BNL 18153

CRISP 73-13

MASTER

BROOKHAVEN NATIONAL LABORATCRY
Associated Universities, Inc.
Upton, New York

ACCELERATOR DEPARTMENT
Informal Report

Analysis of a Quench Event in the 20-in. Nb-Ti Magnet Model Constructed by G. Danby et al.

J.G. Cottingham
August 15, 1973

Abstract

Measurements of the voltage and current that resulted from a quench of a superconducting magnet were studied and a simple computer model of this process was developed. Large layer-to-layer voltages were generated by the quench and methods reducing these were suggested and examined.

In a large superconducting ring of the type proposed for the ISA, protection must be engineered to adequately control the voltage and currents produced by a sudden quench, the return of the superconductor to the normal state. If such protection is defective, the large energies stored in their magnetic field can produce considerable damage.

The team of S.Y. Hsieh, R.K. Stoehr, M. Iwantschuk, J. Weisenbloom and J.W. Jackson, under the direction of G.T. Danby, using their 20-in. Nb-Ti model[(1)] induced a quench under instrumented conditions for the purpose of obtaining information of the physics of the quench process.

The magnet model had a two-turn backleg winding from which the total induced magnet voltage ($N\frac{d\theta}{dt}$) could be determined by multiplying by the turns ratio (160:1). Magnet current was measured by a shunt, 100 millivolts equal 1000 amperes. The results of the observation are shown in Fig. 1. From these data, the apparent resistance (E/I) can be determined and is shown in Fig. 2. As a check on the validity of the measured data, the integral of EIdt can be numerically evaluated and compared with the energy stored in the magnet prior to the quench. This integral yields 45.8 kilojoules as compared to the stored energy of 48.2 kilojoules and is a good check on the measured results.

If all the energy were uniformally distributed in the magnet coil, the temperatures would rise to 61.6°K and the coil resistance would be 324 milliohms. It appears that the measured resistance may be approaching this value (see Fig. 2). This would indicate that most of the dissipated thermal energy remained in the coil and only a small part is carried away by the gas or other means. However, by one second, most of the magnetic energy has been converted to thermal energy and the coil resistance is approximately half of the 324 milliohms. This gives rise to the possibility that the thermal energy is first stored in a "warm spot" and then is conducted into the rest of the coil mass. For this to be possible, the coil material must store proportionately more energy per gram at higher temperatures than the resistance ratio (ρ/ρ 273) increases. The plot of Enthalpy per resistance ratio for copper vs temperature is shown in Fig. 3 and indeed the necessary increase is clearly shown.

At the onset of the "quench" process the "normal" region in the conductor is small and the thermal conduction down the length of the conductor is much greater than the thermal conduction to the liquid media or to adjacent coil turns. However, later in the process, the temperature of the central point rises and the "warm" region expands in length so that thermal conduction to adjacent coil layers may no longer be small compared to that conduction down the length of the conductor.

To determine when this simple conduction process is valid and when it breaks down, a computer model was studied. The computer model contained the thermal conduction properties of the conductor down its length but assumed no heat flow across the turn-to-turn or layer-to-layer boundries. The results of this computation are also shown on Figs. 1 and 2 labeled "Computed". Parameters of the computer model were adjusted to get the best match to the measured results. Best results were obtained with --

1. Cold resistance ratio equal 1/75.
2. Difference temperature between bath and critical temperature equal 0.1°K. Note: The measured quench event was induced by increasing the current thus lowering the critical temperature toward the bath temperature.
3. Thermal conduction of annealed copper was used. Thermal conduction of OHFC copper was tried earlier but the match was not as good.

The match between the computed and measured voltage and current shapes are quite good to one second and, therefore, give evidence that the model used in the computation is a good approximation of the real process to this time. After one second the apparent resistance continues to increase beyond the computed value. This is the result of heat crossing the interlayer barrier and warming copper in adjacent layers, a process not included in the computer model. Temperature differences across these layers has reached 300°K at this time and a sizable interlayer area is exposed to this large temperature difference.

Figure 4 shows the temperature distribution along the conductor as a function of time; symmetry is assumed. Most of the thermal energy is stored in a 20-meter segment (10 meter each side of center) and, therefore, a large part of the resistance and voltage drop will be similarly concentrated. The whole voltage drop can exist on a single layer of coil winding, developing a large layer-to-layer potential difference. Figure 5 illustrates this using data from the computer model of the 20-in. magnet. This figure shows a part of a section through a coil winding. Each square represents a conductor and the lower layer is arbitrarily assigned zero potential. The other potentials represent the IR term only. The voltage induced in each turn by the decreasing magnetic field is about 1/3 volt per turn which will oppose the potentials shown. This was not included in constructing Fig. 5 because of the unknown number of turns that constitute the fold to the adjacent layer. The physical location of the "quench point" is unknown.

As larger magnets with more stored energy are constructed, even larger potentials are developed across the layer-to-layer insulation.

Using the computer model described, the following results were obtained:

Magnet Type	Inductance Henries	Current Amps	Stored Energy-kJ	Layer-to-Layer Voltage
20-in. model	.044	1480	48.2	106
4° bend, single unit	.150	1080	87.5	139
8° bend, double unit	.300	1080	175.0	245

Layer-to-layer voltages of this magnitude create the possibility of electrical failure (arcing) with the sudden and local release of the available stored energy with destructive effect.

There are three possible approaches to the solution of this problem. These may be used in combination:

1. Design of the conductor cross section to control the heat flow and thermal energy absorption to reduce the layer-to-layer voltage.
2. Design and testing of the layer-to-layer insulations to withstand these potentials with adequate safety.
3. Design of protection circuits which detect the onset of the "go normal" process and remove the energy stored in the magnetic field before it is converted into heat within the magnet.

The first and second approaches above, offer the more reliable solution but as a backup, the circuit shown in Fig. 6 is a good fast-acting protection circuit. Its action is simple. When SCR-2 is fired, this series circuit generates a half sine wave of current larger than the operating magnet current. This excess current will try to flow backward through SCR-1 forcing it to the OFF state. Magnet current will flow through SCR-2 until the series capacitor is charged sufficiently to force the magnet current through the diode and shunt resistor at which time SCR-2 will revert to its OFF state. The magnet current will delay to zero depositing part of its energy in the external resistor and part in the "normal" resistance inside the magnet. If energy is removed fast enough, the internal layer-to-layer voltage will be reduced. The following table illustrates the effectiveness of this circuit when operating with the 8° bend magnet described above.

Shunt Resistor	Layer-to-Layer Voltage	Fraction of Energy Dissipated in Magnet
0.0 ohms	245. volts	1.0
0.1	88.87	.3830
0.2	28.30	.1089
0.3	10.45	.0327
0.6	2.66	.0050

Captions

Fig. 1 Measured and computed voltage and current waveform generated by a quench of the 20-in. magnet model.

Fig. 2 Measured and computed internal resistance generated by a quench of the 20-in. magnet model.

Fig. 3 Enthalpy per ratio (ρ/ρ 273) for copper.

Fig. 4 Computed temperature-length distribution as a function of time along the current conductor from line of symmetry at point of origin of the quench.

Fig. 5 Conductor potentials at maximum during quench of 20-in. model, computed.

Fig. 6 Quench protection circuit. Electronic switch and shunt R removes stored energy during the quench event.

References

1. J. Allinger, G. Danby, B. DeVito, S. Hsieh, J. Jackson, A. Prodell. Studies of performance and field reproducibility of a precision 40 kG superconducting dipole magnet. Proc. 1973 Part. Accel. Conf. Also BNL 17825.

Distr.: CRISP

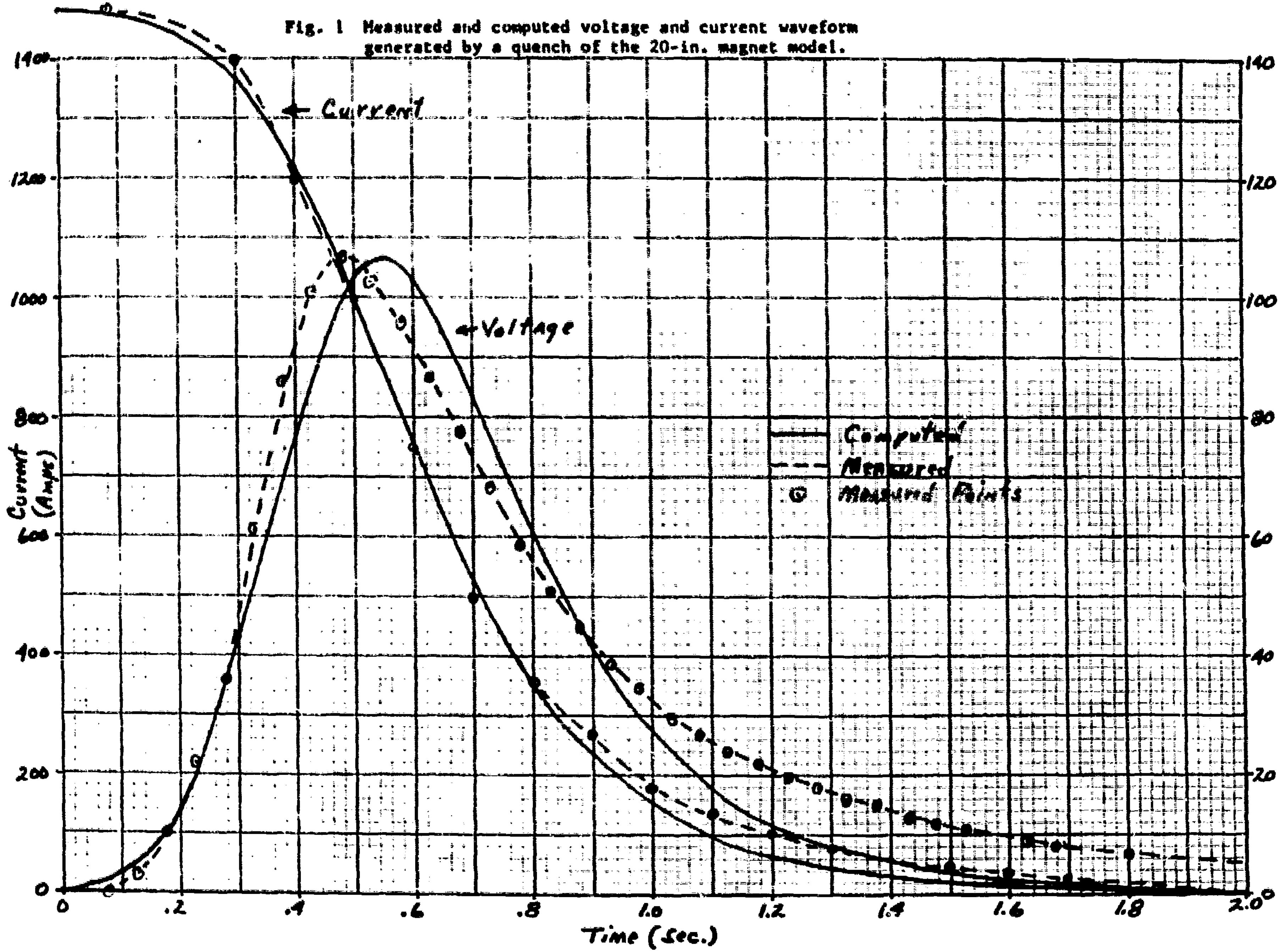


Fig. 1 Measured and computed voltage and current waveform generated by a quench of the 20-in. magnet model.

Fig. 2 Measured and computed internal resistance generated by a quench of the 20-in. magnet model.

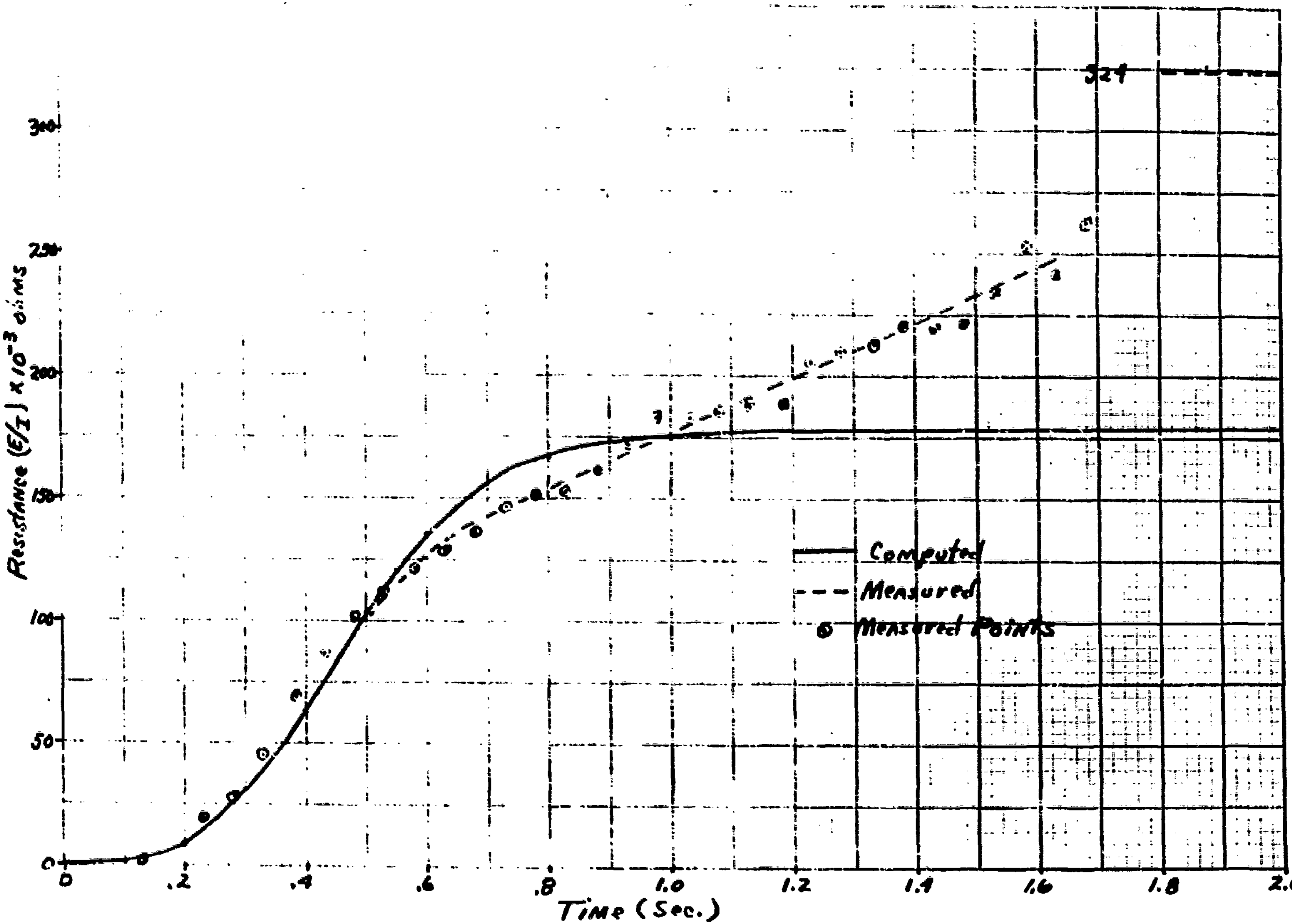
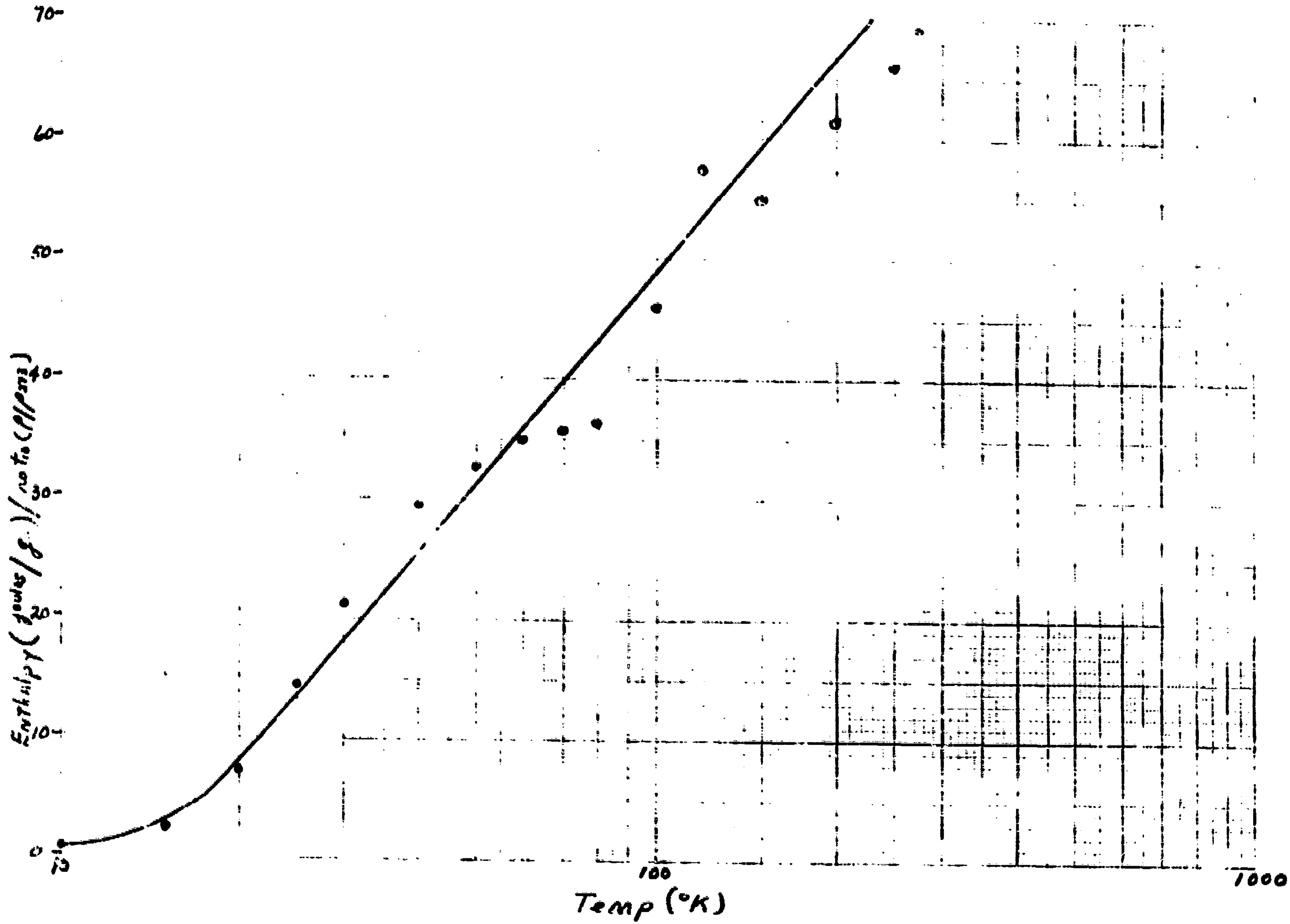


Fig. ? Enthalpy per ratio (ρ/ρ 273) for copper



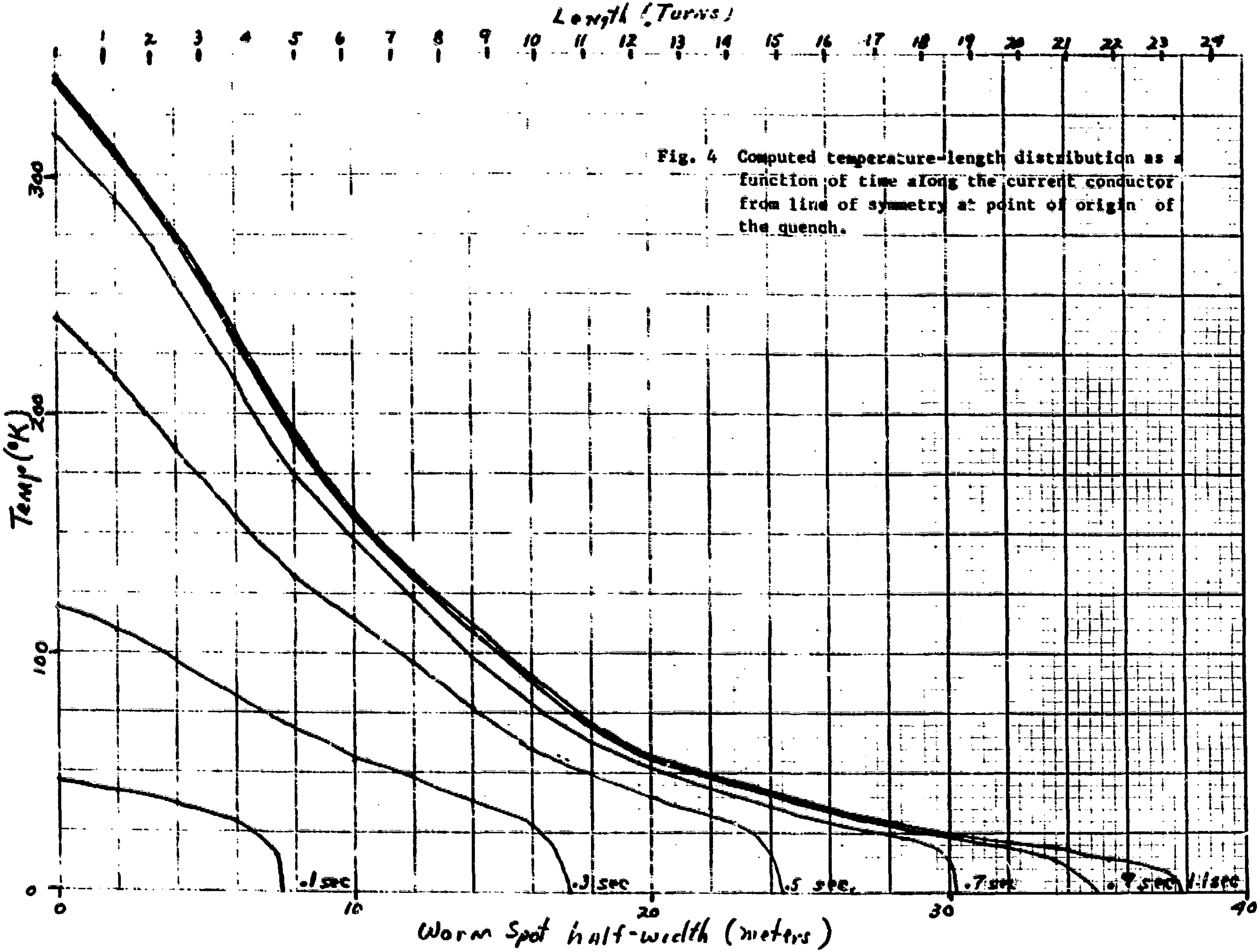


Fig. 4 Computed temperature-length distribution as a function of time along the current conductor from line of symmetry at point of origin of the quench.

Fig. 5 Conductor potentials at maximum during quench of 20-in. model, computed.

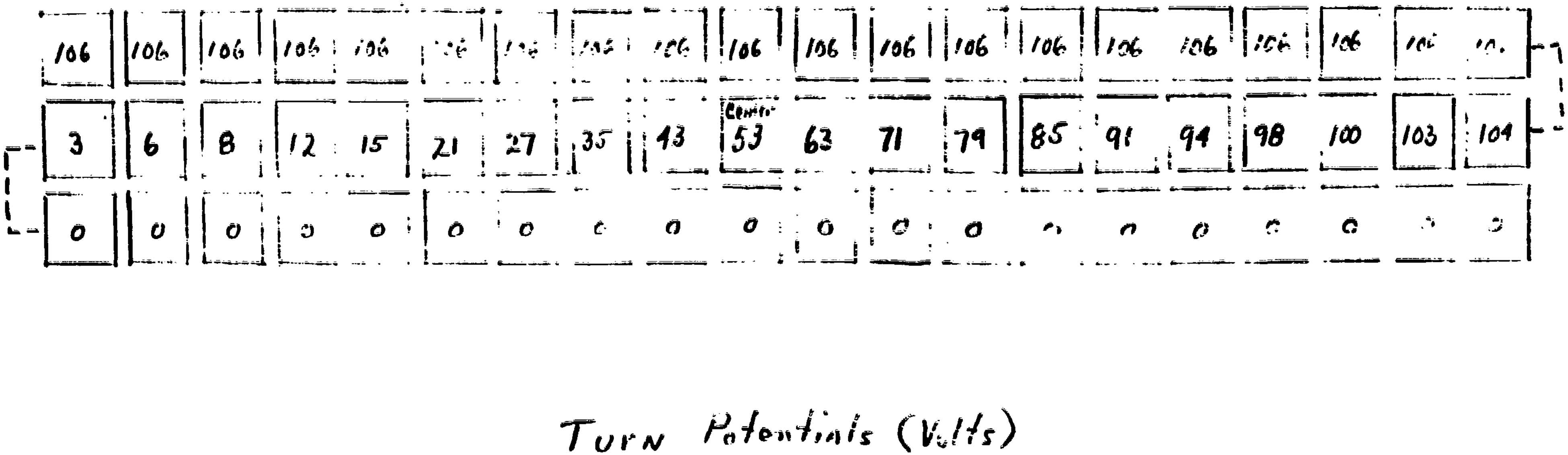


Fig. 6 Quench protection circuit. Electronic switch and shunt R removes stored energy during the quench event.