about 110 °F which is 43 °C. The impact that this elevated temperature has on the resistance is negligible due to stainless steel's extremely low temperature coefficient and can be discounted . For informational purposes, the resistance at 43 °C, which is a 23 °C increase in temperature is approximately:

$$R_f = R_i + \left(R_i \times \alpha \times \Delta t\right) = 49.23 \times 10^{-3}\,\Omega + \left(49.23 \times 10^{-3}\,\Omega \times \frac{0.00094}{°C} \times 23°C\right) = 50.29 \times 10^{-3}\,\Omega$$

R_f = Final resistance value in Ohms
R_i = Initial resistance value in Ohms
α = Resistance Temperature Coefficient of type 304 Stainless Steel: 0.00094 per degree centigrade.
Δt= Temperature differential in degrees centigrade.

Volume

- The volume of steel in the resistor is approximately:

$$\left(12 \times V_1\right) + \left(11 \times V_2\right) = 1728 in^3 + 33 in^3 = 1761 in^3$$

V1 = Volume of a long piece $= \left(L \times W \times T\right) = 144 in \times 4 in \times 0.25 in = 144 in^3$

V2 = Volume of a short piece $\left(L \times W \times T\right) = 1.5 in \times 4 in \times 0.5 in = 3 in^3$

L = Length in inches = 144 (long pieces), 1.5 (short pieces)
W = Width in inches = 4 (both pieces)
T = Thickness in inches = 0.250 (long pieces), 0.500 (short pieces)

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[7]Same as above

Weight

- The total weight of the stainless steel in the dump resistor is approximately as follows. Note that WJ calculated 498.95 lbs because he used a different density value (0.283 lb/cu in versus 0.290 lb/cu in).

$$W = V \times D = 1761in^3 \times 0.290 \, {}^{lb}\!/_{in^3} = 510.7lb$$

W = Weight in pounds
V = Volume in cubic inches
D = Density in pounds per cubic inch

Surface Area

The stainless steel bars will be oriented vertically to facilitate heat transfer by convection to the air moving up through the resistor. There are four types of surface area to consider; 1) Vertical, 2) Top horizontal, 3) Bottom horizontal and 4) Outer. The first three are used in the convection dissipation calculations. Each has vastly different convective heat loss coefficients. The last (outer) is used in the radiation dissipation calculations.

- The vertical surface area (A_V) is approximately as follows. Note, WJ's calculation of 13,956 sq. in did not include the ends of the 144 inch pieces.

$$A_V = (12 \times A_{V1}) + (11 \times A_{V2}) = 13848in^2 + 132in^2 = 13,980in^2$$

A_{V1} = Vertical surface area of a 144 inch bar = $2 \times 144in \times 4in + 2 \times 0.250in \times 4in = 1154in^2$
A_{V2} = Vertical surface area of a 1.5 inch bar = $2 \times 1.5 \times 4 = 12in^2$ (ends hidden so not counted)

- The Top horizontal surface area (A_T) is approximately as follows:

$$A_T = (12 \times A_{T1}) + (11 \times A_{T2}) = 432in^2 + 8.25in^2 = 440.3in^2$$

A_{T1} = Top surface area of a 144 X 0.25 inch bar = 144in X 0.25in = 36 in^2
A_{T2} = Top surface area of a 1.5 X 0.50 inch bar = 1.5in X 0.50in = .75in^2

- The bottom horizontal surface area (A_B) is equal to the top surface area:

$$A_B = A_T = 440.3in^2$$

- The outer surface area (A_O) is approximately as follows:

$$A_O = (2 \times A_{S1}) + (24 \times A_{E1}) + (24 \times A_{E2}) + (11 \times A_{S2}) + (22 \times A_{E2}) = 1152in^2 + 864in^2 + 24in^2 + 66in^2 + 16.5in^2 = 2123in^2$$

A_{S1} = Area of one long side of a 144 inch bar = $144in \times 4in = 576in^2$
A_{E1} = Area of one long edge of a 144 inch bar = $144in \times 0.25in = 36in^2$
A_{E2} = Area of one end of a 144 inch bar = $0.25in \times 4in = 1in^2$
A_{S2} = Area of one side of a 1.5 inch bar = $1.5in \times 4in = 6in^2$
A_{E2} = Area of one edge of a 1.5 inch bar = $1.5in \times 0.5in = 0.75in^2$

Convection Coefficients

All surfaces of the dump resistor will dissipate heat by convection. The top surfaces will dissipate the most heat per unit area and the bottom surfaces will dissipate the least heat per unit area. The rate at which heat is dissipated due to convection, depends on the temperature of the surface of the steel and the temperature difference between the surface of the steel and the ambient air. Several iterations of calculations were made to determine the operating temperature of the dump resistor before the following values were adopted:

- The free convection coefficients for air on a vertical plate at 0 psig and 110 °F surface temperature and 75 °F ambient air temperature (Δt = 35 °F) is approximately as follows[8]:

  h_{cv} = .700 Btu per (sq.ft.)(hr.)(°F) = 0.00486 Btu per (sq.in.)(hr.)(°F)

- The free convection coefficients for air on a horizontal plate at 0 psig and 110 °F surface temperature is approximately as follows[9]:

  For top surface $h_{ct} = h_{cv}$ X 1.27
  For bottom surface $h_{cb} = h_{cv}$ X 0.67

Radiation Coefficients

For all practical purposes, only the exterior surfaces of the dump resistor need be considered when computing heat dissipated via radiation. The interior surfaces, which are all within 1.5 inches of other interior surfaces at the same temperature, should dissipate negligible heat due to net radiation (the air absorbs very little radiant energy). The dissipation due to radiation from the outer surfaces depends on the surface temperature and surface condition of the stainless steel and the other objects in the room; and the emissivity (correction factor) of the type 304 stainless steel compared to a black body.

The radiation coefficient of a black body at reasonable temperatures (100 to 300 °F) is approximately 1.25 Btu per (sq.ft.)(hr.)(°F)[10]. The emissivity (correction factor) for stainless 304 with a medium oxidized surface is approximately 0.57[11].

- The radiation coefficient as corrected is approximately:

h_r = 0.57 X 1.25 Btu per (sq.ft.)(hr.)(°F) = 0.713 Btu per (sq.ft.)(hr.)(°F) = 0.00493 Btu per (sq.in.)(hr.)(°F)

Maximum Temperature Reached During Charging

This is a difficult calculation to make because the resistor will be absorbing power (heating) due to the charging voltage across the bus; while at the same time dissipating power (cooling) by convection and radiation. The rate at which it absorbs power is fixed by the voltage; but the rate at which it dissipates power is a function of its temperature differential with the surrounding air. The temperature differential is in turn a function of the instantaneous difference in the rate of absorption and dissipation.

- The solenoid circuit, which includes the water cooled bus and the solenoid, will charge to its maximum current in five time constants which is approximately:

$$5 \times t = 5 \times \frac{L}{R} = 5 \times \frac{.48Hy}{1.33m\Omega} = 1805 \sec = .5hr$$

t = Time Constant in seconds
L = Circuit Inductance in Henrys
R = Circuit resistance in Ohms (300' of bus @ 4.44 X 10 -6 Ohms/ft)

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[8]Applied Heat Transmission -Herman J. Stover - 1941 charts & formulas on page 102

[9]Applied Heat Transmission -Herman J. Stover - 1941 charts & formulas on page 102

[10]Applied Heat Transmission -Herman J. Stover - 1941 charts & formulas on page 25

[11]Watlow Electric Heating Technology Catalog - April 1992 - Table 2 on page 379

- The energy (Q) absorbed by the dump resistor during the 30 minute charge cycle from the 15 Volt power supply is approximately:

$$Q = \frac{V^2}{R} \times T = \frac{15^2 V}{49.23 m\Omega} \times .5hr = 2.29kWhr = 7.80 \times 10^3 Btu$$

V = Voltage across dump resistor
R = Resistance of dump resistor
T = Time

- The temperature increase (ΔT) expected "assuming no losses from radiation or convection" is approximately:

$$\Delta T = \frac{Q}{C_p \times m} = \frac{7.80 \times 10^3 Btu}{0.12 \times Btu \times lb^{-1} \times ° F^{-1} \times 511 \times lb} = 127° F$$

Q = Energy
Cp = Specific heat = 0.12 Btu x lb^{-1} x F^{-1}
m = Mass = 511lb

- The temperature rise of 127 °F, when added to the ambient temperature of 75 °F, would indicate a **maximum resistor temperature of 127 + 75 = 202 °F** when charging from a room temperature condition. Charging from higher temperature starting points -- such as after a fast dump, will result in higher temperatures. The radiation and convection losses must be calculated and subtracted to arrive at the actual ending temperature. These losses start at zero for a cold resistor and increase as the resistor heats up. This calculation is more extensive and less necessary for this review. It suffices to know that the temperature for this operation should reach a maximum ΔT of 127 °F. This is well within the limits of the materials and the application.

Steady State Power Dissipation

The steady state dissipation depends on the amount of voltage required to deliver the desired current to the solenoid. Since the solenoid is superconducting and therefore nearly zero Ohms, the voltage drop we have to consider is due to the resistance of the dc bus between the power supply room and the solenoid. We will use the worst case approximation of 150 feet of bus. 150 feet of bus results in 300 feet of copper pipe since both supply and return must be considered.

- The resistance (R_t) of 300 feet of bus at 20 degrees centigrade is approximately:

$$R_t = R \times L = 4.44 \times 10^{-6} \frac{\Omega}{ft} \times 300\, ft = 1.33 \times 10^{-3} \Omega$$

R = Resistance of bus conductor in Ohms per foot = 4.44 $X10^{-6}$
L = Length of conductor in feet = 300

- The terminal voltage (V) developed across the bus is then approximately:

$$V = I \times R = 4825A \times 1.33 \times 10^{-3} \Omega = 6.42V$$

I = Current in Amps = 4825
R = Resistance in Ohms = 1.33 X 10^{-3}

- The power (P) dissipated in the resistor under normal operating conditions is then approximately:

$$P = \frac{E^2}{R} = \frac{6.42 V^2}{49.23 \times 10^{-3} \Omega} = 837 Watts$$

E = Voltage across dump resistor in volts
R = Resistance of dump resistor in Ohms

Steady State Temperature

The dump resistor will reach an equilibrium with the ambient air at some temperature where 837 Watts is dissipated continuously by a combination of natural convection and radiation. Dissipation by conduction is negligible due to poor thermal contact with any conducting surface (except of course for the water cooled dc bus connection).

The calculation to determine the equilibrium temperature of the dump resistor is difficult mainly due to the number of variables associated with deriving the loss coefficients. The problem is one of determining the temperature at which the radiant heat loss from the outer surfaces, summed with the convective heat losses from the vertical, top horizontal and bottom horizontal surfaces, are equal to the 837 Watts absorbed by the resistor during normal operation.

- Heat flow (q) for both radiant and convective modes is calculated as follows:

$$q = h \times A \times \Delta t$$

q = quantity of heat
h = heat transfer coefficient
A = area of surface
Δt = temperature differential

- The convective and radiant heat flow (q) from the dump resistor can then be lumped into one equation as follows:

$$q = (h_{cv} \times A_v \times \Delta t) + (h_{ct} \times A_t \times \Delta t) + (h_{cb} \times A_b \times \Delta t) + (h_r \times A_o \times \Delta t)$$

h_{cv} = convection heat transfer coefficient for the vertical surfaces = 0.00486 Btu per (sq.in.)(hr.)(°F)
h_{ct} = convection heat transfer coefficient for the top surfaces = 0.00617 Btu per (sq.in.)(hr.)(°F)
h_{cb} = convection heat transfer coefficient for the bottom surfaces = 0.00326 Btu per (sq.in.)(hr.)(°F)
h_r = radiant heat transfer coefficient for outside surfaces = 0.00493 Btu per (sq.in.)(hr.)(°F)
A_v = vertical surface area = 13,980 sq. in.
A_t = top surface area = 440 sq. in.
A_b = bottom surface area = 440 sq. in.
A_o = outer surface area = 2123 sq. in.
Δt = temperature differential between stainless steel and ambient air

- Combining terms and solving for Δt produces:

$$\Delta t = \frac{q}{(h_{cv} \times A_v) + (h_{ct} \times A_t) + (h_{cb} \times A_b) + (h_r \times A_o)}$$

- Given that 837 Watts is equivalent to 2858 Btu/hr, we can solve for Δt as follows:

$$\Delta t = \frac{2858 Btu \times hr^{-1}}{(67.9 + 2.71 + 1.43 + 10.5) \times Btu \times hr^{-1} \times {}^\circ F^{-1}} = 34.6^\circ F$$

- Thus we expect the dump resistor to operate at about 35° F above ambient temperature during normal operation with a 150' bus and 4825 Amps going to the solenoid. Given an ambient temperature of 75° F, the resistor should stabilize at about **110° F during normal operation**. Note than a bus length of less than 150' will produce less voltage drop. The lower voltage drop will result in less power in the dump resistor and lower operating temperatures.

Maximum Temperature Reached During Fast Dump

During a fast dump, all of the energy being stored in the solenoid must be dissipated. The dump resistor and water cooled bus will each absorb and dissipate a fraction of the total energy in direct proportion to their resistance ratio. Given the assumption we have been using of a 150' bus, the bus resistance would be 1.33 milli-Ohms. The bus resistance is only about 2.5% of the total resistance of the circuit. Thus, the water cooled bus makes very little contribution to dissipating the fast dump energy. For our calculation, we will consider it to be negligible. A fast dump requires in excess of 40 seconds to complete[12] which means some cooling would occur due to convection and radiation. However, we will disregard these effects. Thus giving us a worst case approximation.

- The energy E stored in the solenoid is as follows:

$$E = \frac{1}{2} \times L \times I^2 = 0.5 \times 0.48 \times 4825^2 = 5.6\,MJ = 5.31 \times 10^3\,Btu$$

L = solenoid inductance = 0.48 Henrys
I = solenoid current = 4825 Amps

- The temperature rise (Δt) of the dump resistor material, assuming no losses to convection or radiation is as follows:

$$\Delta t = \frac{Q}{c_p \times m} = \frac{5.31 \times 10^3 \times Btu}{0.12 \times Btu \times lb^{-1} \times {}^\circ F^{-1} \times 511 \times lb} = 87^\circ F$$

c_p = specific heat = 0.12 Btu x lb^{-1} x $°F^{-1}$
Q = energy = 5.31 x 10^3 Btu
m = mass = 511 lb

- Thus, the dump resistor, which normally operates at about 110 °F, can be expected to rise in temperature to nearly 110 + 87 = **197 °F during a fast dump**.

Cool down Time

By revisiting our previously derived formula for heating up the dump resistor, we can calculate the time required for the resistor to cool down to normal operating temperature. The formula is reproduced here for convenience:

$$q = (h_{cv} \times A_v \times \Delta t) + (h_{ct} \times A_t \times \Delta t) + (h_{cb} \times A_b \times \Delta t) + (h_r \times A_o \times \Delta t)$$

h_{cv} = convection heat transfer coefficient for the vertical surfaces = 0.00486 Btu per (sq.in.)(hr.)(°F)
h_{ct} = convection heat transfer coefficient for the top surfaces = 0.00617 Btu per (sq.in.)(hr.)(°F)
h_{cb} = convection heat transfer coefficient for the bottom surfaces = 0.00326 Btu per (sq.in.)(hr.)(°F)
h_r = radiant heat transfer coefficient for outside surfaces = 0.00493 Btu per (sq.in.)(hr.)(°F)
A_v = vertical surface area = 13,980 sq. in.
A_t = top surface area = 440 sq. in.
A_b = bottom surface area = 440 sq. in.
A_o = outer surface area = 2123 sq. in.
Δt = temperature differential between stainless steel and ambient air

[12]Rick Hance Engineering Note H960801A - Solenoid Filter Analysis - Fast & Slow Dump

- By inserting the heat transfer coefficient values, rearranging the equation to extract and solve for the "time" term (hr.) and substituting 87 °F for Δt, the equation becomes as follows:

$$\frac{5.31\times 10^{3}\,Btu}{(67.9+2.71+1.43+10.5)\times Btu\times^{\circ}F^{-1}\times 87\times^{\circ}F}=.74hr=44\min$$

- Thus, although the heat transfer coefficients will change somewhat as the resistor cools, the 44 minutes required to return to operating temperature may indicate that special cooling measures after a fast dump should be considered. An air circulation fan could be used to cool the resistor faster if it is determined that the recovery time would likely interfere with recharging the solenoid. The dump resistor temperature will be monitored by the control system for use as necessary during operation of the system.

Summary

- The resistor design appears to be adequate for the purpose. Its temperature should be monitored by the control system; and also used as an interlock.
- The 20 °C resistance of the dump resistor appears to be about 49.2 mΩ versus the specification of 48 mΩ. The normal operating resistance, assuming a 150' worst case bus length, appears to be 50.3 mΩ.
- Maximum power dissipation by the dump resistor during normal operation appears to be approximately 840 Watts assuming a 150' worst case bus length.
- Maximum temperature achieved during a charge up from room temperature appears to be less than 202 °F.
- Normal operating temperature with 4825 Amps and 75 °F ambient temperature appears to be a maximum of approximately 110 °F also assuming a 150' worst case bus length.
- Temperature at the end of a fast dump from normal operating mode appears to be a maximum of approximately 197 °F also assuming a 150' worst case bus length.
- Time required to return to normal operating temperature after a fast dump appears to be approximately 44 minutes. A cooling fan may be desired if 44 minutes is too long (considering cryo recycling etc.).
- Shorter bus lengths will produce lower voltage drops and significantly less power dissipation in the resistor $P=E^2/R$). Preliminary bus design surveys indicate that the bus may be as short as 75'.