CHAPTER 11

QUENCH CALCULATIONS

11.1 Quench Codes

The quenching of the magnet has been modeled using a version of the program **QUENCH** created by M.N. Wilson [1]. Program **QUENCH** simulates the quenching of a superconducting magnet by propagating an ellipsoidal normal zone throughout the volume of the quenching coil. It calculates the ohmic heating and adiabatic temperature rise of the coil while the current decays as the stored energy of the magnet is dissipated. From a given starting point the normal zone volume is expanded by three orthogonal quench velocities in finite time steps. The quench velocity in the longitudinal direction of the conductor is calculated from the thermal and critical properties of the superconductor, the operating temperature of the magnet, and the current density in the coil. The velocities in the orthogonal directions are scaled from the longitudinal velocity by the one half power of the ratios of the thermal conductivities in the windings. The temperature dependent properties of each material making up the coil is provided, as is the total volume of the coil (expressed as an equivalent parallelopiped), and the resistive characteristics of the external circuit. **QUENCH** conveniently notes the time at which the current has decreased to 1/e of its original value, and the time at which the entire volume of the coil has become normal. Because **QUENCH** assumes adiabatic conditions the peak temperature of the coil occurs at the point where the quench was started. It is conservative to specify the starting point of a quench at one (physically meaningful) edge of the coil parallelopiped to obtain the least amount of coil driven normal per unit time during the quench.

11.2 Quench Study

QUENCH was modified [2] to allow the specification of more than one current density in the windings so that the winding design of the **DØ** magnet could be accommodated. In Figure 11.1 is seen the results of the calculations for the magnet, quenching into a 50 milliohm protection resistor. An **RRR** of 500 was used for the aluminum stabilizer, and the presence of the outer support cylinder was ignored. The quench was initiated at one end of the coil winding. The aggregate time constant of the decay is 11 seconds (**L/R** for the system prior to the quench is $0.48/0.050 = 9.6$ seconds), the maximum temperature of the coil is 58 **K** and the coil resistance rises to 51 milliohms.

The spreading of the normal zone from the starting point is schematized in Figure 11.2. The resistivities of the aluminum and copper in the coil are shown in Figure 11.3. The

RRR of the aluminum is selected to account for magnetoresistivity and a realistic amount of cold work in the material. In Figure 11.4 are shown the specific heat capacities of the coil materials.

The calculations ignore the heat capacity of the outer support cylinder as well as the possibility of "quench back" [3] currents being induced in it. Thus the predicted final peak temperature of less than 60 K is surely conservative. That quenches propagate for certain (ignoring "quench back" effects) in magnets of this type is not greatly in doubt. Both the CDF [4] and Zeus [5] model magnets clearly showed rapid quench propagation independent of the quenchback effect. And of course quenchback effects are seen in actual quenches of the full-sized magnets patterned after these models, as well as in other thin solenoids with closely coupled support cylinders.

11.3 Varying the Protection Resistor

The modified quench program was used to predict quench behavior for different values of the protection resistor. The cases with a protection resistor of 0, 5, 10, 25, and 50 milliohms were studied and the results are shown in Figures 11.5 through 11.8, and 11.1 respectively. The maximum temperature, voltage, and resistivity for all cases are summarized in Table 11.1. In all cases the peak coil temperature remained below 100 K and the maximum voltage less than 450 V. Evidently for this range of dump resistors the solenoid will quench safely. Even for the case of no protection resistor the peak coil temperature did not reach 100 K. This is below the temperature where significant thermal stresses can occur. Furthermore the transient internal voltage in the coil did not exceed 450 V during the quench and this value is less than half the voltage the coil will be tested to prior to operation.

The distribution of the stored energy of the solenoid following the calculated quenches is shown in Table 11.2. With a 50 m dump resistor only 16.7 percent of the initial stored energy is deposited into the coil. As was noted in Chapter 4 this result greatly assists in shortening the recooling time after a quench.

11.4 Adiabatic Estimate of Conductor Maximum Temperature

The complexities of the **QUENCH** program and the simplifications it makes in modeling the quench process for a coil can give rise to concerns that it does not indeed reflect "worst case" assumptions. An alternate calculation is made which avoids certain of these objections. It merely equates the ohmic heat generated in a unit volume of winding with the enthalpy of that volume

$$\int_0^{\infty} J^2(T)\,dT = \int_{\theta_0}^{\theta_{max}} \frac{\gamma C_p(\theta)}{\rho(\theta)}\,d\theta$$

assuming adiabaticity and a given time dependence to the current decay.

A simple code MIITS [6] was used to calculate the value of θ_{max} for the magnet following this formulation. Since the Grade II conductor has small cross section (and thus higher current density), this conductor was studied with the MIITS program. In the formula, γ is the density, $C_p(\theta)$ the specific heat, J the current density, and $\rho(\theta)$ the resistivity, of the coil windings.

The calculated results for this conductor with a dump resistor of 50 milliohms corresponding to the time constant of 9.6 seconds, and with initial current of 4825 A, is shown in Figure 11.9. The peak temperature θ_{max} predicted by MIITS is approximately 134 K. In Figure 11.9 the resistance, energy, and heat capacity for a segment of conductor 1 cm in length are displayed. If an RRR of 1330 for the aluminum were used then MIITS predicts a maximum temperature of 62 K.

11.5 Charging and Discharging the Solenoid

Charging or discharging the DØ solenoid generates eddy current heating in the external support cylinder. The rate of this heating and the total energy dissipated in the support cylinder during the charge or discharge of the magnet, are determined by the rate of the charge or discharge. Clearly, the rate of charge must be limited so that the heating in the support cylinder does not quench the magnet. Also, it is desirable to select a slow discharge resistor that enables the magnet to be discharged in a reasonable time without quenching the coil. Furthermore it is desirable to select a fast discharge resistor that guarantees that the magnet will "quenchback" [3] i.e. will be quenched by the heating in the support cylinder soon after the deliberate initiation of a discharge. This protection mechanism guarantees the uniform absorption of the portion of the magnet stored energy not extracted by the external resistor without depending on the propagation of the quench in the coil windings to drive the coil normal. Such a fast discharge would be initiated for example if a quench has been detected, or if some other upset condition that requires rapid magnet discharge, e.g. loss of cooling of the vapor cooled leads, is detected.

11.5.1 The Coupled Coil and Support Cylinder

It is straightforward to solve the simultaneous differential equations for the flow of current in a primary circuit coupled to a secondary circuit by a mutual inductance, where the circuit resistances are constant. Taking the solenoid to be the primary circuit and the support cylinder to be the secondary circuit and assuming the coil and support cylinder are perfectly coupled and there is no quenching in the coil, for the case of magnet discharge the current in the coil obeys

$$I_1 = I_0 \exp(-\lambda t)$$

where I_0 is the current in the magnet before the discharge, and

$$\begin{aligned}\lambda &= (R_1 R_2)/(L_1 R_2 + L_2 R_1) \\ &= 1/(\tau_1 + \tau_2).\end{aligned}$$

The current in the support cylinder obeys

$$I_2 = \frac{M\lambda I_0}{L_2(\lambda_2 - \lambda)}\left[\exp\left(-\lambda t\right) - \exp\left(-\lambda_2 t\right)\right].$$

with L_1 the inductance of the coil, R_1 resistance of the protection resistor, and L_2 and R_2 the inductance and resistance of the support cylinder, respectively. $\lambda_i = L_i/R_i$ and $M = \sqrt{L_1 L_2}$.

The instantaneous power developed in the support cylinder by this current is just $P_2(t) = I_2^2 R_2$. The total energy dissipated in the support cylinder is just the integral of this power during the discharge, and since $U_1 = (1/2)L_1 I_0^2$, this becomes

$$U_2 = \frac{E_1 R_2 \lambda^2}{\mathrm{L}_2(\lambda_2 - \lambda)^2} \times \left[\frac{1}{\lambda} + \frac{1}{\lambda_2} - \frac{4}{(\lambda + \lambda_2)}\right].$$

For the values of the parameters which pertain to the **DØ** magnet $\lambda_1 \ll \lambda_2$, and $L_1/L_2 = N^2$ where N is the number of turns in the solenoid so that

$$U_2 \simeq U_1 \frac{R_1}{R_2 N^2}.$$

This heating must be compared to the available cooling of the support cylinder and the thermal margin defined by the critical properties of the superconductor.

11.5.2 Cooling the Solenoid

As was shown in Chapter 4, ANSYS modeling of the cooling tube and coil support geometry on the coil support cylinder indicates that the maximum conductor temperature expected during steady-state operation of the magnet is about 4.9 K. The temperature of the helium in the cooling tubing is fixed at 4.7 K as predicted by the flow calculations for the cooling tube system. This 0.2 K temperature elevation of the conductor above the temperature of the cooling tubes is caused by heat conduction to the support cylinder from the support members and radiation from the shield.

Uniform additional steady heat generation can be added to the support cylinder in the ANSYS model and the added elevation of the conductor temperature due to this heating obtained from ANSYS.

In Figure 11.10 is seen the correlation predicted by ANSYS for additional heating in the support cylinder and the conductor temperature elevation caused by it. For e.g. 45 Watts added steady heating in the support cylinder it is seen that the conductor temperature is expected to be elevated about 0.4 Kelvins, to an operating temperature of about 5.3K.

11.5.3 Charging the Solenoid

For the case of a uniform charging voltage E_1 on the superconducting coil, the coupled equations yield the solutions

$$I_1 = \frac{E_1}{L_1}t$$
$$I_2 = \frac{ME_1}{\lambda_2 L_1 L_2}\left[exp(-\lambda_2 t) - 1\right]$$

The power dissipated in the support cylinder during such a chargeup is just $P_2(t) = I(t)_2^2 R_2$. For the values of the parameters pertaining to the DØ magnet, the term in square brackets approaches minus 1 almost immediately and we have

$$P_2 \simeq 0.306 \times E_1^2.$$

For a steady heating power of e.g. 45 Watts, the charging voltage is 12.1 Volts.

For a choice of critical parameters of the superconductor such that the operating current is 50% of the critical current at the nominal operating temperature, the current sharing temperature of the superconductor is approximately 6.8 K, about 1.9 K above the nominal operating temperature of the conductor. Even with this specification and Figure 11.10, it remains judgmental to choose a safe charging voltage. Given the potential for variability in the quality of the conductor and the operational stability of the cryogenic system a charging voltage of 6 V is selected (with perhaps an even lower voltage when near the final operating current). The actual voltage selected may also be reduced during the initial charge-up depending on the frequency and amplitude of any conductor motion perturbations observed.

For a fixed 6V charging rate the full operating current of the magnet is reached in about six minutes. As was shown in Chapter 10 the power supply will have to provide approximately an additional 8 V at full current for the bus resistance to the collision hall.

11.5.4 Discharging the Solenoid

A slow discharge that is conveniently rapid but yet does not cause the magnet to quench is desired for normal turn-off of the magnet. Quenches will cause a measure of upset to the cryogenic system and require re-cooling of the magnet before it can be repowered. Avoiding these complications during normal discharge of the magnet is desirable.

As indicated above it should be conservative to discharge the magnet from full current with 45 Watts initial eddy current heating in the bore tube.

From the discharging equation for I_2 above the instantaneous power dissipated in the support cylinder during a magnet discharge can be evaluated. For the range of values of the discharge resistor R_1 between 0.0015 and 0.09 Ohms this power peaks rapidly in about one second or less after the initiation of the discharge then decays slowly thereafter according to the time constant L_1/R_1 of the primary circuit. In Figure 11.11 is seen this peak power as a function of the value of the discharge circuit resistance. Evidently we can choose the slow discharge resistance to be 0.0025 Ohms or less (corresponding to a peak power of about 45 Watts or less) and be assured that the magnet will not quench.

With a slow discharge resistance of 0.0025 Ohms the magnet is discharged to less than 10 amperes in about 20 minutes.

We can ignore the cooling power provided by the cryogenic system during a discharge and using the discharge equations calculate the total energy dissipated in the support cylinder for various values of the resistor R_1. Using the enthalpy of the aluminum in the support cylinder mass, we calculate the final temperature of the support cylinder due to the energy deposited in it (Figure 11.12). Evidently for even the most rapid discharges the support cylinder temperatures do not approach temperatures where thermal stresses need be considered.

Quench calculations have been made which indicate that for reasonable modeling of the quench velocities in the coil windings the magnet will quench safely. To avoid risk due to the uncertain nature of these calculations a fast discharge resistance can be specified that is certain to cause a rapid quench via the quenchback effect. A fast discharge is in fact desirable to ensure the safety of the vapor cooled leads and buswork in the chimney in the event upsets are detected in these components as detailed in Chapters 9 and 10.

In Figures 11.13a and 11.13b are shown the time after the beginning of the discharge at which the support cylinder has reached 9.2 Kelvins assuming no heat removal from the support cylinder during this exercise, as a function of the time constant of the decay. (Figure 11.13b is a restricted portion of 11.13a. The discretized time values in the expanded-scale plot of Figure 11.13b are caused by the finite time steps selected by the program which calculates the support cylinder warmup).

From Figure 11.13 we specify that a fast discharge resistor ≥ 0.04 Ohms be provided to ensure that the coil will be protected by the quench back effect.

In Figure 11.14 we show the total time for discharging the magnet to less than 10 amperes as a function of the choice of discharge resistor. For the fast discharge resistor selected, the magnet is discharged in slightly less than 2 minutes.

11.5.5 Fast Discharge Quench Threshold

For a choice of fast discharge resistor of 0.050 Ohms a discharge from 5000 Amperes is certain to cause a quench from the quenchback effect. The very high heating rate in the support cylinder causes its temperature to rise beyond the critical temperature of the superconductor within a half second or so.

It is instructive to estimate what the current threshold is below which a fast discharge is not expected to cause a quench. For the conductor specified in Section 2.2 the current sharing temperature of the superconductor at full field is approximately 1.5 **K** above the operating temperature of the magnet. From the steady-state heating curve in Figure 11.10, extrapolated to a **T** of 1.5 **K**, it is seen that the corresponding heating rate is about 180 Watts. From the expression for the power dissipated in the support cylinder during a discharge, the peak power is

$$P_2 = \frac{I_0^2 R_1^2}{R_2 N^2}.$$

An initial current of 485 amperes will therefore result in a peak discharge power of 180 Watts. (The 5083 aluminum support cylinder has a resistance of approximately 3.2×10^{-5} Ohms, not strongly temperature dependent below $\simeq$ 100 **K**).

This result underestimates the actual quenchback threshold current expected since for a current of 485 Amperes the current sharing temperature is substantially more than 1.5 **K** above the operating temperature — almost 3.6 **K** in fact; also, the quenchback power derived is the peak power during the discharge, not the steady-state power required by Figure 11.10.

By integrating the quenchback power throughout the discharge and equating it to the enthalpy of the support cylinder plus one layer of the coil nearest the support cylinder it is seen that for initial currents below about 1770 Amperes the temperature of this portion of the cold mass never reaches the current sharing temperature of the conductor; just above this threshold current the current sharing temperature is not reached until 10 seconds of the discharge have elapsed.

The degree to which this last estimate for the quenchback threshold is conservative or not depends on what effect ignoring the cooling power of the cooling system during the discharge has. For an initial current of 1800 amperes the peak power in the support cylinder is about 2000 Watts. It is not easy to estimate the instantaneous cooling power available from the cooling system, but its steady-state cooling capability is much less than this. It is likely then that ignoring the cooling during the discharge does not constitute a large effect and that the quenchback threshold for the conductor specified is not far from 1800 amperes.

It may be desirable during normal slow discharges to in fact trigger a fast discharge when the magnet current has fallen below this level to safely hasten the slow discharge.

11.6 Protecting the Magnet Buses

The vapor cooled current leads in the magnet control dewar are connected to the magnet by superconducting buses nearly 14 meters long. Each bus is made of a parallel pair of magnet conductors thermally anchored to the helium supply tube in the magnet chimney but electrically isolated from it. After the magnet has been cooled to operating temperature and proper vapor flow is established in the vapor cooled leads, the buses in the chimney become superconducting permitting charge-up of the magnet. Subsequent upsets to the cooling in the chimney must enable magnet power-down without the loss of integrity of these buses.

To determine the operating margins of one of the superconducting buses after it has left the superconducting state we conservatively assume that it is not cooled by the helium supply tube so that ohmic heating in it by the magnet current contributes directly to the temperature rise in it. A discharge resistance (or equivalently a decay time constant) for the magnet is selected and the magnet current is allowed to decay accordingly. The peak voltage drop on the bus during the discharge is calculated, as is the final temperature at the end of the discharge.

Note that ignoring heat conduction along the bus the final temperature calculated is independent of the length of the segment of the bus that has gone normal. The peak voltage drop calculated however assumes that the entire length of the bus, 13.7 meters, has gone normal.

In Table 11.3 are presented the final temperature and peak voltage drop of the bus where the bus consists of one, two, or three of the magnet conductors in parallel, for several choices of discharge resistor. (Composing the bus of multiple magnet conductors is for convenience; the total amount of low-resistivity aluminum in the bus is what is at issue). The onset of the decay is chosen to begin after the voltage drop of 0.025 V is reached.

The final temperature and peak voltage drop are omitted from the table if the temperature exceeded 600K before the discharge was completed. In general the table shows that it is helpful to add extra normal conductors to the buses to protect them from overheating in the event of an upset. For the faster discharges even the single-conductor bus is safe, and the addition of one extra conductor gives all the protection of three or more conductors for all but the slowest discharges.

The peak voltage drop is typically small but adequate for triggering the magnet discharge reliably. The time elapsed before the desired voltage drop is reached is indicated; it is noteworthy that it depends only on the size of the bus (and the choice of voltage drop before triggering the discharge).

If instead of 0.025 V, 0.050 V is chosen for the voltage drop necessary to trigger the discharge the above table is slightly modified: the final temperatures rise a few degrees, and the peak voltage drops (for all but the slowest discharge and the single conductor bus) clamp at 0.050 V rather than the 0.025 V shown in the table. Also, the delays become 2.6 seconds for the single-conductor bus, 19.5 seconds for the double-conductor bus, and 57.1 seconds for the triple-conductor bus. Evidently, the threshold selected for the triggering of the discharge needn't be set unreasonably low and the voltage drop on the bus will tend to clamp at the threshold value selected. The temperature rise in the bus is very much faster than the voltage drop - the conductor reaches the transition temperature for NbTi in typically less than one second or so.

In Figure 11.1 is shown the calculated temperature rise and voltage drop for a discharge of the magnet into a 0.050 Ohm protection resistor. It is assumed that any incident that could drive any portion of the bus leads normal would rapidly lead to the entire length of the bus being driven normal. If this were not the case the voltage drops measured would be correspondingly smaller.

It is not easy to specify what type of incident could lead to upset in the magnet bus leads. Loss of helium flow in the chimney is the only credible upset mode that comes to mind, triggered by loss of pressure in the supply dewar or by misoperation of the JT valve in the subcooler circuit. In any case, flow meters will signal this upset and within a few seconds trigger a fast discharge of the magnet. A calculation shows that there is sufficient liquid helium in the chimney pipe above the buses such that 2 minutes elapse after flow stops before the heat load in the chimney generates enough vapor to displace the liquid down to the level of the buses themselves.

References

[1] M.N. Wilson, "Computer Simulation of the Quenching of a Superconducting Magnet," RHEL/M151, 1968.

[2] A. Mesin and R. Yamada, "Quench Program DDESQUENCH (Modified QT:CNTL)", DØ Note 1138, May 31, 1991. QT:CNTL is a version of the Wilson code installed at Brookhaven National Laboratory by A.D. McInturff (BNL 19883, 1975) and at Fermilab by A.D.McInturff, and subsequently modified by M. Wake, T. Tominaka, and M. Takasaki (1982).

[3] M.A. Green, "Large Superconducting Detector Magnets With Ultra Thin Coils For Use in High Energy Accelerators and Storage Rings", LBL-6717, Aug 1977, and Proceedings of the 6th Int. Conf. on Magnet Technology, Bratislava, 1977.

[4] S. Mori, *et. al.*, "Construction and Testing of Superconducting Solenoid Magnet Model for Colliding Beam Detector", Advances in Cryogenic Engineering **27**, Plenum, 1981, p151.

[5] A. Bonito-Oliva, *et.al.*, "Quench Behaviour of a Thin Solenoid Model", Proceedings of the 11^{th} International Conference on Magnet Technology, Tsukuba, Japan, 1989, p229.

[6] R. Yamada and A. Mesin, "Estimated Maximum Temperature of Conductors for 2 Tesla DØ Superconducting Solenoid in Adiabatic Condition", DØ Note 1975, Nov. 12, 1993. MIITS was developed from program HOTCM created by M. Kuchnir, Fermilab. See also R. Yamada, *et.al.*, "Estimated Maximum Temperature of Conductor of Superconducting Solenoid Coil in Adiabatic Condition (I)", KEK Internal 81-10, January, 1982, TRISTAN.

Table 11.1: QUENCH Calculated Results			
Protection Resistor [mΩ]	Maximum Temp [K]	Maximum Voltage [V]	Maximum Resistance [mΩ]
0	96	430	220
5	92	400	200
10	87	355	185
25	76	230	130
50	58	250	46

Table 11.2: QUENCH Energy Sharing		
Protection Resistor [mΩ]	% Energy In Coil	% Energy In Resistor
0	100	0.0
5	88.0	12.0
10	76.6	23.3
25	47.2	52.8
50	16.7	83.3

Table 11.3: Superconducting Bus Safety

Protection Resistor [Ω]	One Unit [$0.735 cm^2$]	Two Units [$1.47 cm^2$]	Three Units [$2.21 cm^2$]
0.0500	**37 K** (0.33 V)	**31 K** (0.025 V)	**33 K** (0.025 V)
0.0309	**49 K** (0.046 V)	**33 K** (0.025 V)	**34 K** (0.025 V)
0.0120	**296K** (5.1 V)	**44 K** (0.036 V)	**39 K** (0.025V)
0.0072	****** ******	**64 K** (0.11 V)	**44 K** (0.028 V)
0.0025	****** ******	****** ******	112K (0.44 V)
Delay	1.1 Sec	10.7 Sec	34.8 Sec

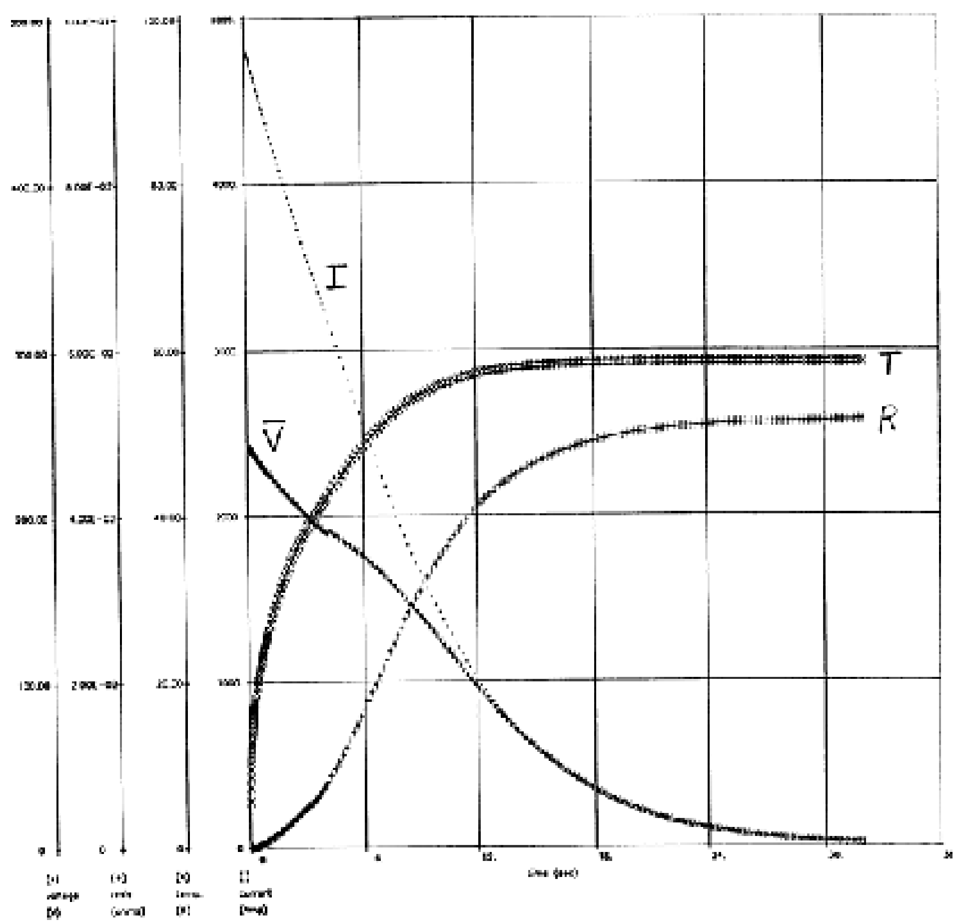

FIG 11.1: Quench with Dump Resistor = 50 mOhm

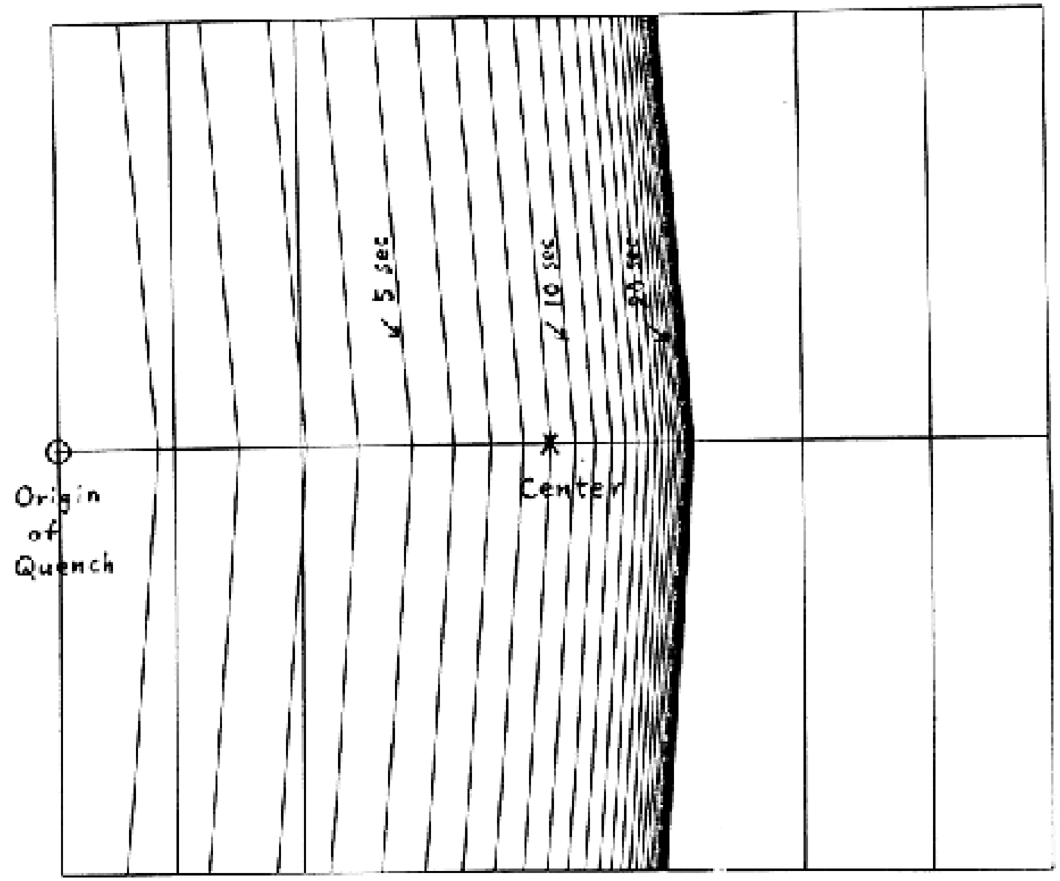

FIG 11.2 Propagation of normal zone along length of 15 mm high coil at 1 second intervals for quench initiated at the end of the coil

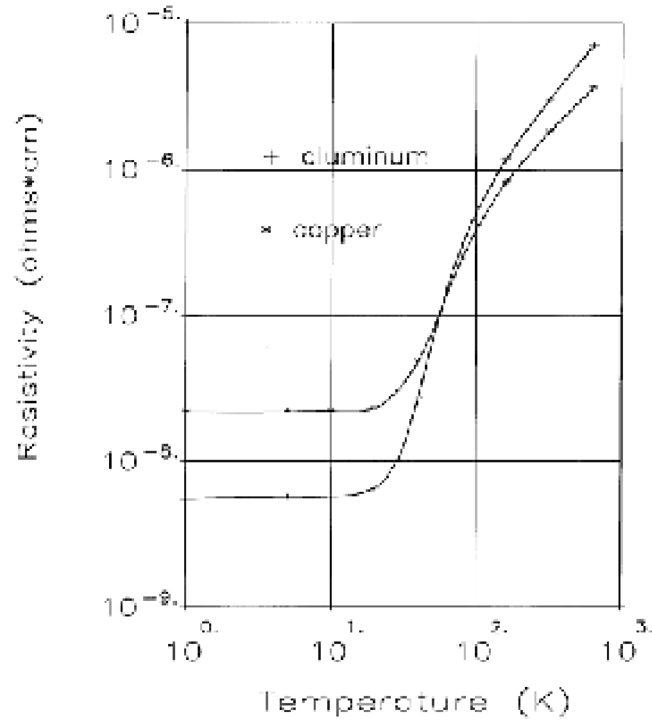

FIG 11.3: Resistivity of Aluminum and Copper

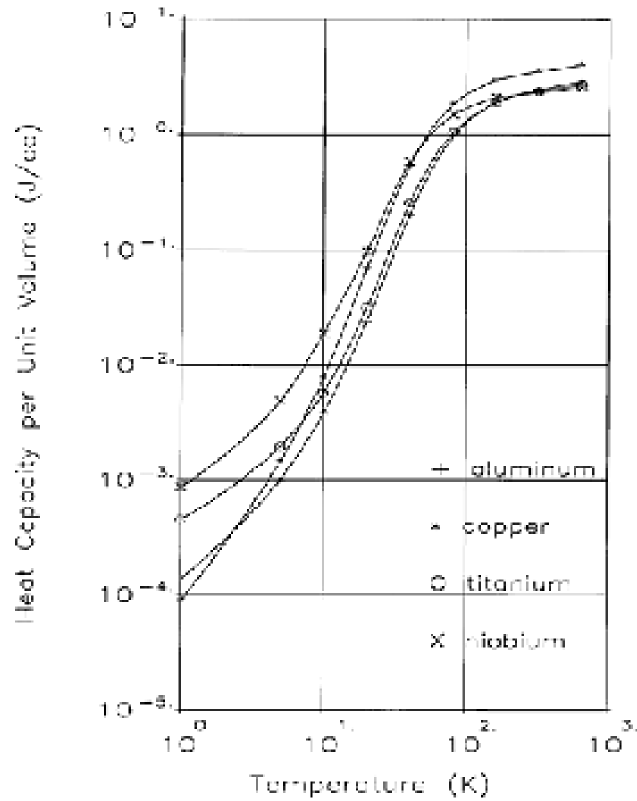

FIG 11.4: Heat Capacity per Unit Volume of the Four Materials

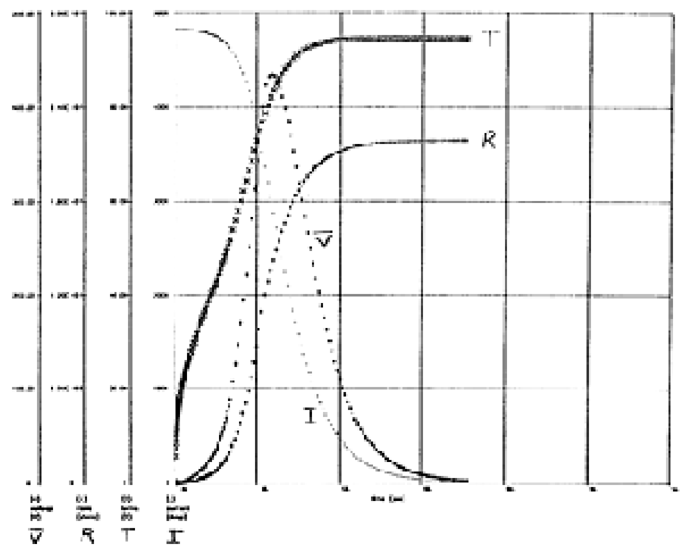

FIG 11.5 : Quench with Dump Resistor = 0 mOhm

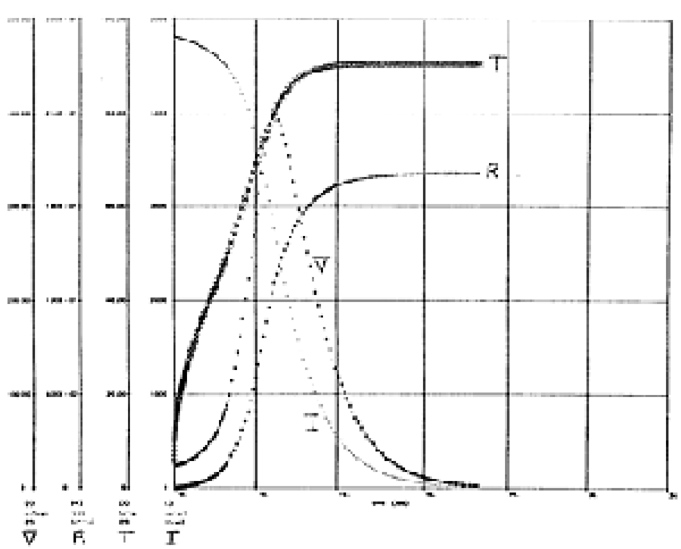

FIG 11.6 : Quench with Dump Resistor = 5 mOhm

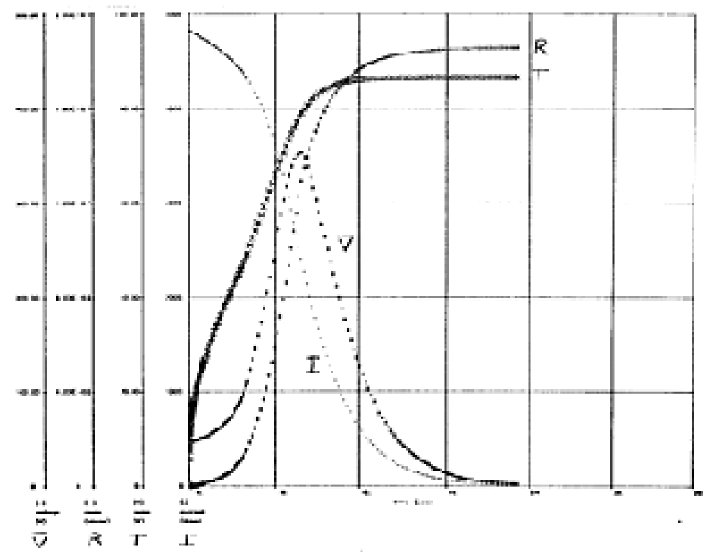

FIG 11.7: Quench with Dump Resistor = 10 mOhm

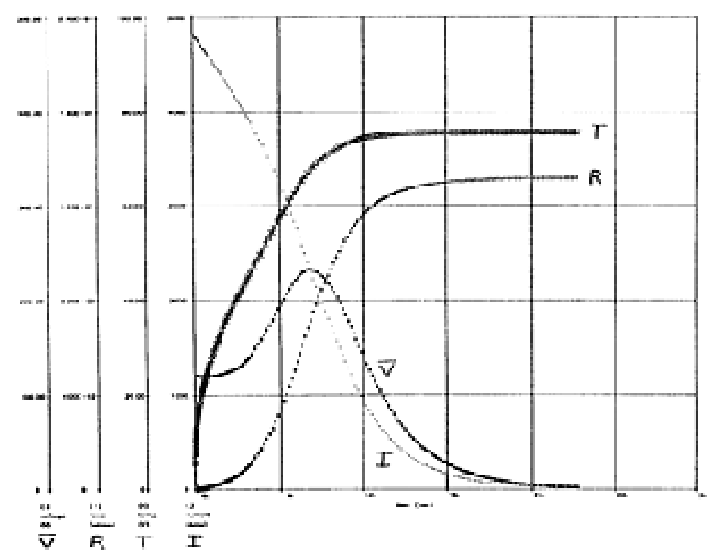

FIG 11.8: Quench with Dump Resistor = 25 mOhm

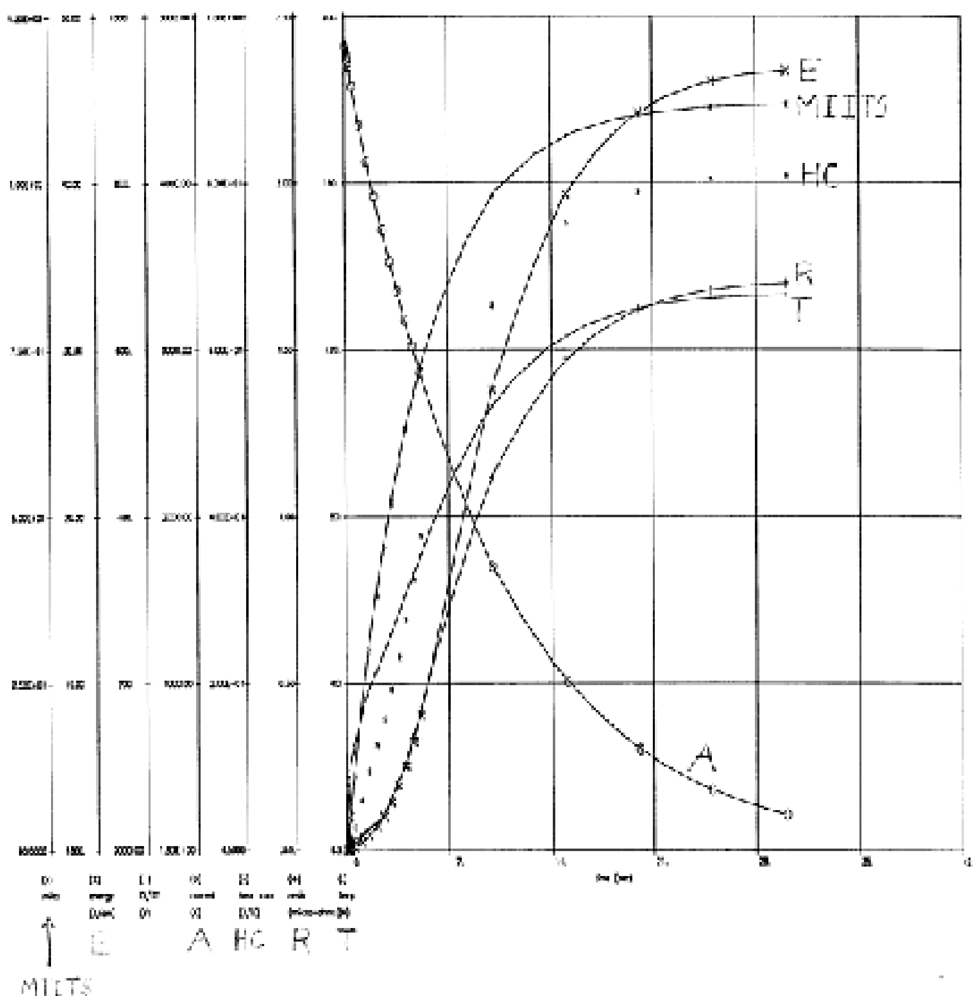

Figure 11.9: MIITS Calculation of Type II Conductor with RRR Values of 500 and 71 for Aluminum and Copper, respectively.

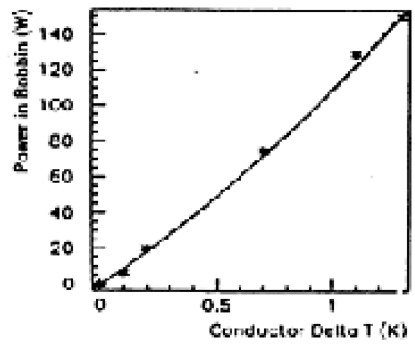

Figure 11.10: Eddy Current Heating in the Bobbin vs. Conductor Temperature Elevation above Nominal.

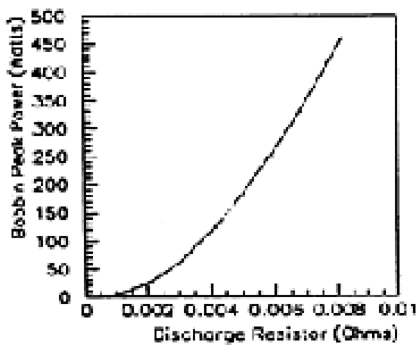

Figure 11.11: Peak Heating Power in Bobbin vs. Choice of Discharge Resistor.

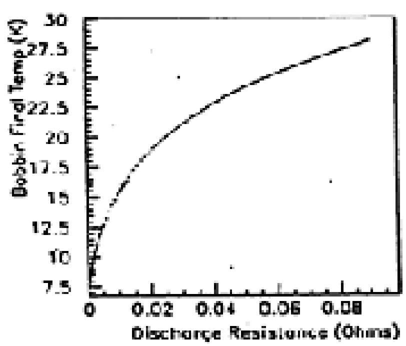

Figure 11.12: Final Bobbin Temperature upon Discharge vs. Choice of Discharge Resistance.

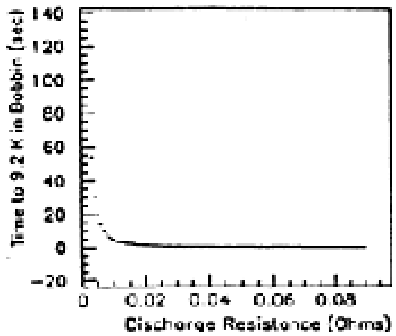

Figure 11.13a: Time after Beginning of Discharge for Bobbin to Reach 9.2 K vs. Choice of Discharge Resistance.

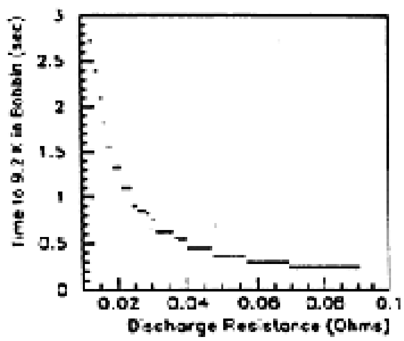

Figure 11.13b: Time after Beginning of Discharge for Bobbin to Reach 9.2 K vs. Choice of Discharge Resistance > 0.01 Ohms.

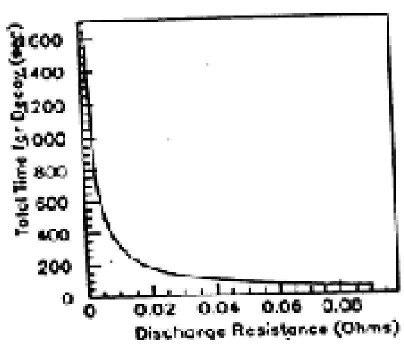

Figure 11.14: Total Time for Discharge vs. Choice of Discharge Resistance.