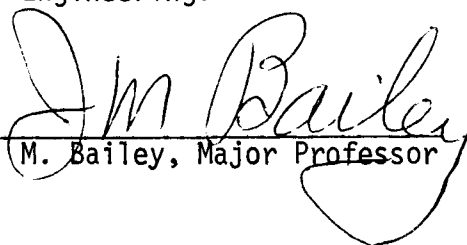
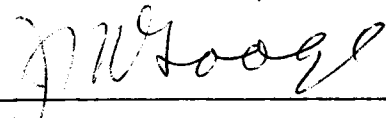
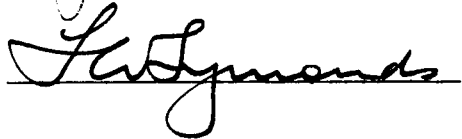


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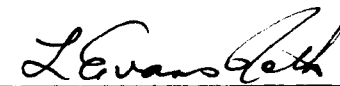
I am submitting herewith a thesis written by Randall J. Wood entitled "Design Considerations of Power Protection Systems in Superconducting Magnets." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Electrical Engineering.


J. M. Bailey, Major Professor

We have read this thesis and
recommend its acceptance:

Accepted for the Council:


Vice Chancellor
Graduate Studies and Research

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DESIGN CONSIDERATIONS OF POWER PROTECTION
SYSTEMS IN SUPERCONDUCTING MAGNETS

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Randall J. Wood

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ABSTRACT

The intent of this thesis is to investigate means of protecting superconducting magnet systems. The types of magnet systems considered are those employed in tokamak fusion reactors for containment of the plasma. The magnetic systems to be considered have current ratings ranging from 10,000 A to 25,000 A dc. The maximum voltages associated with protection of these coils are 1000 V and 2500 V, respectively. The maximum energy storage capability of these coils is approximately 200 megajoules.

The thesis discusses several types of protection systems. The functions of all major power devices of the protection systems are reviewed. The thesis addresses three major current interrupting devices considered for use in the magnetic system protection scheme. The pros and cons of each system will be discussed, and one is selected for use in the protection system. The reasons for selection of this device, rather than the others, will be reviewed. Also, design considerations in engineering the coil dump resistor will be reviewed.

One power interrupter circuit is reviewed in detail to include test results along with a dynamic computer model. The computer model uses the Super-Sceptre II computer program for modeling the transient portion of the circuit. Two types of dump resistors are reviewed in detail to complete the understanding of "Design Considerations of Power Protection Systems in Superconducting Magnets."

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1.0 SCOPE

The fusion reactor or power plant is composed of several major subsystems. The vacuum system, diagnostic system, cryogenic system, and power system for magnetic confinement are among these subsystems.

The toroidal and poloidal magnetic fields are the two major fields employed in magnetic confinement of the fusion reactor plasma. The poloidal field is generated by the current in the plasma, and the toroidal field is an external field generated by a magnetic coil system. Figure 1^{*} presents these field locations with respect to the typical tokamak system.¹ Since the operating currents (dc) of the toroidal coils can range from 2000 to 25,000 A, the efficiency of the fusion reactor can be greatly improved if the I^2R (watts) losses of the toroidal coil system are reduced. The reduction is accomplished by use of superconducting coils. A typical superconducting coil consists of filaments of superconducting material (Nb-Ti or Nb₃Sn) embedded in a copper plate for structural support. The coil is then placed in a vessel where the coils will be immersed in liquid helium at 4°K (superconducting temperatures) and operated as a superconducting coil. A very unique protection scheme is required to protect these coils. The purpose of the protection system is to discharge the coil in the event of system abnormalities or coil quench.

When a coil quenches, the resistance of the superconductor rises rapidly. The length of superconductor that quenches is called the

* All figures appear in Appendix A unless otherwise noted.

normal zone. This increase in resistance will result in catastrophic failure of the coil and other subsystems if the current in the coil is not reduced to zero very quickly. One failure mode is due to the expansion of the liquid helium. The helium, which cools the superconductor down to 4°K, will expand very rapidly when subjected to heating. One liter of liquid helium at 1 atm of pressure requires only 2500 J to be converted to gas. A coil operating at 25,000 A has to increase only 100 mΩ in resistance to generate this amount of joules heating in only 1 sec. Large pressure perturbation can be generated in the coil when a coil quenches even if an energy removal system works properly. The calculated pressure temperature surges of the liquid helium for a typical coil quench can be seen in Figs. 2 and 3. The curves are based on a given heat input due to a coil quench. The pressure and temperature increase is also based on the coil energy removal system working as designed. The coil pressure and temperature profiles modeled are the General Electric Coil of the Oak Ridge National Laboratory experiment, the Large Coil Test Facility (LCTF). One could certainly envision the magnitudes of pressure and temperature levels if the energy removal system was inoperable. If steps are not taken to reduce the current, the normal zone (length of conductor going normal) will grow, causing more and more heating, which will eventually destroy the coil. For this reason, the coil protection system has to be very reliable. If this system fails, the resulting damage due to the expansion of the liquid helium alone could result in systems failures amounting to millions of dollars. Also, the reactor downtime would be enormous. A typical example of one coil cost alone can be seen in the

LCTF experiment presently being conducted at Oak Ridge National Laboratory. The experiment is composed of six "D"-shaped superconducting magnets with a maximum magnetic field capability of 8 tesla each. Each coil has a 3.5×2.5 m bore size and an average cost of \$14 million per coil. Even though a large portion of the above cost is due to research and development, the superconducting coils employed in the future will still cost several million dollars. The coil protection system has to perform reliably when called upon to discharge (dump) the superconducting coil.

This thesis investigates the design considerations required in the design of a reliable coil protection system. It presents the four basic coil protection components:

1. the high current switch,
2. the current interrupter,
3. the transient suppressor, and
4. the energy dump resistor (EDR)

and establishes the criteria for selection of each device. Three types of current interrupters--SCR, vacuum, and dc breaker--are discussed, and the criteria for selection of each device are presented. Also, two types of suppressor networks--R-C and varistor--and one energy dump resistor are reviewed along with a discussion on the advantages and disadvantages of each component.

2.0 PROTECTION SYSTEMS

2.1 Basic System

The four components of the coil protection system are shown in Fig. 4a. Prior to operation of the coil protection system, the high current switch and current interrupter are both closed and carrying the coil current. The EDR is effectively shorted out by the low resistance power supply and high current switch loop. Upon activation of the coil protection system, the high current switch is opened and transfers its current into the current interrupter, which is still closed. Upon transfer of the coil current into the current interrupter, the interrupter is opened and develops the required high voltage to interrupt its current, forcing the coil current into the EDR. The three types of current interrupter circuits are shown in Fig. 4b. The suppressor limits transients generated by the current interrupter during the interruption. The EDR dissipates the coil energy. The power supply of Fig. 4a is used to charge the coil up to its operating current. A typical power supply for these coils has a rating of 12 V dc at 16,000 to 25,000 A. The coil charge rate (amperes per second) is 12 V/L coil ($V = \text{dc volts}$, $L = \text{henrys}$). The high current switch is a low-voltage device whose function is to carry the coil current continuously. Approximately one-tenth of the coil current flows in the interrupter during normal operation. The division of current in the high current switch and the circuit interrupter is accomplished by R_1 . The function of the circuit interrupter is to transfer the current from the long time constant ($\approx 5000 \text{ sec}$) power supply-coil loop to the much shorter

time constant (20 sec typical) energy dump resistor (EDR) coil loop. The function of the EDR is to dissipate the energy of the superconducting magnet ($1/2 LI^2$ J).

The functions of the dump circuit components can be readily understood by comparisons of a typical coil dump circuit (Fig. 5). Figure 5a presents a typical coil equivalent circuit with calculated power supply and coil bus impedance included prior to the interrupter opening. As can be seen, the time constant (τ) of this circuit is 5710 sec. Assuming a dump was required and the high current/interrupter was not opened, the current in the coil will decrease at a rate of $I = I_0 e^{-t/5710}$. With $I_0 = 25,000$ A, the coil current would be 24,913 A in 20 sec, only a 0.35% decrease. Obviously this provides no protection to the coil. On the other hand with the assumed condition of Fig. 5b, the high current switch/interrupter has cleared the low impedance loop, and the time constant is approximately 20 sec. In 20 seconds, the current in the inductor has dropped to 9197 A ($I = 25000 e^{-1}$). A 63% drop from the initial 25,000 A is noted. With the energy in the coil equal to $1/2 LI^2$, the energy has been reduced from 625 to 84 MJ, an 87% drop in energy in 20 sec.

The time constant of 20 sec for energy removal is the typical time constant required on the superconducting coils of the LCTF. This time constant is a typical requirement of superconducting magnets operating in the 25,000-A region.

Since the coil energy has decreased to 84 Mjoules, the EDR has absorbed this energy (541 Mjoules). Hence, the EDR dissipates the

coil's energy at a given rate (τ). The resistance (R_D) being set by the equality $R_D = \frac{L \text{ (inductance of coil)}}{\tau \text{ (desired time constant)}}$.

2.2 Interrupter Types

Since the high current switch/interrupter has to interrupt currents of 10 to 25 kA dc levels, special attention has to be given to this device. Several devices for the interrupter have been developed with proven test results. They are:

1. the Silicon Controlled Rectifier (SCR) interrupter.
2. vacuum interrupter.
3. dc breaker interrupter.

The circuit for each interrupter is shown in Fig. 4b. Each device is discussed in the following sections.

2.2.1 SCR interrupter. The SCR interrupter has been used successfully for high current interruptions in superconducting magnet protection. The SCR interrupter has several advantages over other types of interrupters. Among these are the capabilities of paralleling to obtain the required current carrying capacity. Also, the space requirement for installation is minimal. A major disadvantage is that the SCR interrupter requires a current zero since this is a dc application. The current zero is generated by a commutation system consisting of an inductor, capacitor, and switch. This system forces the dc current in the SCR interrupter to zero.

2.2.1.1 Design considerations. Several SCR specification limits had to be adhered to when designing the SCR interrupter. The

interrupter considered for use in the LCTF protection system is rated for a maximum of 25,000 A and 2500-V dump voltage. The device specification limits that have to be addressed in the design are the maximum junction temperature, dv/dt , reverse bias time, dI/dt , non-repetitive and repetitive forward and reverse blocking voltages. The non-repetitive peak reverse blocking voltage (PRV) and the repetitive forward/reverse blocking voltages (V_{drm}/V_{rrm}) are the maximum voltage the SCR can withstand without failure. The PRV and V_{drm}/V_{rrm} , if exceeded, may cause either voltage isolation breakdown or automatic switch-on of the SCR.² The importance of the dv/dt and dI/dt ratings can be readily understood by reviewing Fig. 6 and Fig. 7a,b.³ In Fig. 6, the turn-off (t_{fr}) and turn-on (t_{on}) intervals are shown. The dI/dt rating when the SCR is turning on is required to allow the J_2 junction of Fig. 7a to be fully turned on prior to large forward currents. If the J_2 junction is not fully turned on when the maximum forward current I_m flows through the device, only portions of the J_2 junction will carry the current, causing excessive heating in these areas. Also, the dI/dt rating during turn-off is required to prevent large peak reverse currents I_{rm} . As seen in Fig. 6, the reverse recovery time t_{rr} is the time required for the reverse recovery current to decay to 10% of I_{rm} . If the off dI/dt is not limited, the peak I_{rm} will reach much higher levels, causing the device to suddenly cease to conduct high reverse currents. This can cause dangerously high induced reverse voltage. The dv/dt rating is required to prevent the SCR from turn-on during the time period from t_c (circuit turn-off time) to t_{fr} (circuit forward recovery time) of Fig. 6. This turn-on phenomenon is understood by

referring to Fig. 7b, the two-transistor analogue of an SCR. The turn-on occurs through the capacitance of the base-to-emitter junction C_{j1} and C_{j3} and capacitance of base-to-collector junction C_{j2} . With a large dv/dt during the t_{fr} interval, current flows through the base-to-emitter and base-to-collector junction capacitance and causes the current gain of the devices to become unity, which turns on the device. The final rating, the reverse bias time, is required to permit the base region to be cleared of minority carriers, allowing the device to block the reapplied forward voltage.

The device picked for this application is the General Electric C712 SCR. The specification sheet on this device is presented in Fig. 8.⁴

2.2.1.2 Circuit description and equations. The circuit in which the SCR is installed is divided into two equivalent circuits, as shown in Fig. 9a and b. The first circuit (Fig. 9a) is applicable during the conducting phase of the SCR and the second (Fig. 9b) is the applicable circuit when the SCR interrupter is forced off or reversed biased. The capacitor C_c of the circuit is the commutation capacitor which is precharged to some E_0 volts. L_c is the commutation inductor which limits the di/dt of the circuit. SCR1 is the commutation switch, and SCR2 is the interrupter. The basic operation of each device during a current interruption is as follows:

1. At $t_{0-} = 0$ seconds SCR1 is gated on (see Fig. 10b).
2. C_c discharges and produces a current $I(t)$ where the di/dt is limited by L_c .
3. At t_0 , SCR2 is reversed bias (see Fig. 10b).

4. The current $I(t)$ forces the interrupter (SCR2) current to zero and reverse biases SCR2 (note: initially SCR2 current equals 25,000).
5. At t_1 SCR2 is off (see Fig. 10b) (Note: t_{0-} , t_0 , and t_1 are determined in the following design).

With the basic operation of each device understood, the design proceeds as follows:

- assume SCR2 interrupter consists of five parallel paths with two SCRs in series
- current/SCR = $25,000/5 = 5000$ A/SCR
- from graph of V_{on} vs current V_{on} at 5000 A = 2.8 V
- power dissipation (P_{max}) = 5000 A (2.8 V) = 14,000 W
- $R_{\theta jc}(t)$ thermal impedance (assume t_{max} for $I_{on} = 30$ msec) = 0.0040°C/W ; neglecting thermal impedance $R_{\theta chs}(t)/R_{\theta chs}$ and assuming $R_{\theta ja}(t)/R_{\theta ja}$ equals $R_{\theta jc}(t)/R_{\theta jc}$;

$$R_{\theta ja}(t) = 0.004/0.023 (0.023 + 0.006) = 0.00504^\circ\text{C/W}$$

$$R_{\theta chs}(t) = \text{transient thermal impedance case to heat sink}$$

$$R_{\theta chs} = \text{thermal impedance case to heat sink}$$

$$R_{\theta jc}(t) = \text{transient thermal impedance junction to case}$$

$$R_{\theta jc} = \text{thermal impedance case to heat sink}$$

$$R_{\theta ja}(t) = \text{transient thermal impedance junction to ambient.}$$

- calculated maximum junction temperature, $T_j = 14,000$ W (0.00504°C/W) + $40^\circ\text{C} = 111^\circ\text{C}$ ($\cong 10^\circ\text{C}$ below max)
- turn off time ≥ 50 μsec (design 100- μsec reverse bias time)

- rate of rise of forward blocking voltage $200 \text{ V}/\mu\text{sec} \leq dv/dt \leq 500 \text{ V}/\mu\text{sec}$ following a 500-A forward current, $T_j = 120^\circ\text{C}$
- $V_{\text{drm}}/V_{\text{rrm}}$ (forward/reverse blocking voltages) = 1800 V each (3600 V with two in series) maximum
- repetitive di/dt rating = 200 A/ μsec maximum.

From the circuits of Fig. 9, the following response characteristics are derived for the two circuits. The solution for SCR2 conducting in the time period t_{0-} to t_0 assuming $\frac{R_B}{4}$ (bus, SCRs, and commutation resistance negligible) is as follows:

$$0 = \frac{1}{C_c} \int I(t) dt + L_c d I(t)/dt . \quad (1)$$

Taking the derivatives of equation (1) with respect to time yields equation (2).

$$\frac{I(t)}{C_c} + L_c \frac{d^2 I(t)}{dt^2} = 0 . \quad (2)$$

A characteristic equation for solution of the above differential equation (2) is

$$D^2 + \frac{1}{L_c C_c} ,$$

$$D = \sqrt{-\frac{1}{L_c C_c}} , \quad \omega_0 \text{ (omega)} = \frac{1}{\sqrt{L_c C_c}} .$$

$$I(t) = A \cos w_0 t + B \sin w_0 t , \quad (3)$$

A and B of equation (3) are constant of integration which are determined as follows

$$I(0^-) = A = 0 ,$$

$$I(t) = B \sin w_0 t .$$

$$\frac{dI(t)}{dt} = w_0 B \cos w_0 t ,$$

$$\left. \frac{dI(t)}{dt} \right|_{t=0} = \frac{E_c(0)}{L_c} = B(w_0) ,$$

$$\therefore \frac{E_c(0)}{L_c(w_0)} = B ,$$

$$B = \frac{E_c(0)}{\sqrt{L_c/C_c}} .$$

Therefore, during the time period t_0^- to t_0 , $I(t)$ of SCR2 is

$$I(t) = \frac{E_c(0)}{\sqrt{L_c/C_c}} \sin w_0 t . \quad (4)$$

$E(t)$ across SCR2 and C_c is determined by integrating equation (4).

$$E(t) = \frac{1}{C_c} \int I(t) dt ,$$

$$E(t) = \frac{1}{C_c} \int \frac{E_c(o)}{\sqrt{L_c/C_c}} \sin(w_o t) dt + \text{constant} ,$$

$$E(t) = E_c(o) \cos w_o t . \quad (5)$$

For the time period t_o to t_1 when the SCR2 is reversed biased, the equivalent circuit (Fig. 9b) equation is

$$0 = \frac{1}{C_c} \int I(t) dt + L_c dI(t)/dt + RI(t) . \quad (6)$$

By taking the derivative of equation (6) with respect to time, equation (7) is formed.

$$\frac{1}{C_c} I(t) + L_c \frac{dI(t)^2}{dt^2} + RI \frac{dI(t)}{dt} = 0 , \quad (7)$$

The characteristic equation of equation (7) is

$$D^2 + \frac{RI}{L_c} D + \frac{1}{C_c L_c} = 0 ,$$

and the roots of the equation are

$$D_{1,2} = -\frac{RI}{2L_c} \pm \sqrt{\frac{R^2 I^2}{4L_c^2} - \frac{1}{L_c C_c}} .$$

The solution to this equation is

$$I(t) = e^{\alpha t} (A \cos w_d t + B \sin w_d t) , \quad (8)$$

$$\omega_0 = \frac{1}{\sqrt{L_c C_c}},$$

$$\alpha = -\frac{R}{2L}, \quad \omega_d = \sqrt{\omega_0^2 - \frac{R^2}{4L^2}},$$

$$\omega_d = \sqrt{\omega_0^2 - \alpha^2}.$$

With a given initial current $I(0)$, $I(0)$ equal to the coil current, the constant of integration (A and B) in equation (8) is determined as follows:

$$I(0) = A,$$

$$\therefore I(t) = e^{\alpha t} [I(0) \cos \omega_d t + B \sin \omega_d t].$$

$$\begin{aligned} \frac{dI(t)}{dt} &= \alpha e^{\alpha t} [I(0) \cos \omega_d t + B \sin \omega_d t] \\ &+ e^{\alpha t} [-I(0)\omega_d \sin \omega_d t + \omega_d B \cos \omega_d t], \end{aligned}$$

$$\begin{aligned} \left. \frac{dI(t)}{dt} \right|_{t=0} &= \frac{E_c(0) - I(0)R_l}{L_c} = \alpha[I(0)] + \omega_d B \\ &= \frac{E_c(0) - I(0)R_l}{L\omega_d} - \frac{\alpha[I(0)]}{\omega_d} = B \\ &= \frac{E_c(0) - \frac{1}{2} I(0)R_l}{L\omega_d} = B. \end{aligned}$$

With A and B of equation (8) known, the current in SCR2 and the commutation loop in the time period t_0 to t_1 is

$$\therefore I(t) = e^{-(R/2L_c)t} \left[I(0) \cos w_d t + \frac{E_c(0) - \frac{1}{2} I(0)R}{L_c w_d} \sin w_d t \right]. \quad (9)$$

By integrating equation (9) and dividing by C_c , equation (10) is formed.

$$\begin{aligned} E(t) &= \frac{1}{C_c} \int \left[I(0) e^{-(R/2L_c)t} \cos w_d t + \frac{E_c(0) e^{-(R/2L_c)t}}{L_c w_d} \sin w_d t \right. \\ &\quad \left. - \frac{\frac{1}{2} I(0)R}{L_c w_d} e^{-(R/2L_c)t} \sin w_d t \right] dt \\ &= \frac{I(0)}{C_c} \int e^{-(R/2L_c)t} \cos (w_d t) dt + \frac{E_c(0)}{C_c L_c w_d} \int e^{-(R/2L_c)t} \sin (w_d t) dt \\ &\quad - \frac{\frac{1}{2} I(0)R}{C_c L_c w_d} \int e^{-(R/2L_c)t} \sin (w_d t) dt. \end{aligned} \quad (10)$$

From integral tables⁵

$$\int e^{ax} \sin (bx) dx = \frac{e^{ax} [a \sin (bx) - b \cos (bx)]}{a^2 + b^2} \quad (11)$$

and

$$\int e^{ax} \cos (bx) dx = \frac{e^{ax} [a \cos (bx) + b \sin (bx)]}{a^2 + b^2}. \quad (12)$$

With $R_1 = R$, $C_c = C$, and $L_c = L$ and applying equations (11) and (12), SCR2 voltage equation for the time period t_0 to t_1 can be found.

$$\begin{aligned}
 E(t) = & \frac{I(o)}{C} \left\{ \frac{e^{-(R/2L)t}}{\frac{R^2}{4L^2} + w_d^2} \left[-\frac{R}{2L} \cos(w_d t) + w_d \sin(w_d t) \right] \right\} \\
 & + \frac{E_c(o)}{CLw_d} \left\{ \frac{e^{-(R/2L)t}}{\frac{R^2}{4L^2} + w_d^2} \left[-\frac{R}{2L} \sin(w_d t) - w_d \cos(w_d t) \right] \right\} \\
 & - \frac{1}{2} \frac{I(o)R_1}{CLw_d} \left\{ \frac{e^{-(R/2L)t}}{\frac{R^2}{4L^2} + w_d^2} \left[-\frac{R}{2L} \sin(w_d t) - w_d \cos(w_d t) \right] \right\} \\
 E(t) = & \frac{e^{-(R/2L)t}}{w_d^2} \left\{ + \frac{I(o)}{C} w_d \sin(w_d t) \right. \\
 & + \frac{E_c(o)}{CLw_d} \left[-\frac{R}{2L} \sin(w_d t) \right] - \frac{E_c(o)}{CLw_d} w_d \cos(w_d t) \\
 & \left. + \frac{1}{2} \frac{I(o)R}{CLw_d} \left[-\frac{R}{2L} \sin(w_d t) \right] \right\} \\
 E(t) = & e^{-(R/2L)t} \left\{ -E_c(o) \cos(w_d t) + \left[-\frac{E_c(o)}{w_d} \cdot \frac{R}{2L} \right. \right.
 \end{aligned}$$

$$+ I(o)(Lw_d) + \frac{1}{2} \frac{I(o)R^2}{Lw_d} \left] \sin(w_d t) \right\}$$

$$\text{at } t_0 = 0, \quad V_c(t) = E_c(o) .$$

$$\therefore E_c(t) = e^{-(R/2L)t} \left\{ E_c(o) \cos w_d t + \left[-\frac{E \cdot R}{2w_d L} + I(o)(Lw_d) + \frac{I(o)R^2}{2w_d L} \right] \sin w_d t \right\} . \quad (13)$$

With $I(t)$ for the second period (SCR off) known at t_1 (see Fig. 10b), $E_c(o)$ at time t_0 can be determined as follows: $I(t)$ for the time period when SCR2 is reversed bias (t_0 to t_1) is equation (9):

$$I(t) = e^{-(R/2L)t} \left[I(o) \cos w_d t + \frac{E_c(o) - \frac{1}{2} I(o)R1}{Lw_d} (\sin w_d t) \right] ,$$

with

$$R1 = 0.1 \, \Omega ,$$

$$L_c = 12 \times 10^{-6} \, \text{H (assumed)},$$

$$C_c = 500 \times 10^{-6} \, \text{F (assumed)}, \text{ and}$$

$$I(o) = 25,000 \, \text{A at } t = 100 \, \mu\text{sec (reverse bias time set at } 100 \, \mu\text{sec to ensure turn-off)}$$

$$w_o = \frac{1}{\sqrt{L_c C_c}}$$

$$w_d = \sqrt{w_0^2 - \frac{1}{4} (R_i/L_c)^2}$$

$$w_0 = 12,910 \text{ rad/sec}$$

$$w_d = \sqrt{12,910^2 - \frac{1}{4} (0.1/12 \times 10^{-6})^2} = 12,219 \text{ rad/sec}$$

$$t_1 = 100 \text{ } \mu\text{sec}$$

$$25,000 = e^{-0.1(10^{-4})/2(12 \times 10^{-6})} \left[25,000 \cos (12,219 \times 10^{-4}) + \frac{E_c(o) - 0.5 (25,000)(0.1)}{12 \times 10^{-6} (12,219)} \sin (12,219 \times 10^{-4}) \right]$$

$$E_c(o) = \left(\frac{25,000}{0.66} - 8546 \right) 0.15 + 1250 = 5650 \text{ V} .$$

With $A \cos x + B \sin x = \sqrt{A^2 + B^2} \sin (x \pm \alpha)$, $\sin \alpha = \pm \frac{A}{B}$, and the voltage across C_c at time t_0 known (5650 V), the current flowing in SCR2 in the reverse bias period t_0 to t_1 is

$$\begin{aligned} \therefore I(t) &= e^{-4166.7t} (25,000 \cos 12,219t + 30,008 \sin 12,219t) \\ &= e^{-4166.7t} [39,056 \sin (12,219t + 0.69)] \text{ A} , \end{aligned} \quad (14)$$

and the voltage across SCR2 is

$$\begin{aligned}
\therefore E(t) &= e^{-4166.7t} [5650 \cos 12,219t - (1926.6 - 3665.7 \\
&\quad - 852.5) \sin 12,219t] \\
&= e^{-4166.7t} 6216 \cos (12,219t + 0.43) \text{ V} .
\end{aligned} \tag{15}$$

With $E_c(o)$ known at time equal to t_o (5650 V), the required initial voltage at time t_{o-} and the current from t_{o-} to t_o are determined as follows:

$$I_c(t) = \frac{E_c(o)}{\sqrt{L_c/C_c}} \sin w_o t \tag{16}$$

$$E_c = E_c(o) \cos w_o t \tag{17}$$

$$w_o = 12,910 \text{ rad/sec}$$

Upon applying the known current and voltage condition to equations (16) and (17), the following results are noted:

$$25,000 = \frac{E_c(o)}{0.15} \sin 12,910 t_o \tag{18}$$

and

$$5650 = E_c(o) \cos 12,910 t_o . \tag{19}$$

By division of equation (18) by (19), the time t_o is determined as follows:

$$4.42 = 6.67 \tan 12,910 t_o ,$$

$$t_o = \frac{\tan^{-1} \left(\frac{4.42}{6.67} \right)}{12,910} = 45.3 \text{ } \mu\text{sec} .$$

Now the voltage required across C_c at the start of commutation t_{o-} is found.

$$E_c(o^-) = \frac{5600}{\cos 0.58} = 6716 \text{ V} .$$

The complete equations for the capacitor and SCR2 voltage and current during the time period t_{o-} to t_o is found by inserting $E_c(o^-)$ into equations (16) and (17) as follows:

$$E_c(t) = 6716 \cos 12,910 t , \quad (20)$$

$$I_c(t) = 44,773.3 \sin 12,910 t . \quad (21)$$

Since the initial voltage required is 6716, the major components voltage ratings are set. The capacitors used can be the standard 4800-V power factor correction capacitors. The peak voltage rating of these capacitors is 6787 V. The capacitor KVAR rating is

$$\text{KVAR} = (4800)^2 \times 2\pi \times 60 \times 500 \times 10^{-6} = 4343 \text{ KVAR} .$$

The inductor L_c can have a very large current density due to the pulsed application. To eliminate large eddy loss at high current density, the inductor should be limited to two times the normal 60-Hz design current density. The resultant KVARs for L_c are then

$$\begin{aligned}
 \text{KVAR} &= \left[(I_{\text{peak}}/\sqrt{2}) \times \frac{1}{2} \right]^2 (w_0 \times L) \\
 &= \left[(29,000/\sqrt{2}) \times \frac{1}{2} \right]^2 [377 \times 12 \times 10^{-6}] \\
 &= 475 \text{ KVARs} .
 \end{aligned}$$

Since the capacitor voltage initially is 6700 V, four SCRs with a PRV rating of 1800 V minimum should be used as the commutation switch. This will give a total of 7200 PRV rating for the switch compared with the 6700 V required. The C712 SCR has to conduct currents on a one-cycle basis. Therefore, since the device has a 20,000-A peak one-half cycle surge rating (8333 μsec) and the actual peak is only 29,000 (100 μsec), two series strings of SCR should be sufficient. By extrapolation of the forward drop curves, the voltage drop at 30,000 A is approximately two times the drop at 20,000 A, and the total energy dissipation is far less than for the rated pulse.

With the above design calculation completed, the complete SCR interrupter switch (2500 V at 25,000 A) and associated wave forms are presented in Fig. 10. These curves are generated by applying equations (20) and (21) during the time period t_{0-} to t_0 and equations (14) and (15) during the time period t_0 to t_1 .

2.2.2 Vacuum interrupter. Another viable approach is to replace the SCRs of the SCR interrupter with a vacuum interrupter. The vacuum interrupter is provided with a mechanical actuator that opens the interrupter, causing the interrupter to develop the required arcing voltage. The vacuum interrupter has many excellent advantages, which include the following:

1. they are not flammable;
2. they are capable of working reliably at extremely high voltages;
3. they can be mounted in any orientation;
4. they have a relatively small space requirement; and
5. they are less susceptible to noise.

2.2.2.1 Manufacturers. Several manufacturers make vacuum interrupters that appear to be suitable for superconducting magnetic coil protection. Three of those manufacturers are General Electric, Westinghouse, and Toshiba. Figure 11 shows a typical view of the vacuum interrupter contact arrangement with an externally applied magnetic field. This axial field appears to aid the interrupter by causing the arc to burn in many parallel spots across the contact face, thus reducing the amount of local destruction of the contact at one spot due to arcing at only one spot.

2.2.2.2 Design consideration. The vacuum interrupter, like the SCR interrupter, requires a current zero to work in dc application. This requires a commutation circuit very similar to the commutation circuit described in Sect. 2.2.1. Figure 12a presents typical commutating circuits required when using the vacuum interrupter as the circuit interrupter for coil protection. As can be seen in Fig. 12a, the interrupter is opened and the switch S is commanded to close and discharges the capacitor C. The capacitor and inductor (L) are sized to produce the required current (I_2), di/dt , and dv/dt . The requirements are based on the ratings of the interrupter. Typical ratings for the larger interrupter with current interrupting ratings of 25 to 30 kA are

$$\frac{dv}{dt} = 25 \text{ kV}/\mu\text{sec} ,$$

$$\frac{di}{dt} = 20 \text{ A}/\mu\text{sec} .$$

As can be seen, the circuit equation prior to the interrupters current zero is identical to the SCRs equations:

$$\frac{1}{C} \int I(t)dt + \frac{LdI(t)}{dt} = 0 ;$$

and after the current zero,

$$\frac{1}{C} \int I(t)dt + \frac{LdI(t)}{dt} + RI(t) = 0 .$$

The solution of this yields the following time-dependent equation:

prior to current zero

$$I(t) = \frac{E_c(0)}{\sqrt{\frac{L}{C}}} \sin w_0 t ,$$

$$E(t) = E_c(0) \cos w_0 t ;$$

after current zero and assuming the interrupter clears,

$$I(t) = e^{-(R/2L)t} \left[(I(0) \cos w_d t + \frac{E_c(0) - \frac{1}{2} I(0)Rl}{Lw_d} \sin w_d t) \right] ,$$

$$E_c(t) = E_I(t) = E_c(0) \cos w_d t + \left[\frac{ER}{2w_d L} + I(0)Lw_d - \frac{I(0)R^2}{2w_d L} \right] \sin w_d t .$$

With the above equation, the required size of L and C are determined as in Sect. 2.2.1. The period of low voltage required in the vacuum interrupter should be 20 to 30 μsec .⁶ This prevents any possibilities of restrike due to the ionized gases in the interrupter. Figure 12b shows typical wave forms which might be expected when using the vacuum interrupter and associated counter pulse system.

2.2.3 dc breaker interrupter. The third type of device available for current interruptions is a power circuit breaker. Many types of circuit breakers are available. Some of the available types of breakers are as follows:

1. oil circuit breaker,
2. air blast circuit breaker,
3. SF_6 circuit breaker, and
4. air break circuit breakers.

Since the operating voltage levels for the superconducting magnets discussed herein are 1000 to 2500 V, the one considered is the air break circuit breaker. Many of the design points are applicable to all circuit breakers. Figure 13 presents the data sheets for typical dc breakers considered for possible use as interrupters.

2.2.3.1 Basic operation. The air circuit breaker principle of operation is as follows:⁶

1. open the set of circuit breaker contact,
2. control the resulting arc inside the breaker arc chute, and
the arc chute increases the arc resistance by
 - a. increasing the length of the arc,

- b. cooling the arc, and
- c. splitting the arc in a number of series arc.

Since the superconducting magnets considered have dc current, dc breakers are required. The dc circuit breaker opens and establishes an arc in the breaker. The basic schematic of the current interruption process is shown in Fig. 14a.⁶ When the breaker starts to open, the arc is transferred to the arcing contacts by the delayed opening of these contacts. With the initial opening of the arcing contacts, the breaker current is transferred to the magnetic blow out coil. This generates a force which is equal to $F = I \times B$. I equals the current in the arc, and B is the magnetic field strength. The direction of the resultant force is toward the arc chutes. This force will cause the arc to enter the arc chute. Figure 14b shows the arc geometry for an arc in a typical breaker arc chute. As can be seen in Fig. 14b, the arc length has reached considerable length when the arc is forced into the arc chute. It is this increase length of the arc which causes the arc resistance to increase. Figure 15 shows the relationship to the arc resistance, arc voltage, and currents. As seen in Fig. 15, the arc resistance increases and causes the voltage drop across the arc to increase. This process continues until the arc voltage becomes greater than the applied system voltage, and then the arc must extinguish, as it can no longer be maintained by the system voltage.⁶

2.2.3.2 Design factor. Several factors have to be considered when choosing a dc breaker for coil protection in superconducting magnets. The first factor, which might appear trivial at first, is the

voltage rating. As discussed earlier, the normal system voltage is V_{dc} of the charging power supply. This voltage is normally very low due to the cost of providing extra kilovolt amperes just to charge the coils (charge rate amperes per second = V_{dc}/L_{coil}). When the coil is charged to its operating current, the only voltage needed is that required to overcome the resistive losses of the coil bus system. Therefore, it would appear that the continuous dc rating of the breaker would be the system operating voltage (V_{dc} power supply), typically 12 to 50 V dc. This rating is not the required voltage rating of the breaker but rather the initial dump voltage ($R_D I_0$) (see Fig. 5). For example, three coils of the LCTF facility have a dump voltage of 2500 V ($25,000 \text{ A} \times 0.1 \Omega$). Therefore, the breaker for these coils should have a continuous service rating of 2500-V minimum.

The breaker arc chute has several ratings of prime importance. The breaker arc chute has to develop a voltage greater than the initial dump voltage. If the breaker arc chute voltage rating is less than the dump voltage, the breaker could not generate an arc voltage high enough to force the current into the dump resistor. This would result in the part of coils stored energy going into the breaker and would destroy the breaker arc chute. The energy rating of the breaker arc chute must not be exceeded. The arc chute rating is normally expressed in joules. Typical joules ratings for semi-high-speed breakers are 150 to 200 kJ. Figure 16 presents a measured current and voltage profile for the dc breaker employed on the LCTF coil protection. At time t_1 the breaker starts to open, and at t_4 the breaker has successfully interrupted its current. By averaging the arc voltage and breaker

current over several intervals, the average joules deposited in the breaker can be calculated. The calculated energy of 153 kJ is below the 160 kJ rating of the breaker.

The final ratings considered are the maximum current interrupting rating and the continuous current rating. These ratings are a function of the inductance which determines the energy ($1/2 LI^2$) the breaker interrupts. Assuming the breaker energy interruptions rating is not exceeded, the current interruption rating should be a factor of two times (typically) higher than the coil current. This provides a safety margin in the breaker bracing system. Tremendous forces can be exerted on the breaker due to the coil currents. The breaker continuous current rating should be 125% of the continuous current permitted to flow through the breaker. This is set by the series resistor in the breaker (interrupter)/low voltage-high current switch circuit. The final rating which should be considered is the short time rating. This rating is important as the total coil current is transferred into the breaker by the low-voltage/high-current switch. Some delay in recovery voltage is required in the low-voltage switch to allow it to withstand the arc-voltage of the dc breaker. The breaker has to carry this current for approximately 50 msec before it starts to open.

2.3 Dump Resistor Types

As discussed in Sect. 2.1, the dump resistor function is to discharge the coil energy. Several different types of resistors are available, with proven test data to show their operational capabilities.

Many different types of dump resistors have been constructed. One type which is employed in the LCTF experiment consists of spiral

wound steel (#406) coils. These coils are sized to give the required resistance to mass ratio for a maximum temperature rise. This design uses 20 coils connected in parallel, and 4 groups of these paralleled modules are connected in series to obtain the required resistance-to-weight ratio. The approximate weight of resistive material required for a 200-MJ rated dump resistor with a 600°C temperature rise is 2400 lb. Another approach is flame cut steel plate to obtain a resistor of given length with minimum joints. Also, these types of resistors can be fabricated from aluminum to reduce construction, material, and weight costs. Figure 17 shows the two typical dump resistors discussed. Details of the dump resistor design techniques are discussed in Sect. 6.

3.0 INTERRUPTER SELECTION

3.1 Reliability Assessment

The reliability of each type of interrupter system is of prime importance due to the critical demands placed on the interrupter in protection of the superconducting magnets. The normal procedure used in predicting the reliability is to sum the failure rate (λ) of all parts within a given system to determine the system failure rate or reliability. Considerable effort is required to generate sufficient data on a part class to report a statistically valid reliability figure for that class.⁷ For this reason, the reliability assessments of the interrupters are based on an empirical method.

The component failure rate for the SCR interrupter system can be listed as follows:

λ_{SW} = failure rate of SCR switch,

λ_{CS} = failure rate of commutating switch (SCR),

λ_C = failure rate of commutating capacitor,

λ_L = failure rate of commutating inductor,

λ_{CPS} = failure rate of commutating power supply,

λ_{GPS} = failure rate of SCR gate power supply.

The total failure rate is the sum of all failure rates:

$$\Sigma \lambda_{SCR} = \lambda_{SW} + \lambda_{CS} + \lambda_C + \lambda_L + \lambda_{CPS} + \lambda_{GPS} .$$

The vacuum interrupter major component failure is as listed:

λ_V = failure rate of vacuum bottle (for example, bottle restrike after commutation),

λ_{AAS} = failure rate of vacuum bottle air actuator system,

λ_{CS} = failure rate of commutating switch (SCR),

λ_C = failure rate of commutating capacitor,

λ_L = failure rate of commutating inductor,

λ_{CPS} = failure rate of commutating power supply.

Therefore,

$$\Sigma \lambda_{VI} = \lambda_V + \lambda_{AAS} + \lambda_{CS} + \lambda_C + \lambda_L + \lambda_{CPS} .$$

The failure rate of the dc breaker interrupter is listed as follows:

λ_{AC} = failure rate of dc breaker arc chute (dc breaker restrikes and fails to interrupt current),

λ_{AS} = failure rate of breaker actuator system (solenoid and mechanical trip system).

Therefore,

$$\Sigma \lambda_{BKR} = \lambda_{AC} + \lambda_{AS} .$$

The high failure items of the SCR, vacuum, and breaker interrupter are as follows:

SCR — λ_{CS} , λ_{CPS} , λ_{GPS} , and λ_C ,

Vacuum — λ_V , λ_{CS} , λ_{CPS} , and λ_C ,

breaker — λ_{AC} .

Tests have been conducted which show that λ_{CS} and λ_V can be very high due to large current, recovery voltage, and noise that these devices are subjected to during the commutation. Also, the voltage levels of 6 to 8 kV require high voltage system whose failures increase dramatically with these high voltages. The breaker interrupter concept is a very rugged device that is capable of surviving harsh operating conditions. The breaker is not susceptible to noise, and no high voltage components are required for its operation. Also, unlike the counter-pulse systems where the interruption process is based on one counter-pulse, the breaker can restrike several times and still work reliably. This is possible because, with a restrike in the breaker, the forces exerted on the arc by the magnetic blow-out coil will increase, causing the arc to re-enter the arc chute. This process will continue until the breaker has interrupted its current or the breaker is destroyed. It is for these reasons that the breaker interrupter appears to be a more reliable device for protection of superconducting magnets.

3.2 Economic Considerations

Reliability is, of course, the major factor in selection of a coil protection scheme; the cost of the system is another factor which enters into the decision-making process. Typical costs of the three interrupters are shown in the following paragraph.

The 25,000 kA/2500 V SCR interrupter cost breakdown is as follows:

SCR switch assemble (include eight each clamps/C712 SCR)	\$ 5,500
Commutating inductor (12 μ H and 475 kVA)	9,000
Commutating capacitors (500 μ F and 4340 kVAR)	7,000
Charging power supply	1,000
Miscellaneous parts	1,000
Total	<u>\$23,500</u>

The 25,000 kA/2500 V vacuum interrupter cost breakdown is listed below.

Vacuum interrupter and actuator	\$ 9,000
Commutating inductor (assume same size as SCR)	9,000
Commutating capacitors (assume same size as SCR)	7,000
Charging power supply	1,000
Miscellaneous parts	1,000
Total	<u>\$27,000</u>

The 25,000 kA/2500 V dc breaker interrupter is a 4000-A continuous-rated single pole breaker.

dc breaker (DMD-4000)	\$12,000
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As noted in the reliability and economical considerations, the dc breaker appears to be the logical choice for the interrupter; therefore, the dc breaker with the high current low-voltage switch (see Fig. 4) is the device selected for protection of the superconducting magnets in the LCTF. The detailed design considerations for

installation in the coil protection system are discussed in the following sections.

4.0 25,000-A SWITCH/BREAKER INTERRUPTER

The switch/breaker interrupter is a very reliable approach in coil protection of high dc superconducting magnets. The reliability is improved by the simplicity of its operation. The basics of operating the combination switch and breaker are as follows:

1. Initially, the switch and breaker are closed and are carrying 23 and 2 kA, respectively.
2. The switch open solenoid is energized, and a 90-psi air supply opens the switch.
3. The switch transfers its current into the breaker.
4. After current transfer is complete and the switch is completely open, the breaker trip coil is energized via an open limit switch actuation on the high current switch.
5. The breaker then opens, develops the required commutation voltage (see Sect. 2.2.3), clears its current, and forces the coil current into the dump resistor (see Sect. 2.3).

4.1 Design Details

Particular attention was directed toward the design of a low-voltage/high current switch. The switch design details addressed were voltage isolation capabilities, current carrying and transfer capabilities, and packaging. The interrupter or dc breaker is required to carry one-tenth (2500 A) of the coil current (25,000 A) continuously, as shown in Fig. 18.

4.1.1 Mechanical layout. The low-voltage/high current switch is developed from an ITE type CR switch. The basic switch is shown in Fig. 19. The switch is composed of large copper busses with a total copper cross section of 9 in.² and movable contacts mounted on a rocker-arm assembly. To obtain the voltage isolation rating of 10 kV, the switch is placed in an oil-tight container and completely covered in a silicone-based oil. The container is fabricated from G-10. The oil used for isolation was Dow Corning DC-200 fluid. The oil provides an extremely high voltage isolation capability as the dielectric rating of this fluid is approximately 300 V/mil. A silicone-based oil was used to reduce the possibility of explosions. To obtain the required current rating of 25 kA, an oil cooling recirculating system was used to pump the oil through a heat exchanger. To determine the amount of cooling required, the resistance of the switch was estimated. Then the total I^2R losses of the switch was determined at rated current. As seen in Fig. 18, the total resistance of the switch is calculated to be $3.22 \mu\Omega$, which at 25,000 A gives a total of 2012 W dissipated in the switch. The cooling system was designed for a steady-state oil temperature of 160°F, well below the oil flash point of 572°F. With the voltage isolation and continuous current rating requirements met, the other design factor is the current transfer capability. The current transfer rate of the low-voltage/high current switch has a direct relationship to the switch life expectancy. The transfer rate was improved by designing a switch actuation mechanism, which caused the switch to open in 50 msec. The switch opening was provided by a 3-in.-diameter air cylinder with a 7-in. stroke. The 7-in. stroke causes the switch rockerarm to pivot 60°.

The 50-msec opening time caused the switch to produce a full open circuit voltage of approximately 15 V instantaneously with initial opening of the switch contacts. The current transfer rate, assuming a 10- μ H loop inductance (switch and breaker), is 1.5×10^6 A/sec. With a 25,000-A initial switch current, the total current transfer time is estimated at 12.5 msec. With all major design tasks considered for the low-voltage/high current switch, the entire coil protection device is completed by connecting the dc breaker in parallel with the switch, as shown in Fig. 20.

4.1.2 Electrical ratings. The modified low-voltage/high current ITE switch has a 25,000-A continuous current rating. The arc voltage capability of the switch is 15 V, and the voltage between contact and ground after current transfer is 10,000 V. The open time of the switch is designed for 50 msec.

The basic specification of the dc breaker, which is in parallel with the switch, is as follows:

TYPE — dc circuit breaker, one pole, stationary mounting

Rated amperes: 4000 A,

Rated volts: 2500 V,

Arc chute volts: 5000 V,

Dielectric withstand: 5000 V,

Interrupting rating: 50 kA at 100 μ H,

Short time rating: 0.5 sec (60 kA).

With the switch designed and dc breaker specified as in the previous paragraphs, an interrupter for use in superconducting magnet protection is developed with the following ratings:

Rated current: 25,000 A,

Rated voltage: 2500 V,

Rated dielectric: 5000 V.

4.2 Switch/Breaker Interrupter Testing

Due to the critical requirements placed on the interrupter and the new application for these devices, the device was tested to determine its operational integrity. Since no superconducting coil was available for testing, a circuit was developed by Los Alamos National Laboratory (LANL) which employed high voltage capacitors.⁸ The actual testing of the device was performed by an integrated test effort with LANL and Oak Ridge National Laboratory.

4.2.1 Test circuit. The basic test circuit is shown in Fig. 21. The operation of the test circuit was as follows:

1. The capacitor C was charged to a given voltage level to produce a given current 25 kA maximum ($I = V_C / \sqrt{L/C}$).
2. With the capacitor C full charged, switch S was closed and C discharged through L.
3. When the voltage across C reversed D1 turned on (forward biased), effectively shorting out C.

4. With the current flowing through D1, BP (test switch), DCCB (test breaker), and L loop, BP was commanded to open. BP opened (~ 50 msec) and transferred its current to DCCB.
5. DCCB was then opened and transferred the coil current into the R and D2 branch. D2 is forward biased when the voltage across C reverses.

4.2.2 Test results. The heat rise of the oil inside the switch was measured at 25 kA continuous current. The peak oil temperature was 140°F . This was approximately 20°F below the design value, well within the oil operating range. The open time of the switch was measured to be 51.4 msec. This open time included both the delay of the open solenoid and mechanical opening. The average arc voltage was approximately 15 V, with a total measured current transfer time of 1.4 msec. The switch was tested for 200 operations without failure.

The dc breaker transfer characteristic is shown in Fig. 22a and b. In Fig. 22a, the breaker current profile is presented. At $t = 0$ the breaker starts to open, and at $t = 10$ msec the breaker has cleared the current. Figure 22b shows the measured transient voltage profiles for the interruption. As can be noted, the restrikes in the dc breaker cause additional voltage transient peaks of 7000 to 8000 V. These restrikes were noted when the dump voltage was greater than 1500 V. This can be expected since the breaker tested (Westinghouse DMD-4000) is a 1500-V breaker. A 2500-V rated breaker would probably reduce, if not eliminate, these restrikes. Even though the breaker did restrike at dump voltages

above 1500 V, the breaker always cleared the current. The breaker was tested at several current levels and dump voltages. A summary of these tests is shown in Table I.

TABLE I
RESTRIKE DATA FOR SINGLE INTERRUPTER TESTS X/Y IS ENTRY
WHERE X = NUMBER OF TESTS AND Y = AVERAGE
NUMBER OF RESTRIKES

Interrupted current (kA)	Dump voltage (V)						
	750- 1000	1000- 1250	1250- 1500	1500- 1750	1750- 2000	2000- 2250	2250- 2500
6-10	2/0	2/0	1/0				
11-15		2/2	3/4				1/2
16-20			6/1.6	5/1.8			14/3.1
21-25				2/1		12/3.3	23/3.6
26-30				2/1.5			10/4.1

As can be seen in the above summary, the average number of restrikes increases significantly from left to right but only slightly from top to bottom. These trends indicate that the restriking is more dependent on high voltages than on high currents. Regardless of recovery voltage, restriking was somewhat more frequent with the high current interruptions.

With the test of the switch and breaker completed and no failures noted, the excellent operational integrity of this protection scheme was proved.

5.0 TRANSIENT SUPPRESSION

5.1 Transient Review

One major problem with using dc breakers as the circuit interrupter is the high voltage transients generated when the breaker interrupts the current. As shown in Fig. 22, voltage transient peaks of 7000 to 8000 V were measured across the breaker terminals during a current interruption. These high voltages could produce a possible hazardous condition by stressing the voltage isolation capabilities of the coil to the level at which breakdown of the coil insulation could occur.

Preliminary analysis of the simplified circuit model (see Fig. 7b) shows predicted voltage transient across the coil and dump resistor during a dump to be

$$V_{\text{coil}} = V_{\text{dump}} = R_D I_0 e^{(-R_D/L)t},$$

where R_D is the dump resistor (ohms), I_0 is the initial coil current (amperes), and L is the superconducting magnets (henrys). The maximum value of this transient, occurring at time zero, is the dump voltage, which is used to establish the insulation requirement for the system. The dump resistor is sized as large as possible to increase the energy removal rate of the coil during a quench, thereby reducing pressure build-up in the coil due to helium expansion. The actual maximum dump resistor resistance is usually based on a compromise between the maximum

coil isolation requirements and the maximum allowable dump system time constant (minimum R_D).

Further analysis of the circuit shows that the peak voltages that appear across the test coils in the LCTF experiment are generated by the energy stored in the bus system and dump resistor inductances when the currents in these elements are abruptly changed by the dump. Current in a section of the bus in series with the circuit breaker is interrupted, thus causing arcing in the breaker to an extent largely governed by the size of the inductance in this section of the bus work. The inductance of the bus connecting the dump resistor to the large coil and the dump resistor inductance are responsible for the $L di/dt$ voltage transient, which shows up across the coil when the dump switch opens and the large coil current transfers to the dump resistor. It is this second phenomenon which makes the dump voltage larger than $R_D I_0$. To reduce the likelihood of coil insulation breakdown, these higher voltage transients must be reduced. The transients can be reduced by employing two types of conventional suppression or snubber networks. One is a conventional RC snubber and the other utilizes a varistor. Both types of suppressors are reviewed in Sect. 5.2.

5.2 Suppression With R-C and Zn-O Networks

5.2.1 Analysis of R-C suppression. The R-C snubber scheme is a very effective method of suppressing voltage transients when breaking an inductive circuit. A general rule for suppression of high voltage transients in power systems is $1/8$ to $1 \mu\text{F}$ capacitor in series with a

1 Ω /kV resistor. This normally provides an effective suppression network across inductive loads. Of course, the suppression network should be critically damped.

With the above rule applied, a 0.5- μ F capacitor in series with a 3- Ω resistor should be a reasonable approximation of the snubber circuit for coil dump voltages of 2500 V. By reviewing the equivalent circuit of the superconducting magnets (Fig. 23a) and the transient profile of Fig. 22, it can be determined that the above values for the snubber are not the required values. With the breaker arc simulated as a variable resistance (R_6), the distributed bus and resistor inductance neglected, and the coil represented as a constant current source, the simplified circuit of Fig. 23b is generated. The snubber reduces the transient voltages by diverting a portion of the coil current from R_T branch when the breaker opens (R_6 increases rapidly). With a 3- Ω resistor used as the snubber resistance, a very small quantity (less than 10%) of the coil current [$I_s \cong I(t) (0.033)$] will transfer into the snubber. Therefore, R_s will have to be 0.02 Ω or less to effectively shunt the breaker during the initial open transient. The value of C_s is also in question. With $C_s = 0.5 \mu\text{F}$ and $R_s = 0.02 \Omega$, the time constant of the snubber system is approximately

$$\tau_{\text{snubber}} = 1/R_s C_s \cong 100 \times 10^6 \text{ sec} .$$

Figure 21b shows measured transients in the 0.1- to 2-msec range. Therefore, a snubber with a time constant of 40×10^6 sec would be ineffective. Actually a snubber at 1000 sec would be effective.

Assuming R_s equals 0.02Ω , C_s has to be 0.05 to 0.005 F to produce a snubber circuit with an effective time constant.

With the above values approximated for the snubber, the effectiveness of the snubber is shown through a computer simulation.

5.2.2 Computer model. The computer model used to simulate the transient portion of the breaker open/transfer characteristics, the Super Sceptre Computer Program, is employed.^{9,10} The computer model circuit is shown in Fig. 24. The elements of the model represent actual coil parameters and associated bus impedances. R_6 is the resistance value used to simulate the breaker transient arc resistance. The arc resistance profile used in the model for the 2500-V dump voltage coil is shown in Fig. 25. The arc resistance used in the model without suppression was chosen so the voltage transients calculated by the computer matched those of the measured transients (see Fig. 22b).

5.2.3 Computer program and results

5.2.3.1 No suppression. As stated previously, a computer model and program were developed which simulated the arc voltage profile of Fig. 22b. The basic computer model for simulation of the coil dynamic response is shown in Fig. 24. The snubber circuit was omitted for the computer program for the simulation without suppression. The following program is the computer program developed for the coil without suppression:

```
CIRCUIT DESCRIPTION
ELEMENTS
R6,2-1=TABLE 1 (TIME)
R1,2-3=0.000100
```

```

R2,1-6=0.000040
R3,7-5=0.1
C1,2-1=0.000001
L1,6-5=0.000030
L2,4-3=0.000060
L3,4-7=0.000100
L4,4-5=2.05
DEFINED PARAMETERS
DPBKR=X2(VR6*IR6)
DPDMP=X3(VR3*IR3)
OUTPUTS
VL4,VR6,IR6,PLOT WOOD
PBKR,PDMP,PLOT JOULES
DPBKR,DPDMP,PLOT WATTS
IL4,IR3
INITIAL CONDITIONS
IL1=25000
IL2=25000
IL3=0.0
IL4=25000
FUNCTIONS
TABLE 1
0, 0.0001
0.01, 0.02
0.0113, 0.15
0.0118, 0.08
0.0121, 0.17
0.013, 0.08
0.0135, 0.15
0.0141, 0.1
0.015, 4.0
0.0163, 0.001
0.0176, 0.01
0.018, 100
RUN CONTROLS
PLOT INTERVAL=0.000169
STOP TIME =0.020
END

```

END OF PRE-PROCESSOR.

The plotted output is shown in Appendix B, "Transient without Suppression." From review of the computer plots, the following items are noted:

VOLTS PEAK ACROSS MAGNET (VL4) = 5200 V ,

VOLTS PEAK ACROSS BREAKER (R6) = 7400 V .

Joules deposited in the breaker arc chute (18 msec) are equal to 180 kJ. With the program output approximating the measured values, the R-C circuit was then added to the model.

5.2.3.2 Suppression with the R-C snubber. The series R-C snubber was connected directly across the breaker. This appears across R6 in the computer model (see Fig. 24). The snubber consisted of a 0.02- Ω resistor along with a 0.005-F capacitor. The computer program is as follows:

```
CIRCUIT DESCRIPTION
ELEMENTS
R6,2-1=TABLE 1 (TIME)
R1,2-3=0.000100
R2,1-6=0.000040
R3,7-5=0.1
R4,2-8=0.02
C1,8-1=0.005
L1,6-5=0.000030
L2,4-3=0.000060
L3,4-7=0.000020
L4,4-5=2.05
DEFINED PARAMETERS
DPBKR=X2(VR6*IR6)
DPDMP=X3(VR3*IR3)
DPCAP=X1(VC1*IC1)
OUTPUTS
VL4,VR6,IR6,PLOT WOOD
PBKR,PDMP,PCAP,PLOT JOULES
DPBKR,DPDMP,DPCAP,PLOT WATTS
IL4,IR3
INITIAL CONDITIONS
IL1=25000
IL2=25000
IL3=0.0
IL4=-25000
FUNCTIONS
TABLE 1
```

```

0, 0.0001
0.01, 0.02
0.0113, 0.15
0.0118, 0.08
0.0121, 0.17
0.013, 0.08
0.0141, 0.1
0.015, 4.0
0.0163, 0.001
0.0176, 0.01
0.018, 100
RUN CONTROLS
PLOT INTERVAL=0.000169
STOP TIME =0.020
END

```

END OF PRE-PROCESSOR.

The results are plotted in Appendix C, "Transients with R-C Snubber Networks." From review of the computer plots, the following are noted:

VOLTS PEAK ACROSS MAGNET (VL4) = 3200 V,
 VOLTS PEAK ACROSS BREAKER (VR6) = 3900 V,
 JOULES DEPOSITED IN BREAKER ARC CHUTE = 155 kJ (at 18 msec),
 JOULES DEPOSITED IN CAPACITOR C_s = 38 kJ (at 18 msec).

Obviously, the R-C network is a reliable solution to the transient suppression problem; however, due to the enormous high voltage capacitance (5 to 50 mF) required, the R-C network would be impractical. Due to the voltage levels required, a 4.8-kV (rms) capacitor system would be the minimum safe capacitor voltage rating. If system costs and size requirements are not of prime importance, this R-C network would provide safe suppression. If size and cost are of major concern, the use of a zinc-oxide (Zn-O) varistor provides an alternative solution.

5.2.3.3 Suppression with Zn-O varistors. After analysis of the RC network, it was discovered that the value of high voltage capacitance needed to effectively clamp these voltages was extremely high. In fact, the required amount of approximately 5 mF was impractical from an engineering view point. The second suppressor considered was the Zn-O (zinc-oxide) varistor. Analysis of the characteristics of this type of device has shown it to be a reliable component for suppression of the transients in the LCTF coils.

The suppressor scheme for a 2500-V dump voltage coil consists of two Panasonic Zn-O varistors, part number ERZ-A80JK112C, in series. The type "C" device consists of four basic ERZ-A80JK112 units in parallel. The volt-ampere curves are shown in Fig. 26 for the basic ERZ-A80JK112 device.¹¹ These curves show that the maximum clamping voltages for this device vary from 1130 V at 1 mA to 3150 V at 10,000 A. With two such devices in series, the voltage ranges above are multiplied by two. An individual type "C" device has a 40-kJ surge rating.

Figure 27 presents the V-I curve for a typical varistor. As can be seen, the normal varistor operation region is described as $I = K V^a$.¹² K is a constant which varies with each device, and "a" is the exponent that defines the degree of non-linearity. The "a" term is defined as follows:

$$a = \frac{\log (I_2/I_1)}{\log (V_2/V_1)} .$$

To represent the varistor, the K and "a" terms were determined from the basic ERZ-A80JK112 device curve (see Fig. 26) to be as follows:

$$a = 25.5 ,$$

$$K = \frac{1}{1610} \quad (\text{note: } K = IV^{-a}) .$$

With these values known, the formula that simulates the varistor voltage vs current for device ERZ-A80JK112 is as shown:

$$V_{\text{VAR}} = 1610 I_{\text{VAR}}^{1/25.5} + 0.0845 I_{\text{VAR}} ,$$

$$R_{\text{VAR}} = 1610 I_{\text{VAR}}^{-0.961} + 0.0845 ,$$

$$V_{\text{VAR}} = \text{total voltage across varistor} ,$$

$$I_{\text{VAR}} = \text{current in varistor} .$$

Note: The last term in the equation, $0.0845 I_{\text{VAR}}$, represents the voltage drop due to internal resistance.

The above equation can be compared with the actual curve (Fig. 25) to confirm the exactness of the equation.

The equation used in the computer model for the varistor device ERZ-A80JK112C was as follows:

$$2500\text{-V dump voltage: } V_{\text{VAR}} = 3050 I_{\text{VAR}}^{1/25.5} + 0.0422 I_{\text{VAR}} ,$$

$$R_{\text{VAR}} = 3050 I_{\text{VAR}}^{(-0.961)} + 0.0422 .$$

The computer model with the Zn-O varistor is as follows:

CIRCUIT DESCRIPTION

ELEMENTS

R6,2-1=TABLE 1 (TIME)

RX,2-1= $X4(2*((1525*IRX**(-0.961))+0.0211))$

R1,2-3=0.000100

R2,1-6=0.000040

R3,7-5=0.10

C1,2-1=0.000001

L1,6-5=0.000030

L2,4-3=0.000060

L3,4-7=0.000100

L4,4-5=2.05

DEFINED PARAMETERS

DPBKR=X2(VR6*IR6)

DPDMP=X3(VR3*IR3)

DPVAR=X1(VR6*IRX)

OUTPUTS

VL4,VR6,IRX,IR6,PLOT WOOD

PVAR,PBKR,PDMP,PLOT JOULES

DPVAR,DPBKR,DPDMP,PLOT WATTS

VRX,PLOT(IRX)

RX,IL4,IR3

INITIAL CONDITIONS

IL1=25000

IL2=25000

IL3=0.0

IL4=25000

FUNCTIONS

TABLE 1

0, 0.00001

0.01, 0.02

0.0113, 0.15

0.0118, 0.08

0.0121, 0.17

0.013, 0.08

0.0135, 0.15

0.0141, 0.1

0.015, 4.0

0.0163, 0.001

0.0176, 0.01

0.018, 100

RUN CONTROLS

PLOT INTERVAL=0.000169

STOP TIME =0.020

END

END OF PRE-PROCESSOR.

The results are plotted in Appendix D, "Transients with Varistor Snubber Network."

5.3 Suppression Summary

The Zn-O varistors concept would seem to be the most economical and reliable device from an engineering view point. The size required for installation is minimum, and the cost is small compared to 50 mF of high voltage capacitance.

The voltage transients due to the breaker opening can be greatly reduced by use of the varistors previously described. The calculated transients, even with the varistor, are considerably higher than the dump voltage. The transients with an inductance of 100 μ H assumed in the dump resistors cause transients of 750 V for the 2500-V dump voltage. These calculated transients are much greater than those to be anticipated in actual dump circuit, because the inductance in the dump resistor circuit will be lower than the assumed value of 100 μ H. Also, the simulations used as a driving function are the worst-case voltage transients measured in the LANL tests. If the 100- μ H inductance (L3) of the model is reduced to 20 μ H, the resulting voltage peaks are only slightly above the 2500-V dump voltage coils. The 20 μ H is a more accurate value for lumped inductance of the dump resistor and associated bus. The calculated voltage peak for this case is 2700 V for a 2500-V dump voltage.

6.0 DUMP RESISTOR DESIGN CONSIDERATIONS

To complete the coil protection system for a superconducting magnet, a detailed design and reliability assessment of the EDR of Fig. 5 must be completed. As discussed in Sect. 2.3, the EDR increases the removal rate of the coil energy during a quench. The EDR has to be design reliable to ensure coil protection. If the EDR was destroyed during a coil dump, the resulting over voltages that would be impressed across the coil would destroy the coil. Also, other system components would be destroyed due to this over voltage.

6.1 Basic Design Techniques

The object of the dump resistor design is to develop a dump resistor with the required mass and resistance. The mass is determined by equating initial energy in the coil ($1/2 LI_0^2$) to the maximum temperature rise. The resistance is fixed by the maximum allowable coil terminal voltage. The latter is normally determined by the coil manufacturer. With the above two parameters fixed, the dump resistor design proceeds as follows:

$$R \text{ (ohms)} = 0.1 \, \Omega \text{ (given),}$$

$$\text{MJ (} 10^6 \text{ joules)} = 200 \text{ MJ (given).}$$

Assuming an adiabatic temperature rise during a coil discharge, the volume of resistance material required for a given temperature rise is

$$\text{volume (cubic centimeters)} = \frac{\text{energy (joules)}}{4.2 \text{ J/cal} \times \text{density} \times \text{specific heat} \times \Delta T},$$

density — grams per cubic centimeter of resistive material,

specific heat — calories per gram-degrees centigrade of resistive material,

ΔT — maximum allowable temperature rise (degrees centigrade).

The required area of the resistance material is then determined as follows:

$$\text{area (centimeters squared)} = \left[\frac{\text{volume (cubic centimeters)}}{\text{resistance/resistivity}} \right]^{1/2},$$

resistance — ohms at 20°C (required resistor resistance),

resistivity — ohms - centimeters at 20°C (resistivity of resistance material).

With the volume and area of the resistor known, the required length of resistance material is determined:

length (centimeters)

$$= \frac{\text{area (centimeters squared)} \times \text{resistance (ohms at 20°C)}}{\text{resistivity (ohms - centimeters at 20°C)}}.$$

The basic requirements of the dump resistor have been set by the previous three formulas. Assuming carbon steel is the resistance material, the volume, area, and length of the resistor for 600°C temperature rise is:

volume (centimeters squared)

$$= \frac{200 \times 10^6 \text{ J}}{4.2 \text{ J/cal} \times 7.85 \text{ g/cm}^3 \times 0.107 \text{ cal/cm}^2 \cdot ^\circ\text{C} \times 600^\circ\text{C}}$$

$$= 94,488 \text{ cm}^3 ;$$

$$\text{area (centimeters squared)} = \left[\frac{94,488 \text{ cm}^3}{0.1 \text{ } \Omega / (12 \times 10^{-6} \text{ } \Omega \cdot \text{cm})} \right]^{1/2}$$

$$= (11.34 \text{ cm}^4)^{1/2}$$

$$= 3.37 \text{ cm}^2 ;$$

$$\text{length (centimeters)} = \frac{3.37 \text{ cm}^2 \times 0.1 \text{ } \Omega}{12 \times 10^{-6} \text{ } \Omega \cdot \text{cm}}$$

$$= 28,962 \text{ cm} .$$

With the volume, area, and length of the resistor determined, the final construction details can now be determined.

6.2 200-MJ Construction Details

Several types of resistors are available which will meet the requirements of the 0.1- Ω 200-MJ resistor. As discussed in Sect. 2.3, two types available are the plate- and spiral-type construction. The design should have parallel paths to improve the reliability of the resistor. If a resistor has four parallel paths for current flow and one path becomes open during a dump, the coil over-voltage would be limited to 132% of the coil normal dump voltage. This would certainly

prevent coil failure due to an open circuit in the dump resistor. Assuming the plate-type construction is chosen, the construction consists of several plates in parallel to achieve the required mass and resistance ratio. If carbon steel plates of 137.2 cm $\times$ 228.6 cm $\times$ 0.64 cm are selected as the resistance material, the detail assembly can be determined.

As seen in Fig. 28, the required volume, area, and length of steel is shown. For reliability, the resistor is subdivided into four modules of 23,622 cm³ and 0.4 Ω each. The required cross section, area, and length for one module is

$$\text{area (module 1-4)} = 3.37 \text{ cm}^2 \left(\frac{0.1}{0.4} \right)^{1/2} = 1.69 \text{ cm}^2 ,$$

$$\text{length (module 1-4)} = 28,062 \text{ cm} .$$

Since the width of the plate is set at 0.64 cm, the required cross-sectional length is

$$\text{length} = \frac{1.69 \text{ cm}^2}{0.64 \text{ cm}} = 2.64 \text{ cm} .$$

With the plate cutting detail as shown in Fig. 29a, the number of plates required per module is equal to

$$\text{plates/module} = \frac{\text{total resistance length required}}{\text{total resistance length/plate}} ,$$

$$\begin{aligned}
 \text{total resistance length/plate} &= \text{mean resistance length/path} \times \\
 &\quad \text{number of paths/plate} \\
 &= 134.56 (70) = 9419.2,
 \end{aligned}$$

$$\text{plates/module} = \frac{28,062}{9419.2} \cong 3 \text{ plates} .$$

With the number of plates per module defined, the resistor is connected as shown in Fig. 29b. Of course each plate will require an isolation structure, bracing for structure, and magnetic forces. The basic resistor design has been completed.

One additional design parameter which is very important and requires review is the inductance of the dump resistor. Figure 29 shows the current paths for a typical plate within the dump resistor. As can be seen, the field that produces a flux on one leg of the plate is cancelled out by the flux in the other. The currents flow in opposite directions. Since the flux linkages are cancelled, the inductance of the resistor is practically zero. This low inductance value is desired because this will reduce transient voltage and improve commutation time.

7.0 CONCLUSION

This thesis has shown particular design considerations of the coil protection system. This type of system will provide the sole protection of superconducting magnets on tokamak fusion reactors of the future. By employing a reliable coil protection scheme, power outages due to malfunctions of those reactors will be minimized.

Each component of the protection scheme has to be designed with reliability and functional adequacy of prime importance. As was noted, a single failure in the interrupter or dump resistor must be avoided. This can be avoided by simply providing redundant interrupters and parallel current paths in the dump resistor. Three major types of interrupters are available for current interruption. They are

1. SCR interrupter,
2. vacuum interrupter, and
3. dc breaker interrupter.

Two types of suppressor network are available for elimination of high voltage transient during current interruption by the dc breaker. The dump resistor can be constructed from aluminum, carbon steel, or stainless steel. Two types of dump resistor construction are available for the engineer. They are

1. plate type construction and
2. spiral wound construction.

In summary, a reliable coil protection can be designed when care is exercised in selection of each component, as shown in Table II.

TABLE II
COIL PROTECTION SYSTEM SELECTION SUMMARY

Element	Criteria	Advantages	Disadvantages
Current interrupter dc breaker	Transfers coil current and generates voltage greater than coil dump voltage	Rugged, minimum components, minimum costs, highest reliability	High voltage transient
Plate-type EDR construction	Limits coil overvoltage and dissipates energy safely	Minimum inductance, redundant design, minimum joints	Small allowable delta T due to support system
Transient suppressor zinc-oxide varistor	Limits coil overvoltage and safely dissipates energy deposited in varistor	Minimum cost, minimum size, excellent transient response	Possible short failure mode

LIST OF REFERENCES

LIST OF REFERENCES

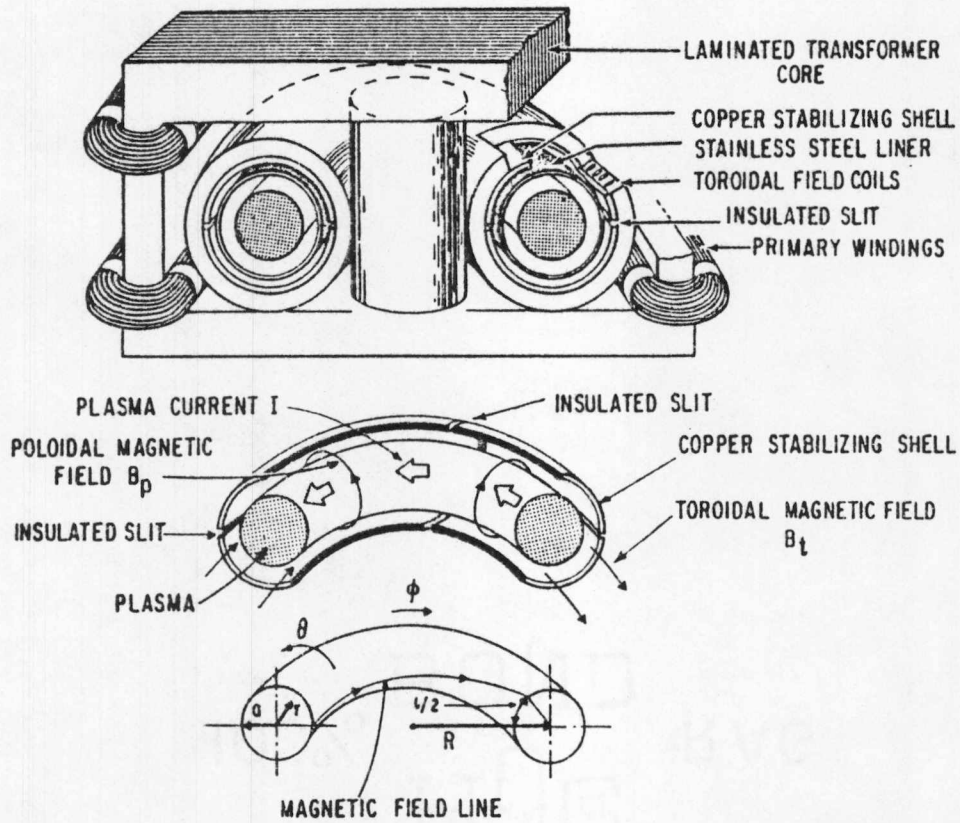
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- ¹⁰Sedore, S. R., and Sents, J. R., "Sceptre Support II," No. AFWL-TR-69-77, Vol. 1, IBM Corporation, 1979, pp. 1-150.
- ¹¹Panasonic, "High Energy "ZNR" Transient/Surge Absorbers, Type J," RZ-CA06-1, pp. 2-9.
- ¹²General Electric Company, "Transient Voltage Suppression," 3rd edition, 1982, p. 48.

APPENDIXES

APPENDIX A

General Figures and Illustrations

Appendix A groups together all the figures and illustrations referenced in the text of this report. The figures appear in numerical order as they are mentioned in the text.



Basic tokamak system: a toroidal plasma confined in a helical magnetic field comprised of a strong, externally generated toroidal field and a poloidal field generated by the current in the plasma.

Fig. 1. Typical tokamak reactor profile.

GENERAL ELECTRIC COIL DESIGN

COIL PRESSURE vs TIME

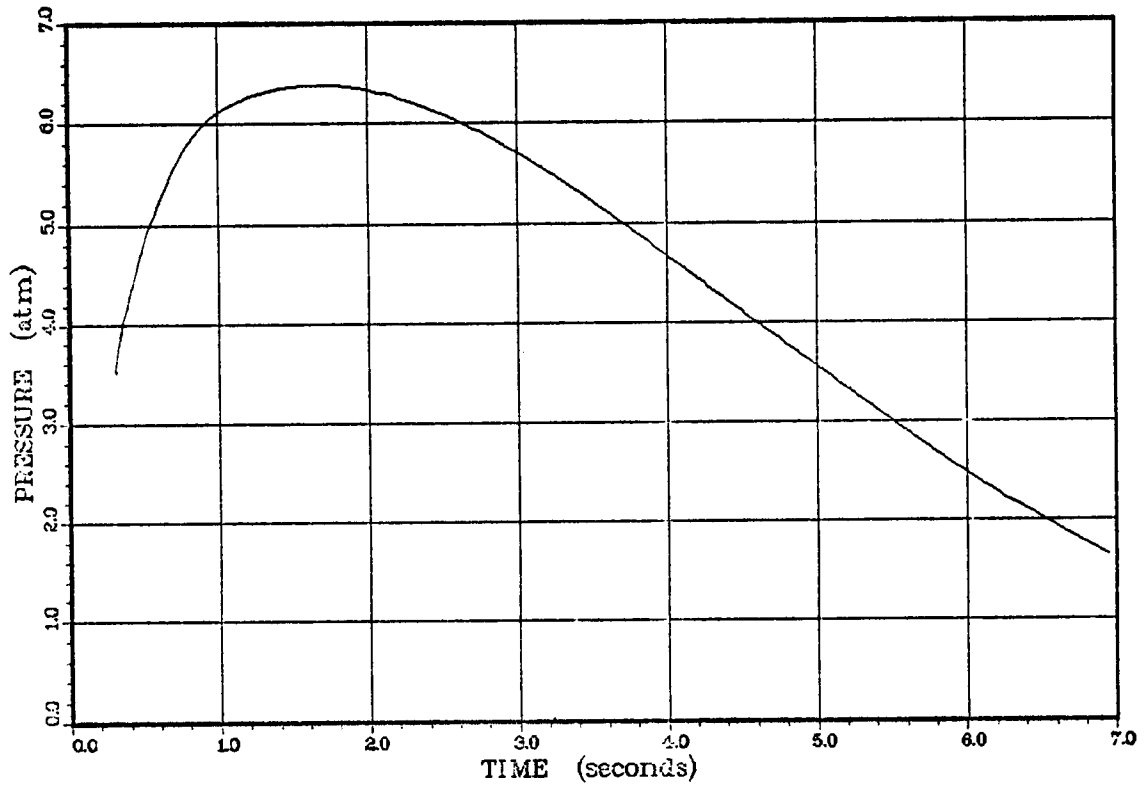


Fig. 2. Typical coil pressure vs time for a coil quench.

GENERAL ELECTRIC COIL DESIGN

HELIUM TEMPERATURE vs TIME

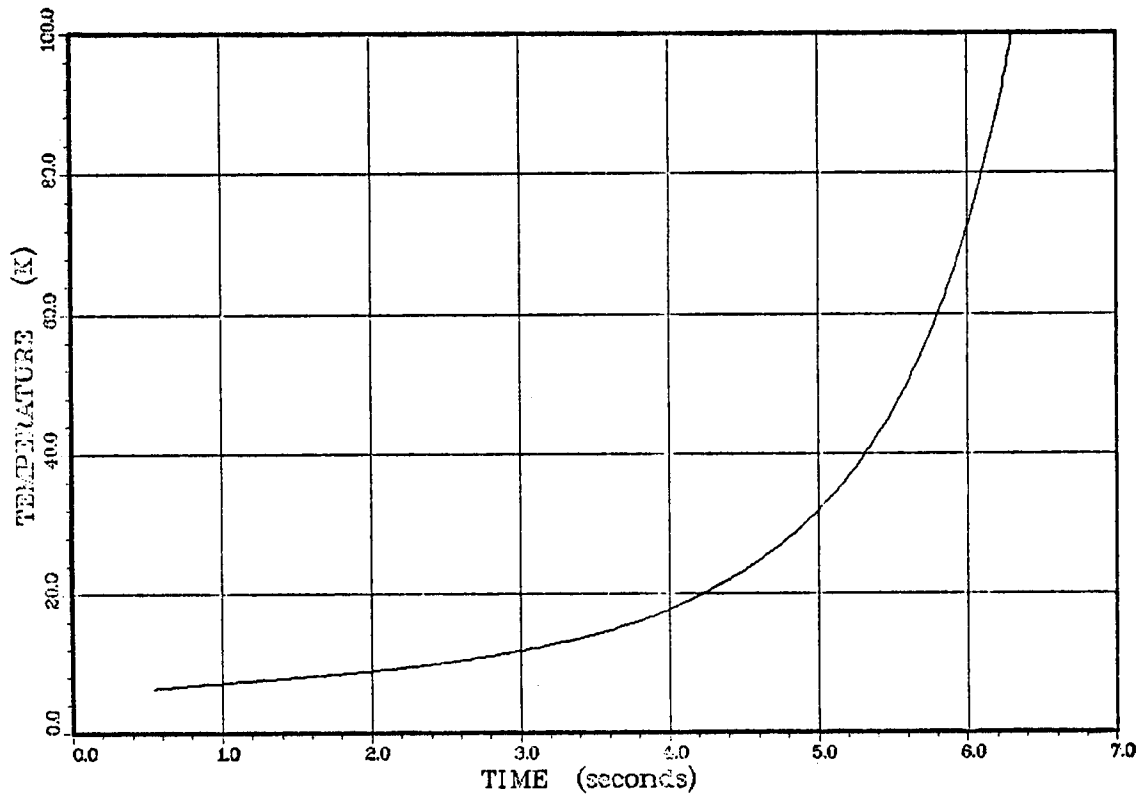
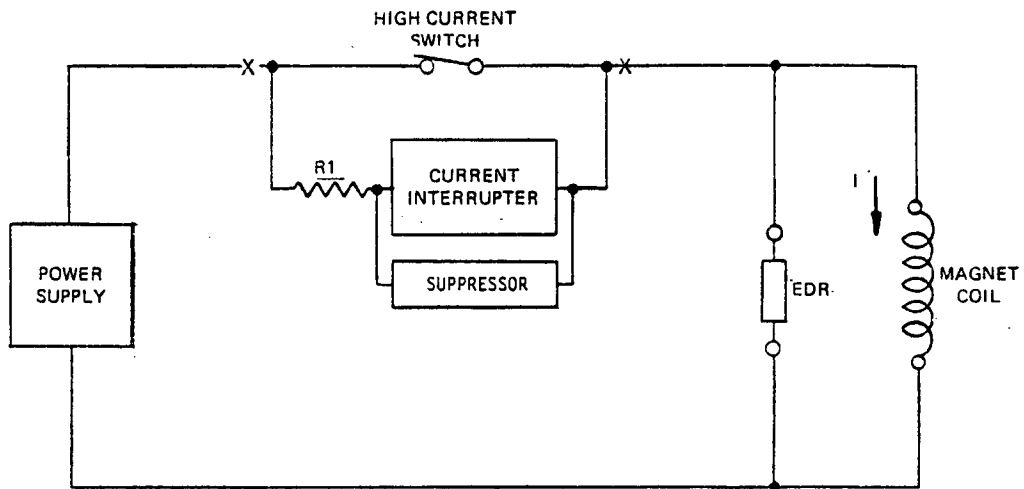
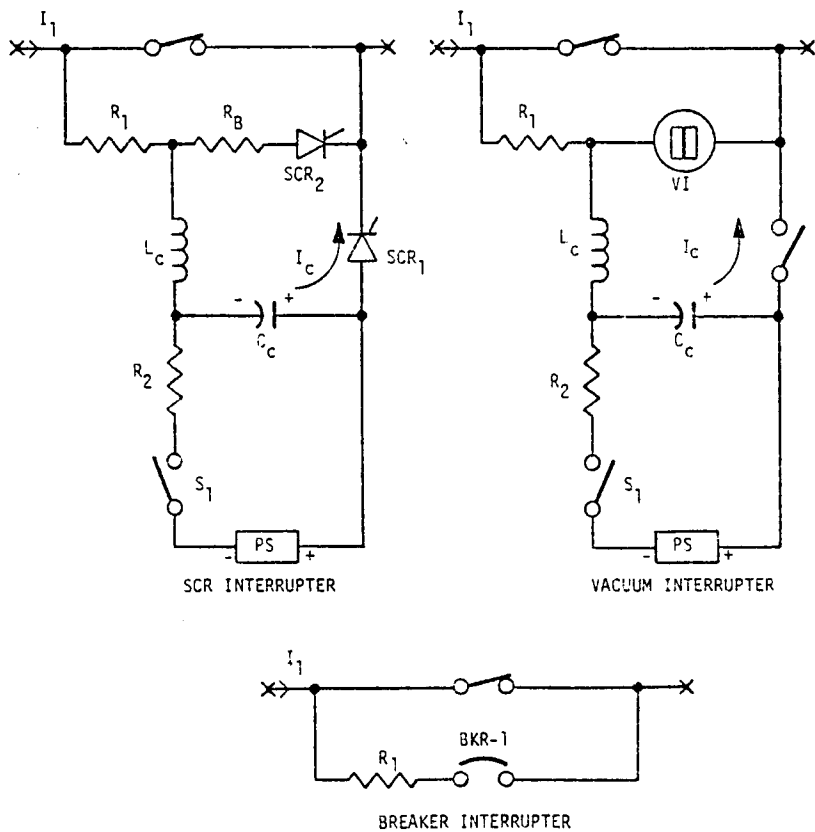


Fig. 3. Typical helium temperature vs time during a coil quench.



a. Emergency dump circuit



b. Interrupter circuits

Fig. 4. Emergency dump and interrupter circuits.

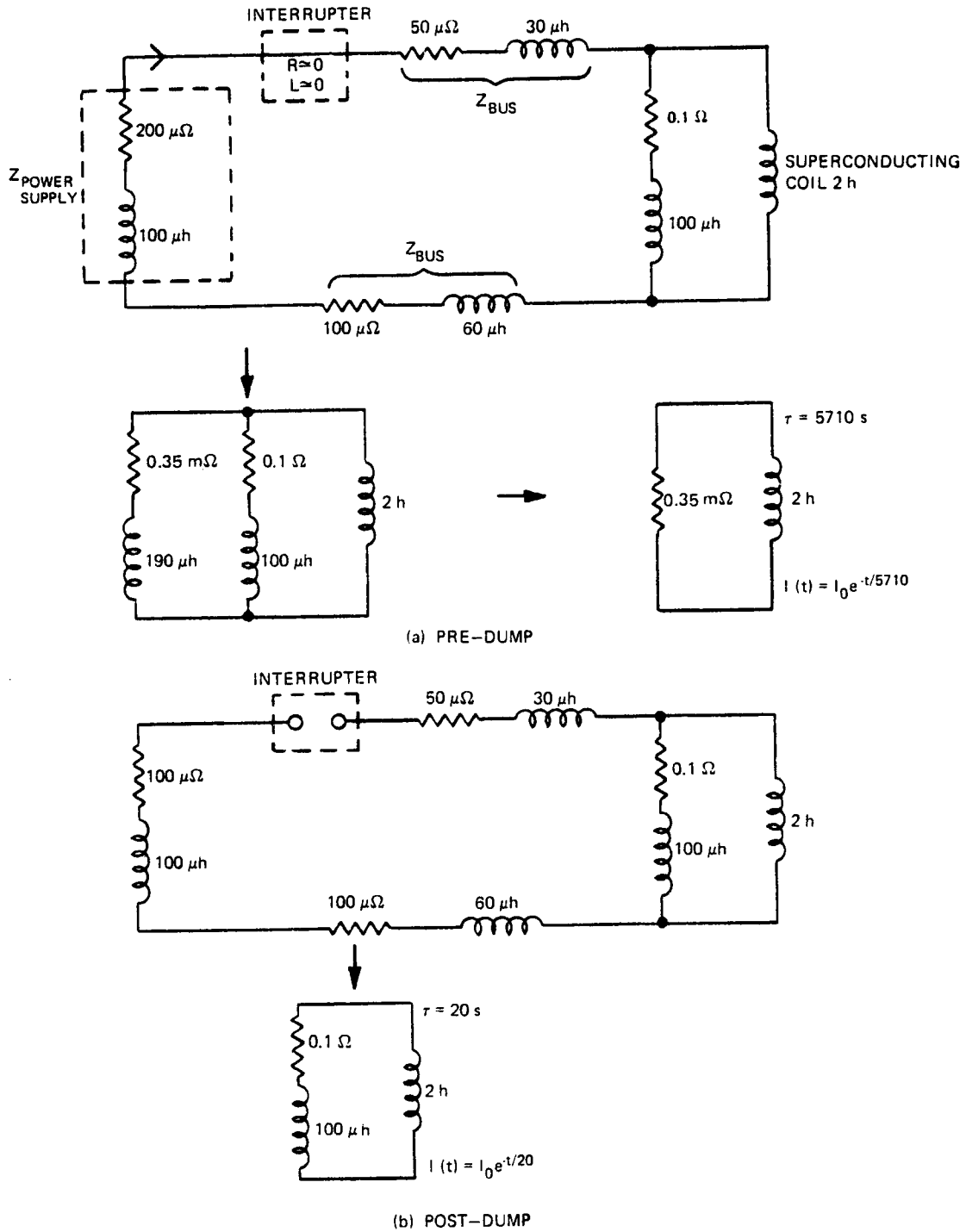
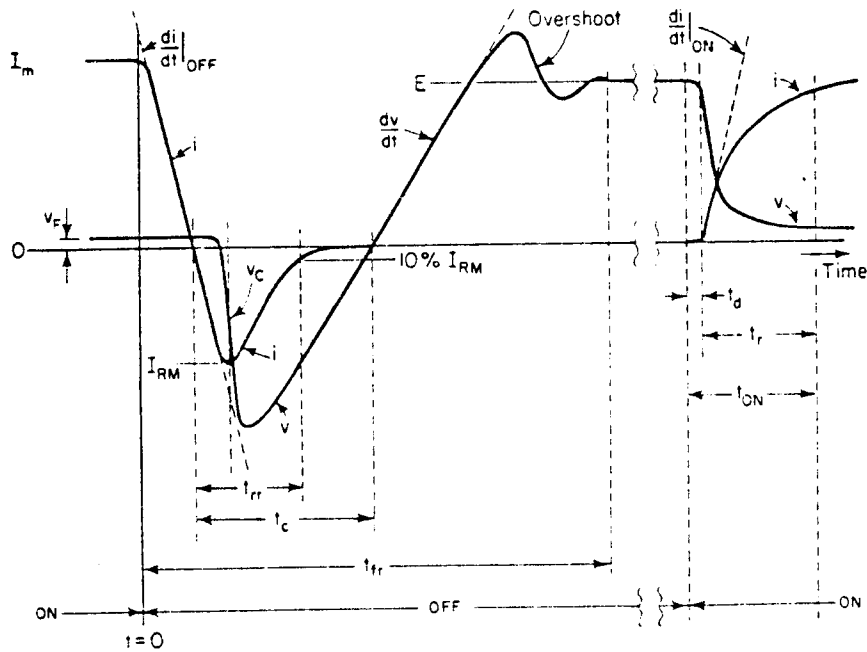
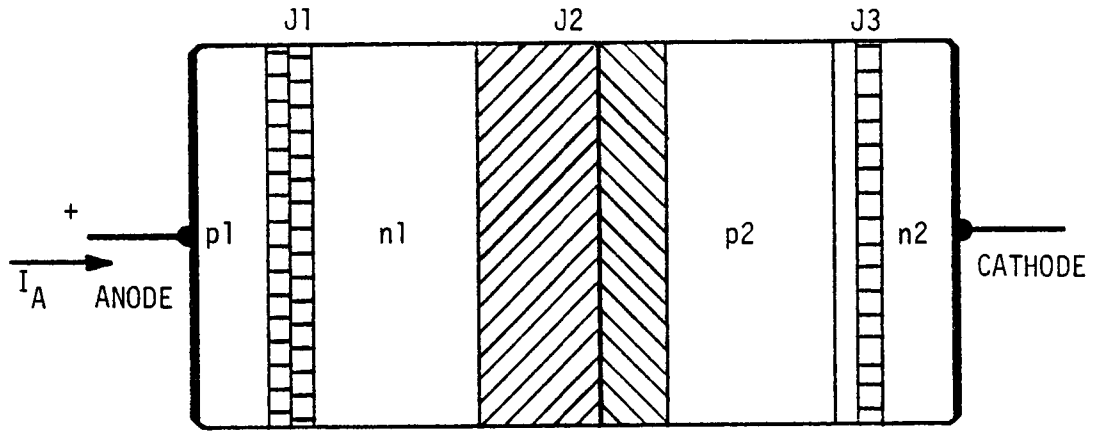


Fig. 5. Pre- and post-dump equivalent circuits.

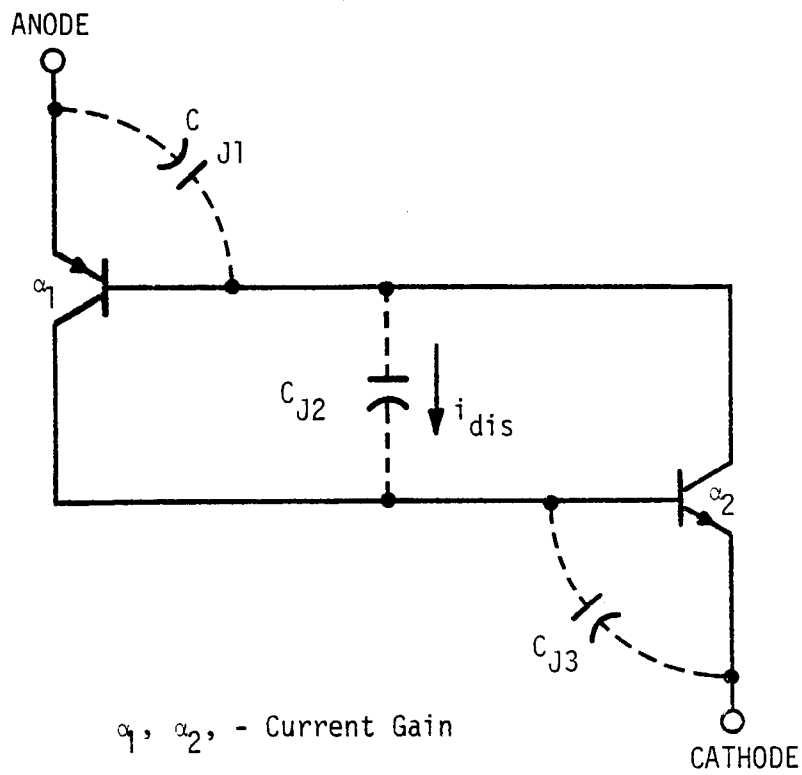


t_{rr}	Reverse recovery time	t_d	Delay time of SCR
t_c	Circuit turn-off time (Time SCR is reverse-biased by circuit)	t_r	Rise time of SCR
I_m	Peak forward anode current at time of initiation of turn-off at $t = 0$	t_{on}	Turn-on time of SCR
V_F	SCR on voltage (forward voltage drop)	T	Period of output waveform
E	Forward blocking voltage applied to SCR by circuit	t_{fr}	Circuit forward recovery time
		dv/dt	Initial rate of application of forward blocking voltage
		I_{RM}	Peak reverse current

Fig. 6. SCR turn-off and turn-on intervals.



a. SCR junction model



b. SCR two-transistor analogue

Fig. 7. SCR junction and two-transistor analogue.

MAXIMUM ALLOWABLE RATINGS

TYPE	V_{ORM}/V_{RRM}^I REPETITIVE $T_J = -40^{\circ}\text{C}$ to $+125^{\circ}\text{C}$	V_{ORM}/V_{RRM}^I REPETITIVE $T_J = 0^{\circ}\text{C}$ to $+125^{\circ}\text{C}$	TRANSIENT PEAK REVERSE VOLTAGE, V_{RRM}^I $T_J = -40^{\circ}\text{C}$ to $+125^{\circ}\text{C}$
C712L	2000 Volts	2100 Volts	2100 Volts
C712PT	1900	2000	2000
C712PN	1800	1900	1900
C712PS	1700	1800	1800
C712PM	1600	1700	1700
C712PE	1500	1600	1600

Consult factory for lower rated voltage devices.

Peak One-Cycle Surge On-State Current, I_{TSM} (8.3 msec)	20,000 Amperes
Maximum Rate-of-Rise of Anode Current Turn-On Interval (Switching From 1200 Volts)	800 A/ μ sec
Repetitive di/dt Rating ²	200 A/ μ sec
I^2t (for fusing) (at 8.3 milliseconds)	1,000,000 Ampere ² Seconds
Peak Gate Power Dissipation, $P_{G(M)}$	100 Watts
Average Gate Power Dissipation, $P_{G(AV)}$	5 Watts
Peak Reverse Gate Voltage, V_{CRM}	20 Volts
Storage and Operating Temperature, T_{STG} and T_J	-40°C to +125°C
Mounting Force Required	5000 Lb. + 1000 - 0 Lb. 22.2 KN + 4.4 - 0 KN

NOTES:

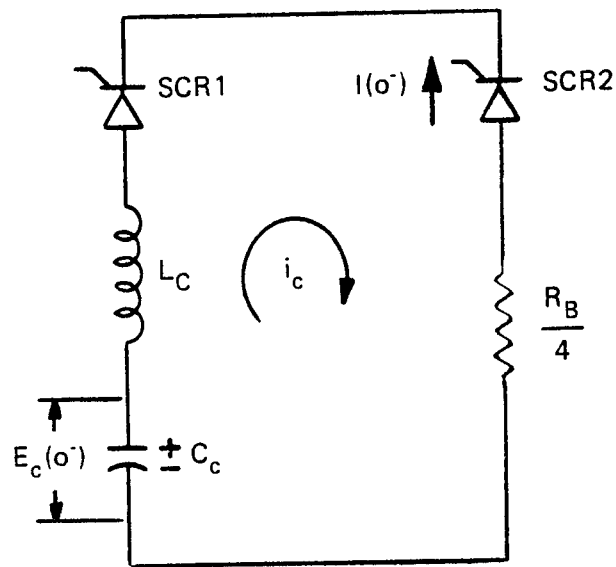
¹ 10 msec voltage sine wave.

10 msec voltage sine wave.

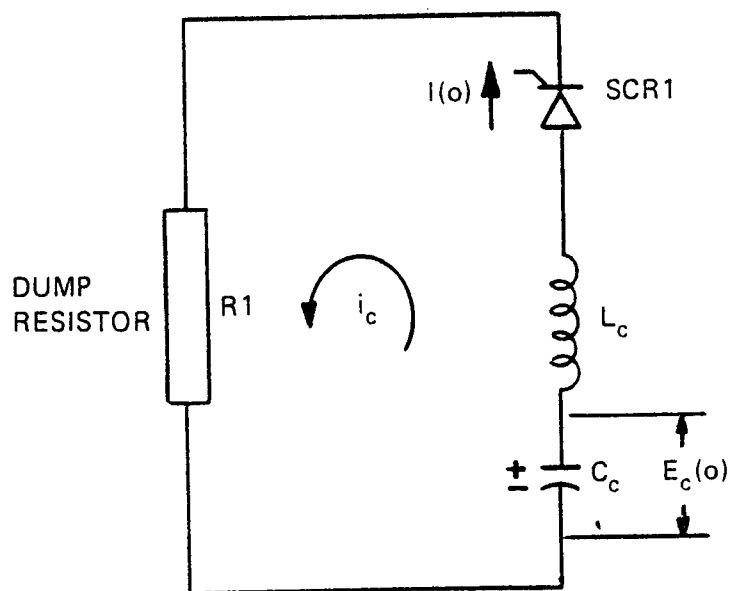
CHARACTERISTICS

C712	TEST	SYMBOL	MIN.	TYP.	MAX.	UNITS	TEST CONDITIONS
	Peak Reverse and On-State Blocking Current	I_{DRM} and I_{RRM}	—	20	∞	mA	$T_J = +125^\circ\text{C}$, $V = V_{DRM} = V_{RRM}$
	Effective Thermal Resistance, Junction-to-Case	$R_{\theta JC}$	—	—	.023	$^\circ\text{C/Watt}$	Double-Side Cooled (DC)
	Critical Linear Rate-of-Rise of Forward Blocking Voltage (Higher values may cause device switching)	dv/dt	500	—	—	V/ μsec	$T_J = +125^\circ\text{C}$, $V_{DRM} = .80$ Rated V_{RRM} Gate Open.
	Delay Time	t_d	—	1.5	—	μsec	Switching from 140 Volts, 30 Volt, 10 Ohm Gate 0.5 μsec Rise Time. $T_J = 25^\circ\text{C}$
	Gate Pulse Width Necessary To Trigger		—	—	10	μsec	$T_J = 25^\circ\text{C}$
	Gate Trigger Current	I_{GT}	—	120	—	mAdc	$T_C = 25^\circ\text{C}$, $V_D = 10$ Vdc, $R_L = 3$ Ohms $T_C = +125^\circ\text{C}$, $V_D = .5 \times \text{Rated}$, $R_L = 1000$ Ohms
	Gate Trigger Voltage	V_{GT}	—	3.0	—	Vdc	$T_C = 0^\circ\text{C}$ to $+125^\circ\text{C}$, $V_D = 10$ Vdc, $R_L = 3$ Ohms
	Peak On-State Voltage	V_{TM}	—	—	1.45	Volts	$T_C = +125^\circ\text{C}$, $I_T = 1000$ Amps. Peak Duty Cycle $\leq 0.01\%$
	Conventional Circuit Commutated Turn-Off Time (With Reverse Voltage)	t_q	—	—	50	μsec	(1) $T_C = +125^\circ\text{C}$ (2) $I_T = 500$ Amps. (3) $V_R \geq 50$ Volts (4) 80% V_{DRM} Reapplied (5) Rate-of-Rise of Forward Blocking Voltage = 300 V/ μsec (6) Gate Bias = Open During Turn-Off Interval = 0 Volts, 100 Ohms (7) Duty Cycle $\leq 0.01\%$
	Conventional Circuit Commutated Turn-Off Time (With Feedback Diode)	t_q	—	55	60	μsec	(1) $T_C = +125^\circ\text{C}$ (2) $I_T = 500$ Amps. (3) $V_R = 2$ Volts Min. (4) 30% V_{DRM} Reapplied (5) Rate-of-Rise of Forward Blocking Voltage = 300V/ μsec . (6) Gate Bias = Open During Turn-Off Interval (7) Duty Cycle $\leq 0.01\%$

Fig. 8. Data sheet: GE SCR No. C712.

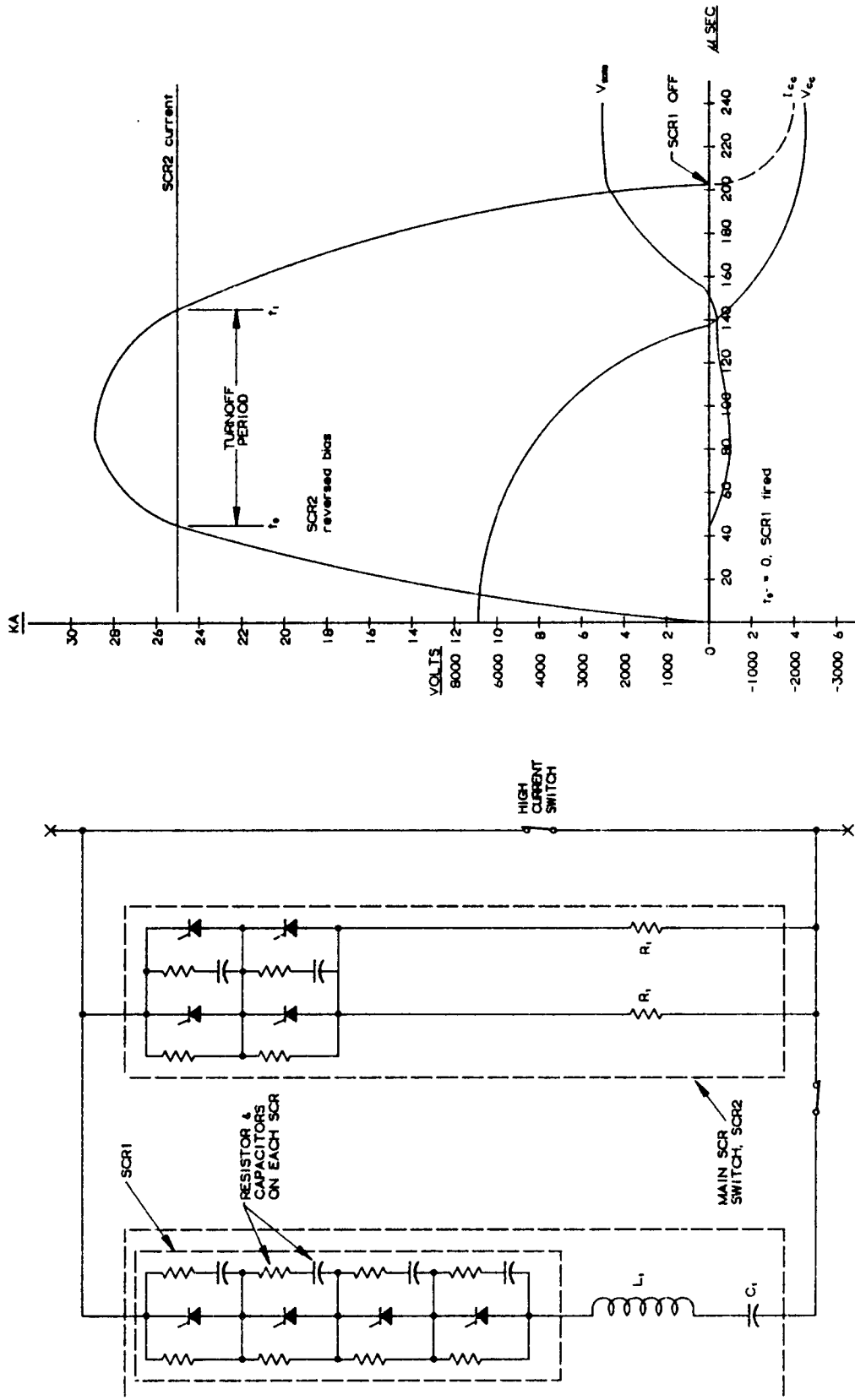


(a) CONDUCTING PHASE EQUIVALENT CIRCUIT



(b) REVERSE BIAS EQUIVALENT CIRCUIT

Fig. 9. SCR interrupter equivalent circuit.



(a) 25 kA/2500 V SCR INTERRUPTER

(b) WAVEFORMS DURING COMMUTATIONS

Fig. 10. SCR switch and commutation waveforms.

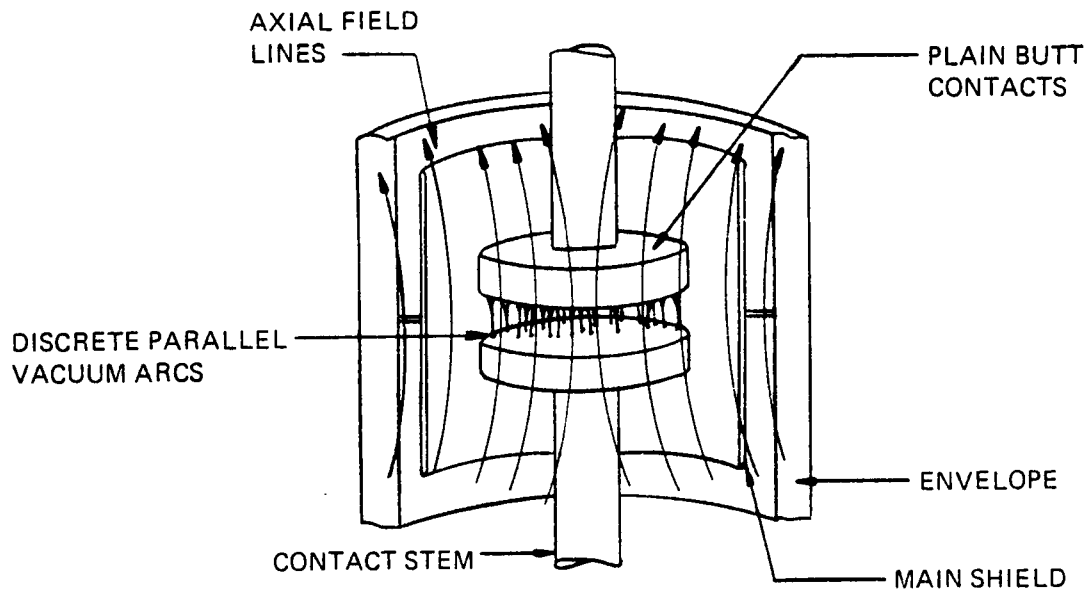
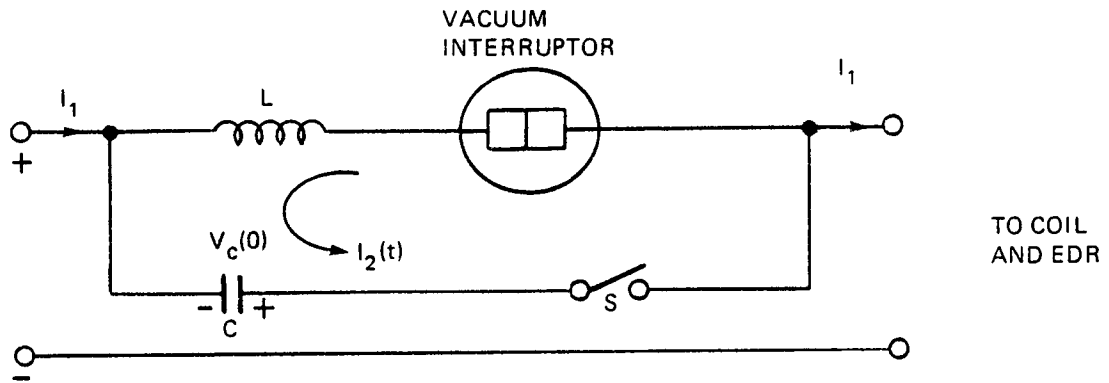
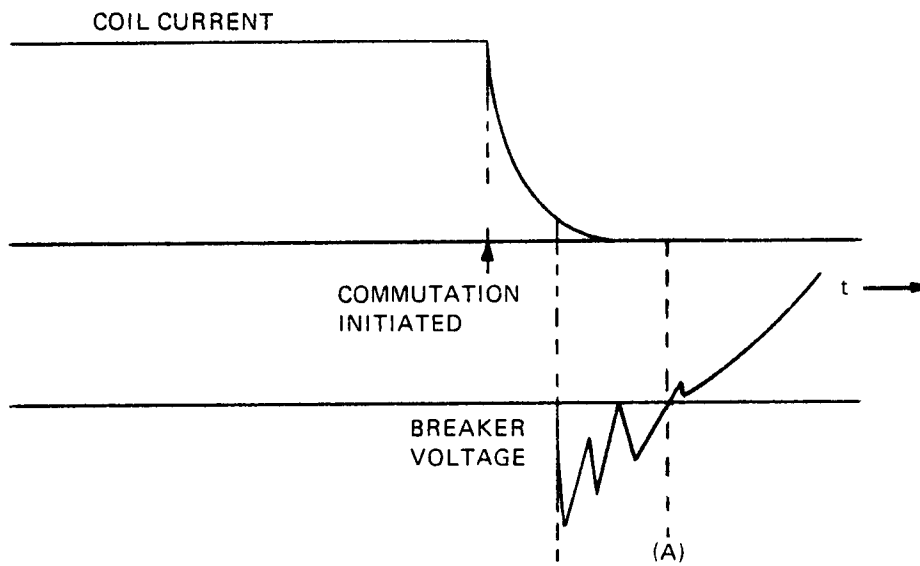


Fig. 11. Vacuum interrupter with axial field.



(a) VACUUM INTERRUPTER CIRCUIT

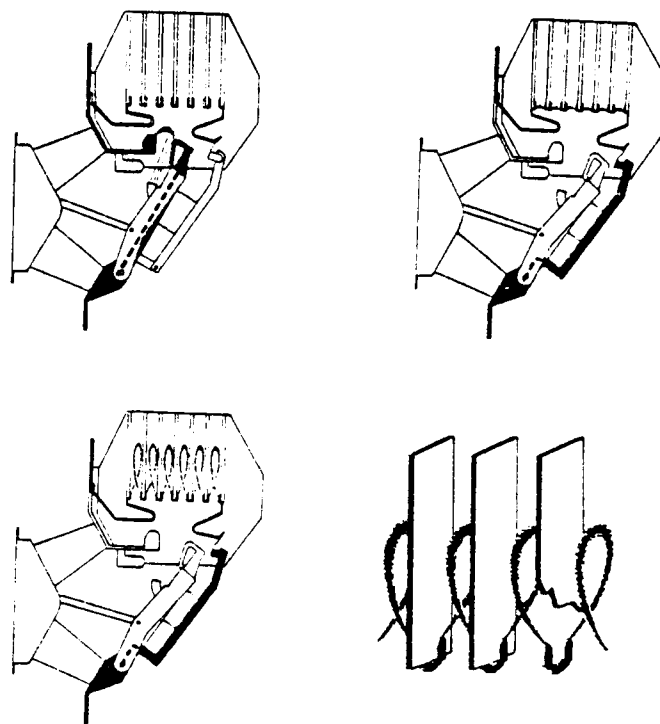
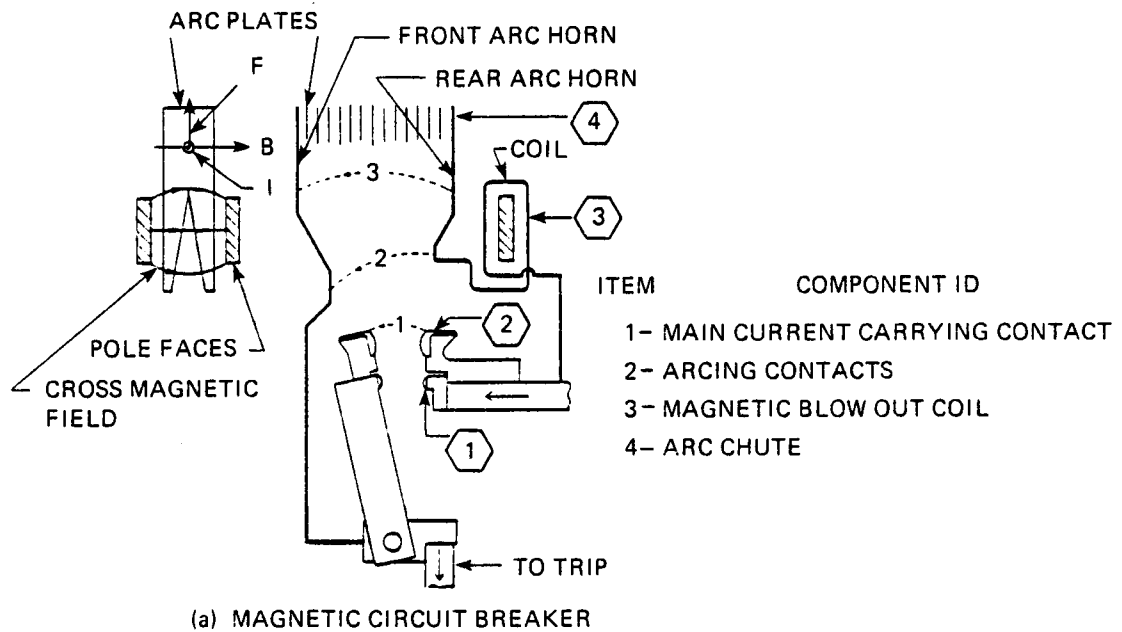


(b) TYPICAL TRANSIENT WAVEFORM

Fig. 12. Vacuum interrupter circuit and typical waveforms.

PARAMETER	BROWN BOVERT		AEG-TELEFUNKEN		WHIPP & BOURNE (PER ANSI STDS.)		WESTINGHOUSE (PER ANSI STDS.)			
	UR26	42T	UR26	44	S6003	S6003	MM74	MM74	DMD	HS
NOMINAL SYSTEM V.	2000		4000		2000	3000	1500	3000	1500	3000
ARC CHUTE VOLTAGE	4600		9200		5000		3500	5000	5000	
NOMINAL CURRENT (A)	2600		2600		6000	6000	2000 3000 4000	2000 3000 4000	2000 4000	
SURGE CURRENT (10 ms)	40 kA		35 kA		15 kA (20 s)	15 kA (20 s)	151 kA	151 kA	100 kA	
V INSUL. TO GROUND	20 kV		20 kV		10 kV	10 kV			8.8 kV	8.8 kV
V INSUL. BETWEEN CONT.	15 kV		15 kV		10 kV	10 kV			8.8 kV	
NO. OF OPERATIONS	50000		50000		10000	10000				
di/dt RATING (A/microsec.)	>5.0		>5.0				21.0	5.9	5.0	5.0
TYPE OF BREAKER	HIGH SPEED		HIGH SPEED				HIGH SPEED	HIGH SPEED	SEMI-HIGH SPEED	SEMI-HIGH SPEED

Fig. 13. dc Breaker specification summary.



(b) TYPICAL ARC CHUTE ARC PROFILE

Fig. 14. Typical dc breaker interruptions.

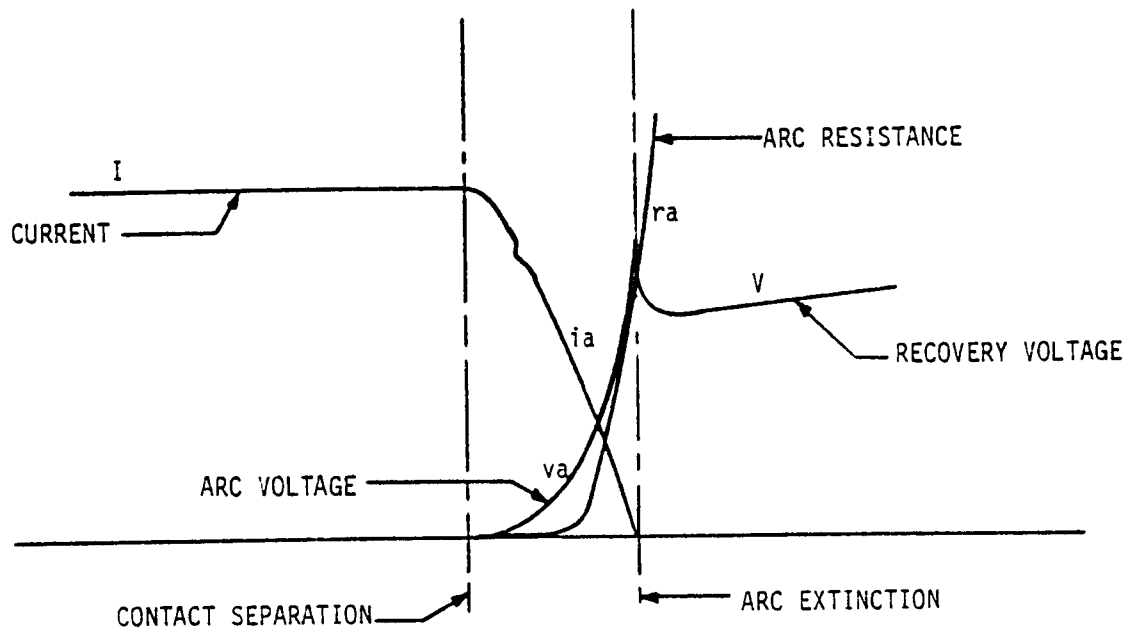
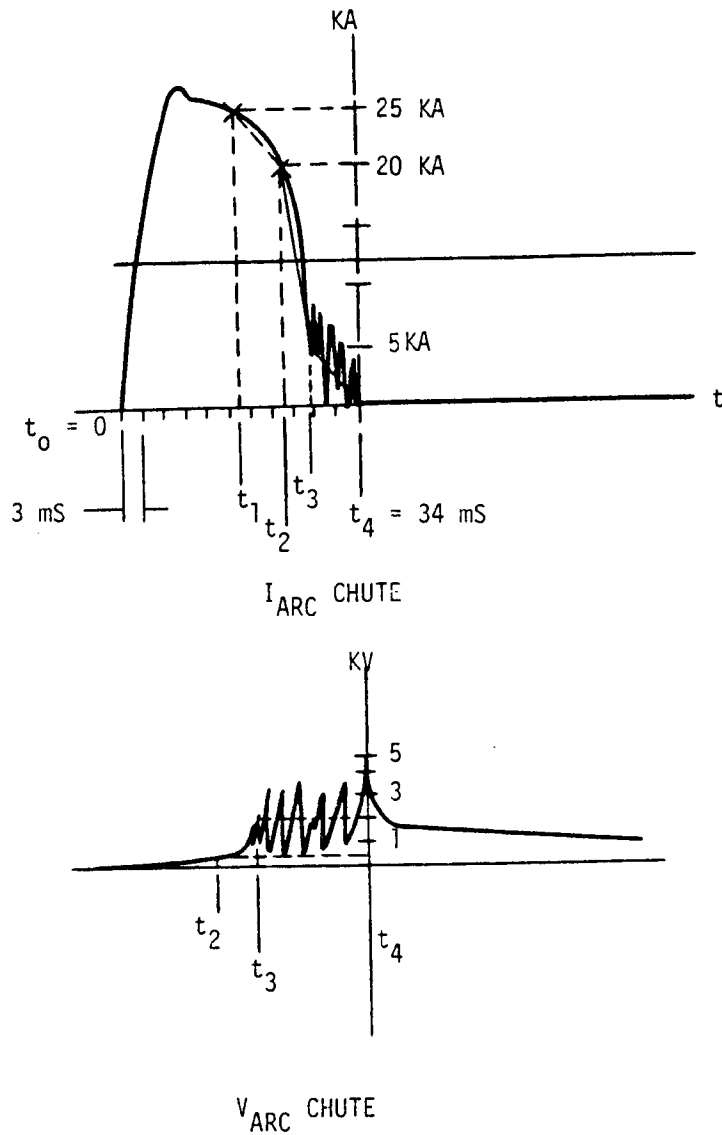


Fig. 15. Arc resistance profile.



$$\text{AVERAGE ENERGY OVER PERIOD "t" (SECONDS)} = I_{AVE} V_{AVE} (t)$$

$$\text{TOTAL ENERGY} = \Sigma (t_1 - t_2) = 22.5 \text{ KA} \times 250 \text{ V} \times 6 \text{ mSec} = 33.8 \text{ kJ}$$

$$(t_2 - t_3) = 12.5 \text{ KA} \times 1250 \text{ V} \times 4 \text{ mSec} = 62.5 \text{ KJ}$$

$$(t_3 - t_4) = 2.5 \text{ KA} \times 3250 \text{ V} \times 7 \text{ mSec} = \underline{56.9 \text{ KJ}}$$

$$\Sigma = 153.2 \text{ KJ}$$

Fig. 16. Measured arc voltage/current profile.

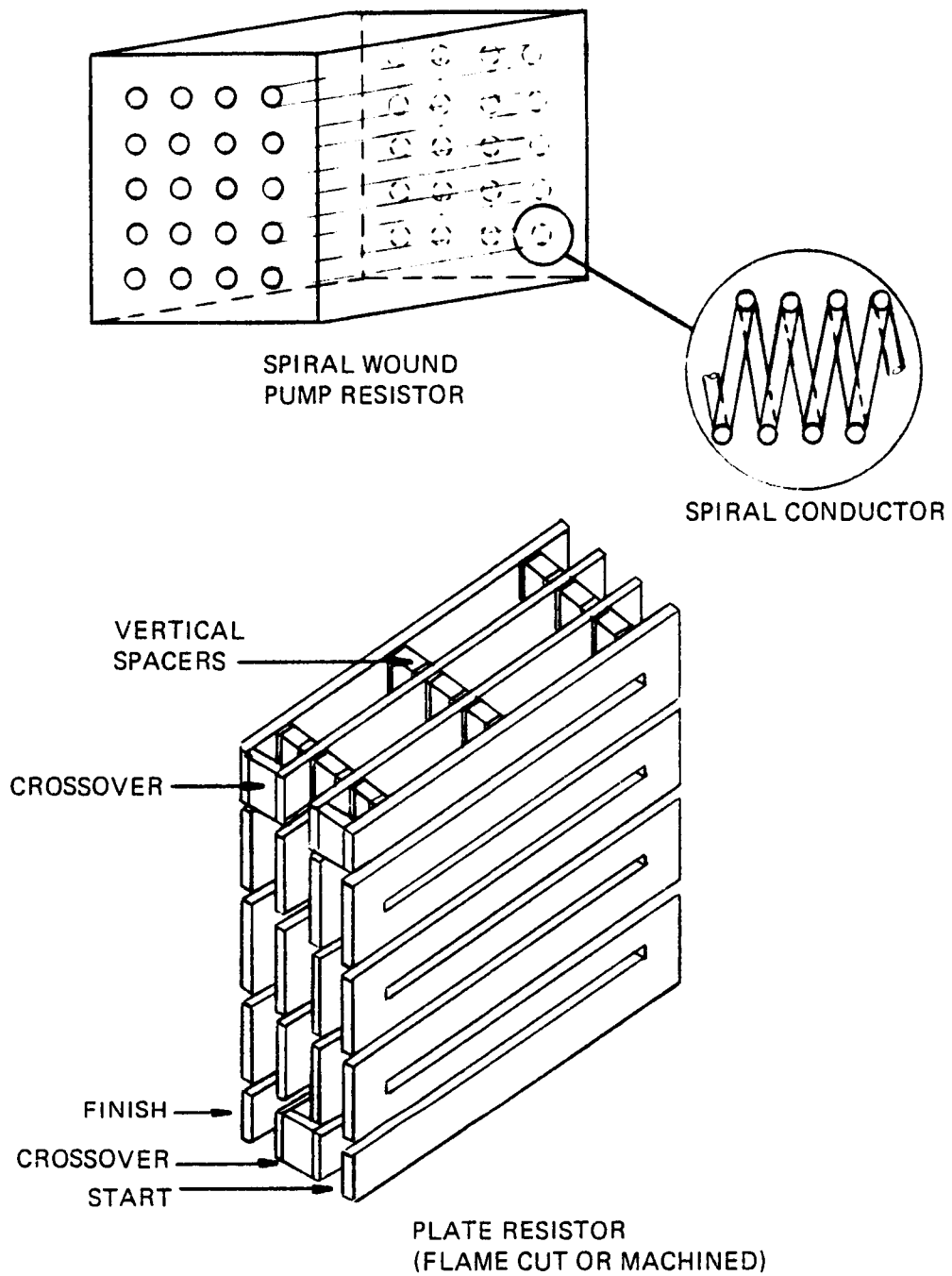
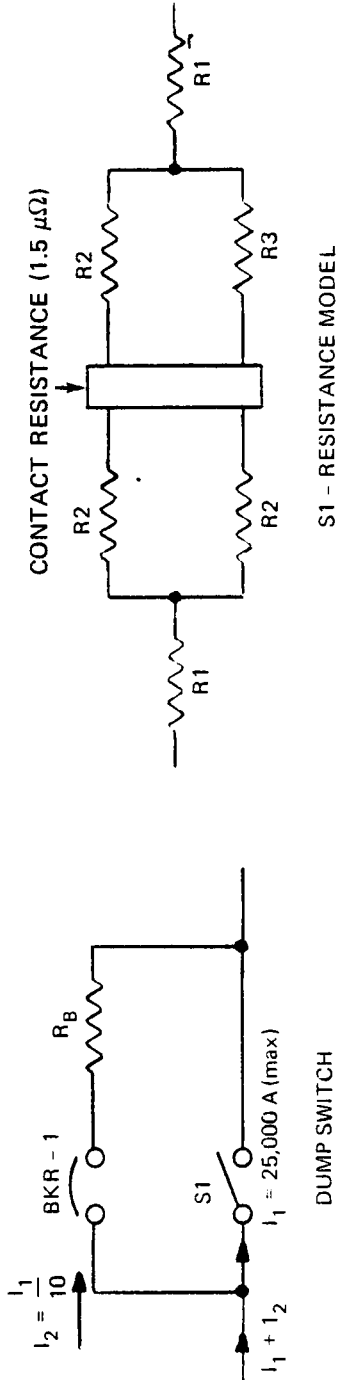


Fig. 17. Typical dump resistor construction.



$$R = \rho l / A$$

R = RESISTANCE Ω

ρ (COPPER RESISTIVITY AT 20°C) = $1.72 \times 10^{-6} \Omega \cdot \text{in.}$

l = LENGTH OF CONDUCTOR (cm OR in.)

A = CROSS-SECTIONAL AREA OF CONDUCTOR (cm^2 OR in.^2)

$R_1 = 2 - 12 \text{ in.} \times 1 \text{ in.}$ COPPER BARS IN PARALLEL ($L = 11.5 \text{ in.}$)

$R_2 = 1 - 3/4 \times 6 \text{ in.}$ COPPER BAR ($L = 9 \text{ in.}$)

$R_1 = .33 \times 10^{-6} \Omega$

$R_2 = .53 \times 10^{-6} \Omega$

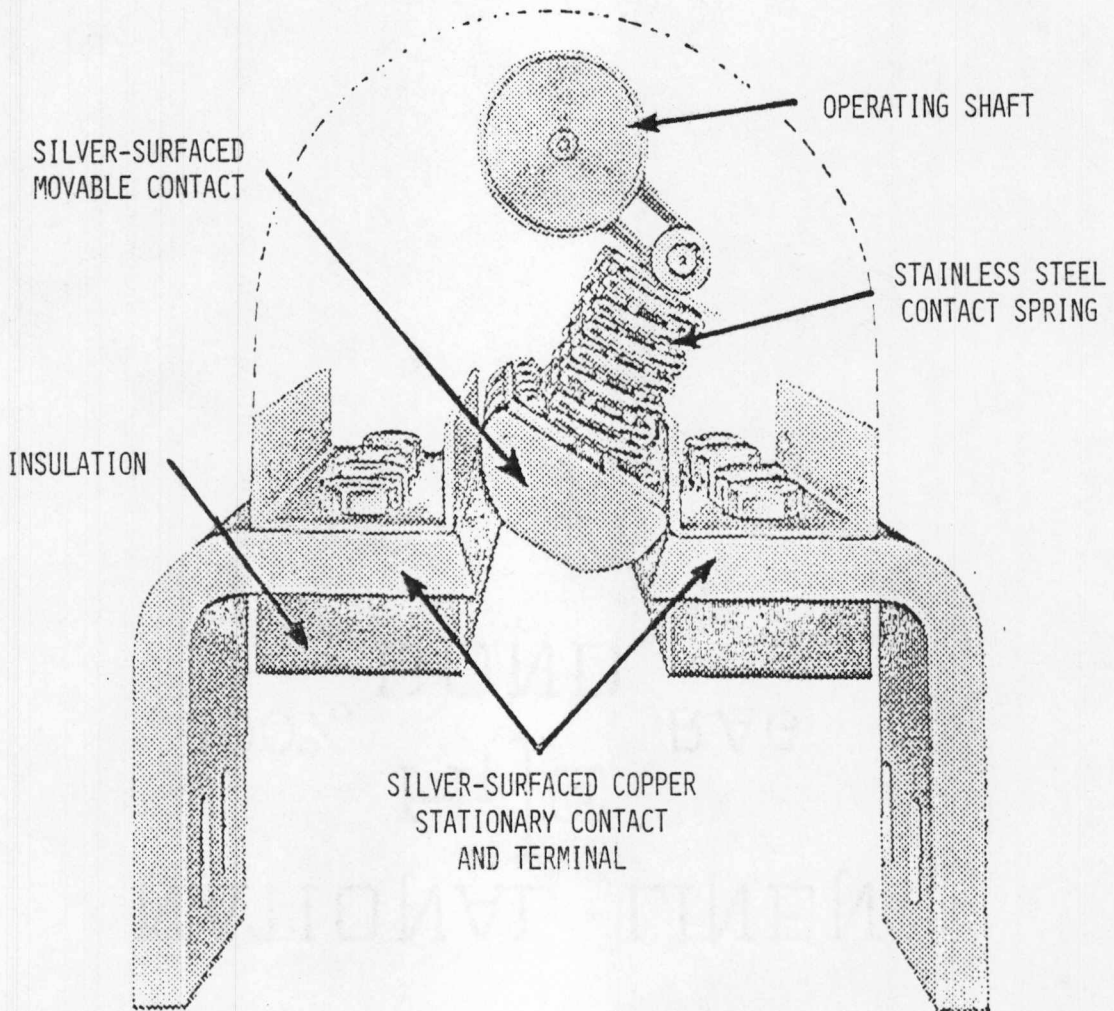
$S1$ (BUSS RESISTANCE) = $.33 + .53 + .33 = 1.72 \mu\Omega$

$S1$ (CONTACT RESISTANCE) = $1.5 \mu\Omega$ (ESTIMATED)

$S1$ (TOTAL RESISTANCE) = $3.22 \mu\Omega$

$\therefore$ RESISTANCE IN $BKR-1$ BRANCH EQUAL $32.2 \mu\Omega$ FOR A 10 TO 1 CURRENT RATIO. WITH THE BREAKER INTERNAL RESISTANCE ASSUMED TO BE $7.2 \mu\Omega$, a 100 mV AT 4 kA SHUNT WILL PROVIDE THE CORRECT RESISTANCE IN THE $BKR-1$ BRANCH.

Fig. 18. Switch resistance model.



- REQUIRED MODIFICATION
- IMMERSE IN OIL BATH
- PROVIDE OIL FILTERING/RECIRCULATION SYSTEM
- ADD G-10 INSULATING MATERIAL FOR VOLTAGE RATING IMPROVEMENT

Fig. 19. ITE high current switch.

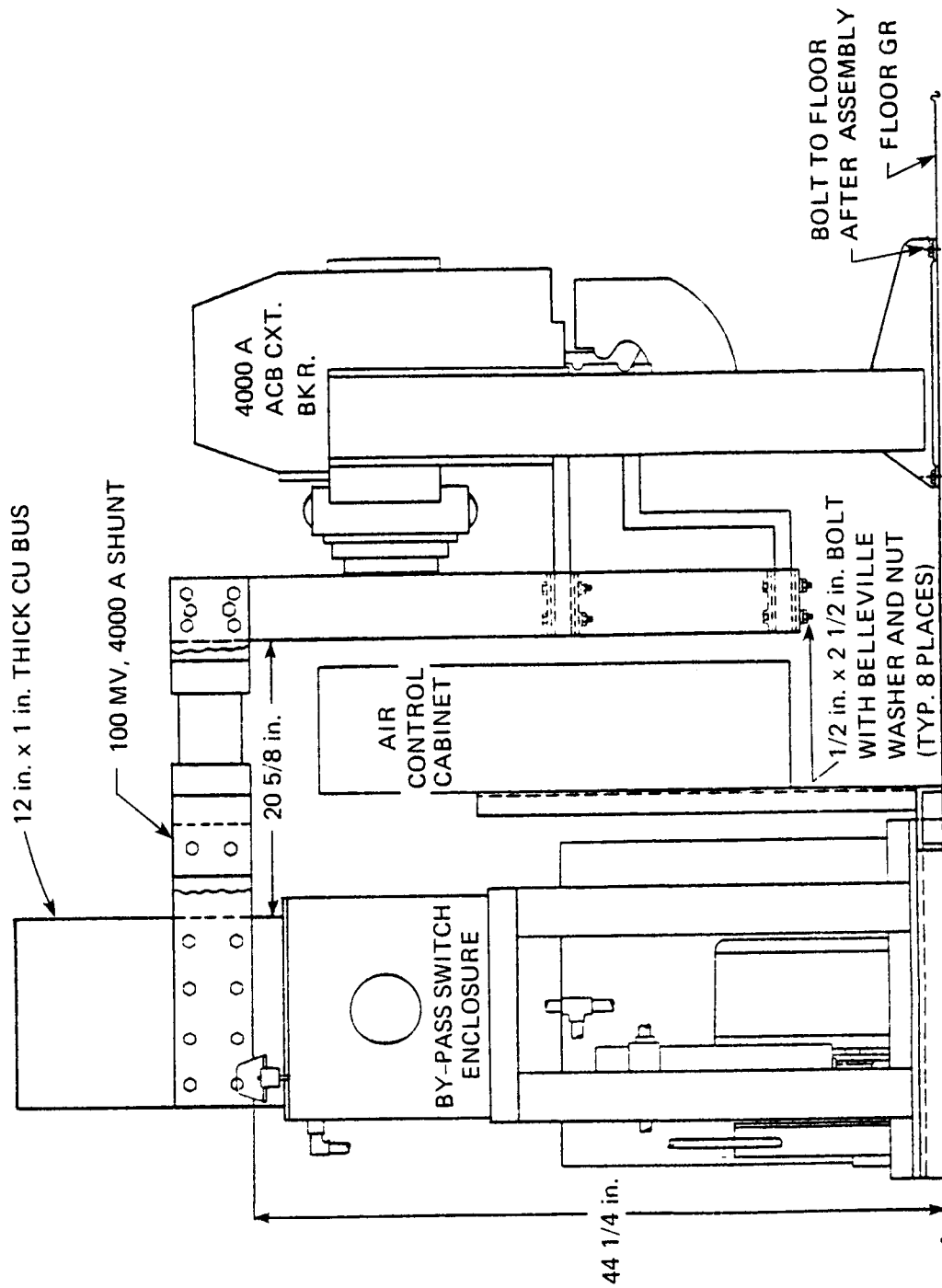


Fig. 20. 25-kA/2.5-kV dump switch.

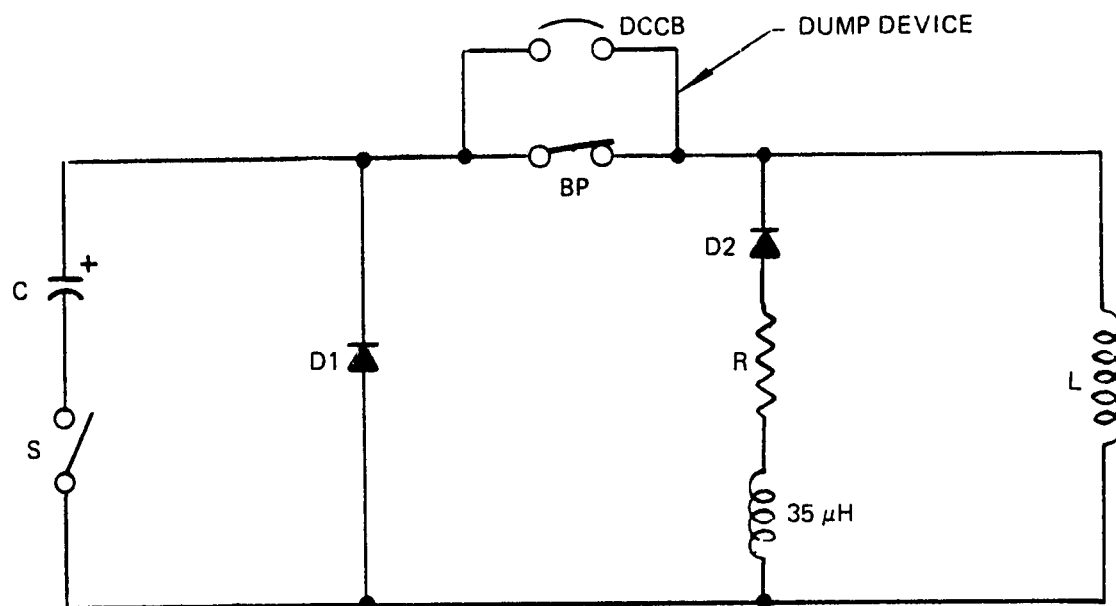
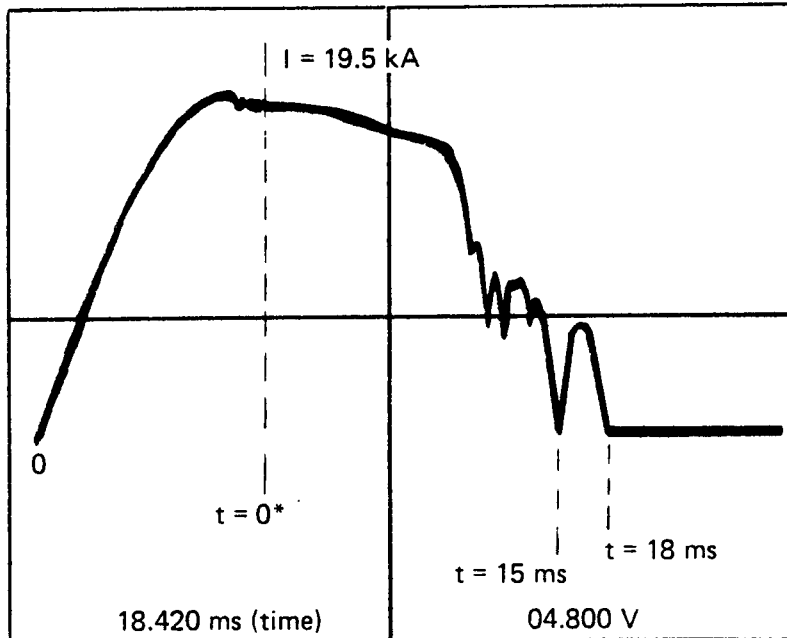
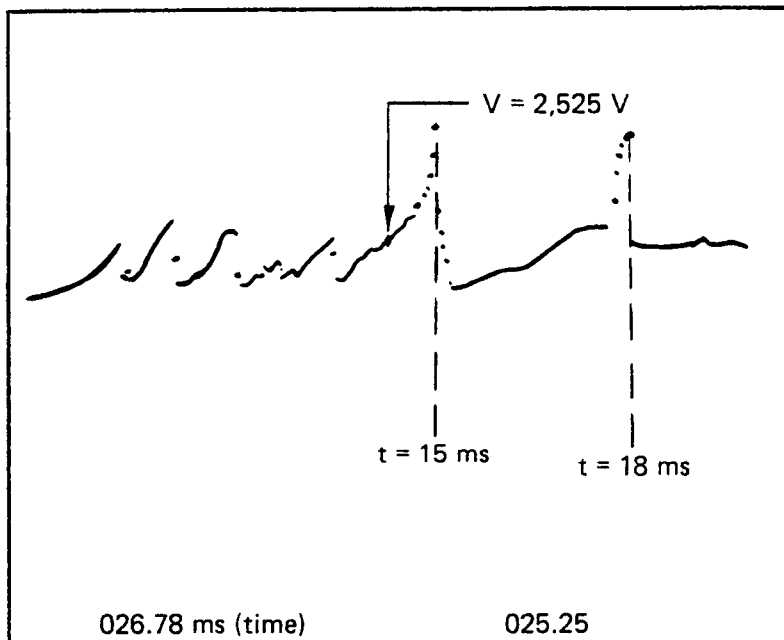


Fig. 21. Dump device test circuit.



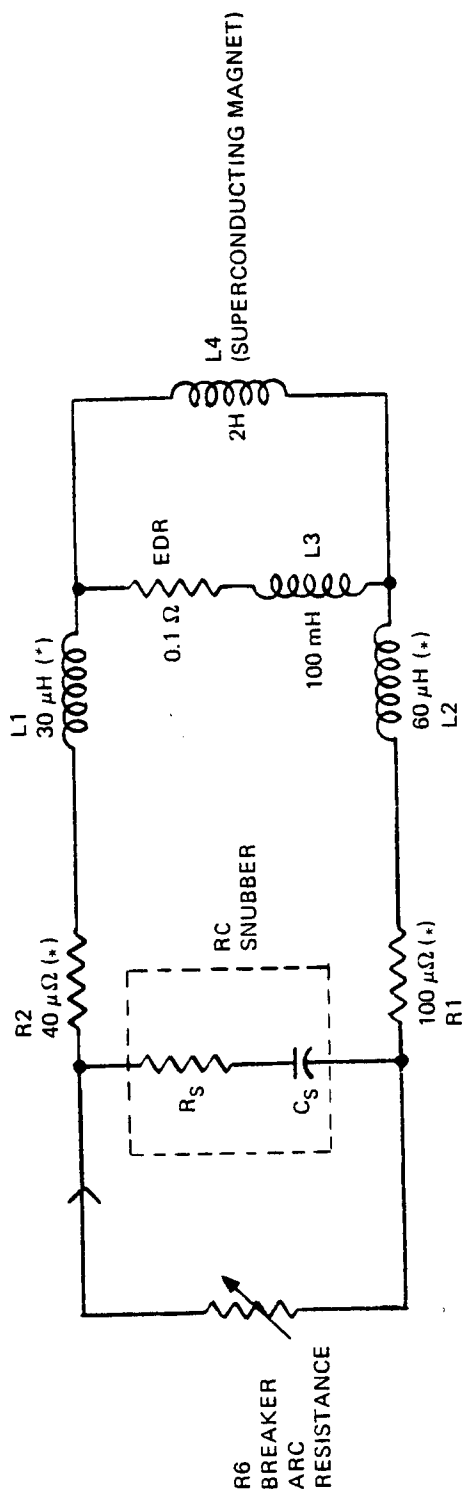
(a) MEASURED BREAKER CURRENT INTERRUPTION PROFILE



*NOTE: $t = 0$ IS APPROXIMATE START OF BREAKER CONTACT OPENING

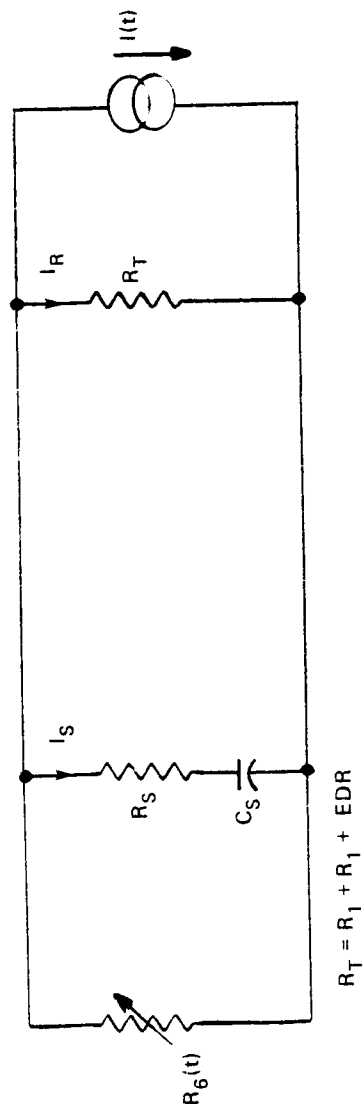
(b) BREAKER TRANSIENT VOLTAGE PROFILE (DURING INTERRUPTION)

Fig. 22. Measured dc breaker interruption profile.



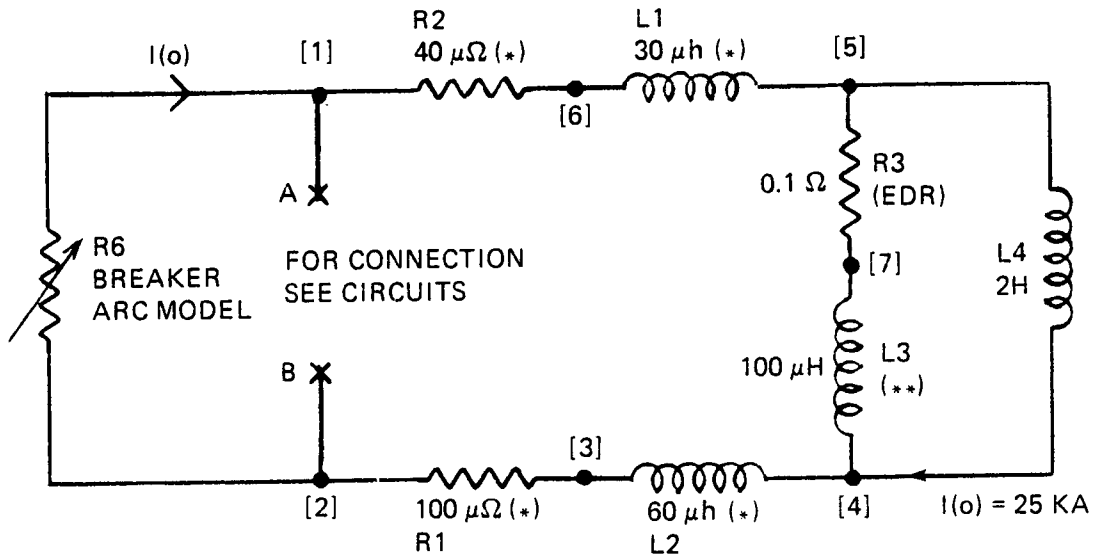
*CALCULATED BUSS IMPEDANCES

(a) EQUIVALENT CIRCUIT



(b) SIMPLIFIED CIRCUIT

Fig. 23. Superconducting magnet equivalent and simplified circuit.



- [*] INDICATES NODE NUMBER IN COMPUTER PROGRAM
 * BUS IMPEDANCES - CALCULATED
 ** DUMP RESISTOR INDUCTANCE - ASSUMED MAXIMUM

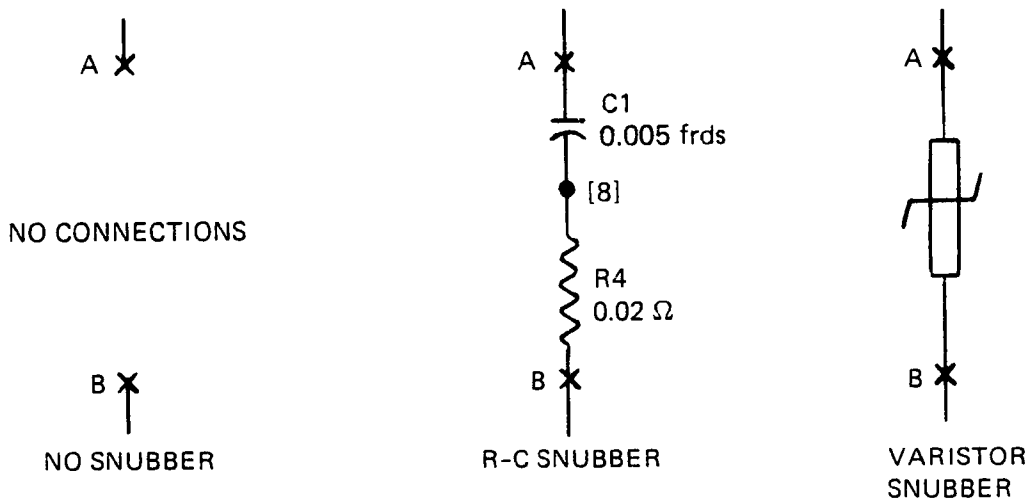
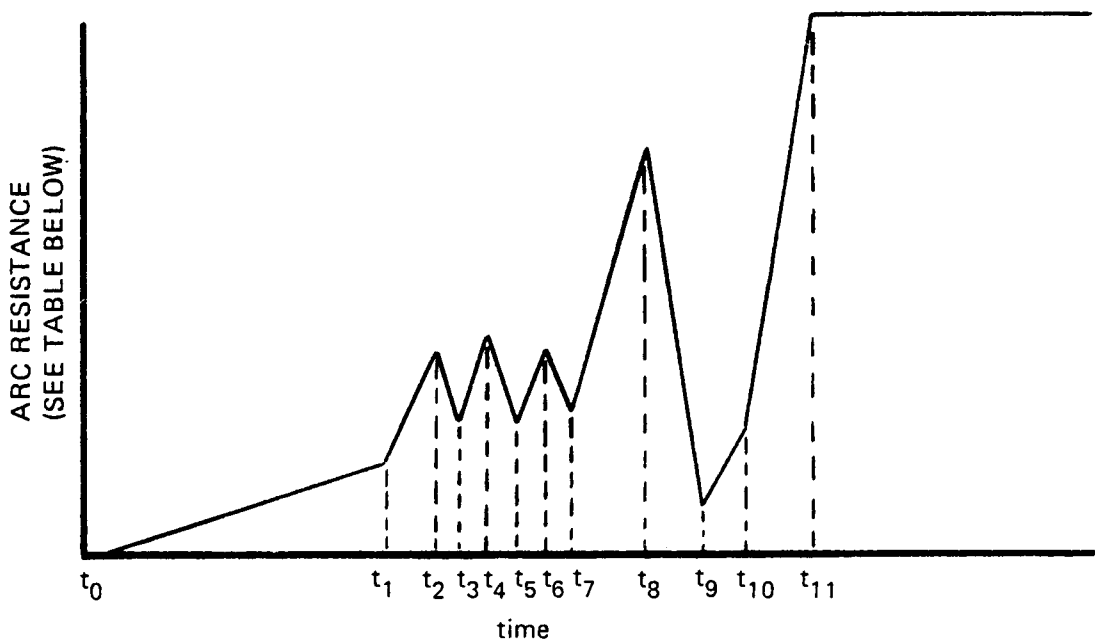


Fig. 24. Computer model for LCTF coil protection simulation.



	<u>TIME (s)</u>	<u>ARC RESISTANCE (OHMS)-R6</u>
t_0	0	0.001
t_1	0.01	0.02
t_2	0.0113	0.15
t_3	0.0118	0.08
t_4	0.0121	0.17
t_5	0.013	0.08
t_6	0.0135	0.15
t_7	0.0141	0.1
t_8	0.015	4.0
t_9	0.0163	0.001
t_{10}	0.0176	0.01
t_{11}	0.018	100

Fig. 25. Arc resistance profile (2500-V dump voltage).

V-I Curve (Max. Values)

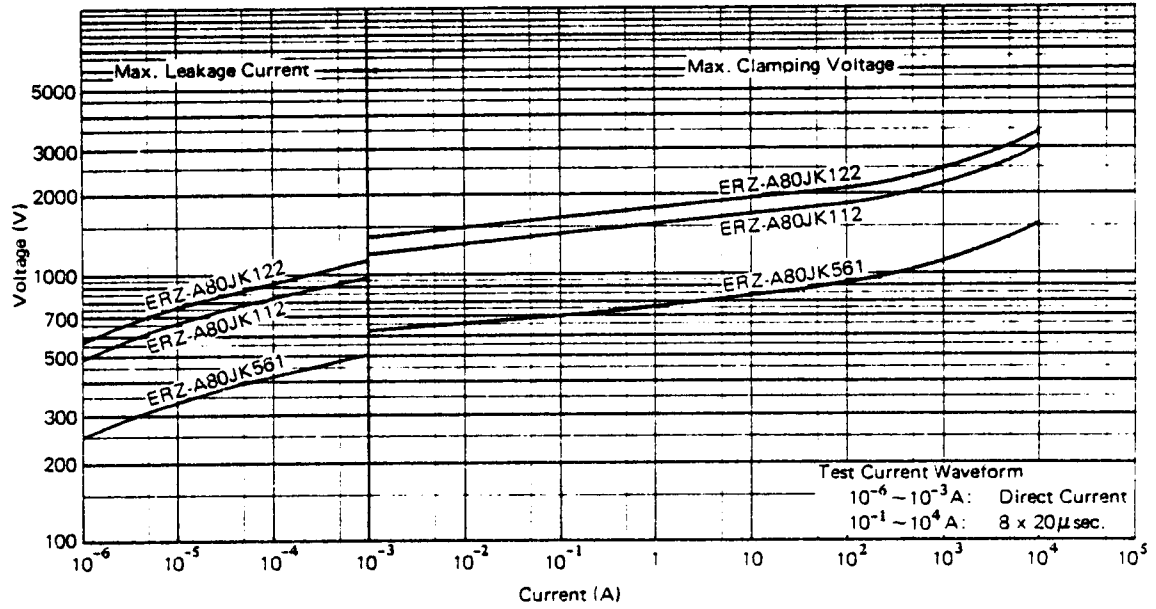


Fig. 26. Varistor Panasonic (No. ERZ-A80JK112) V-I curves.

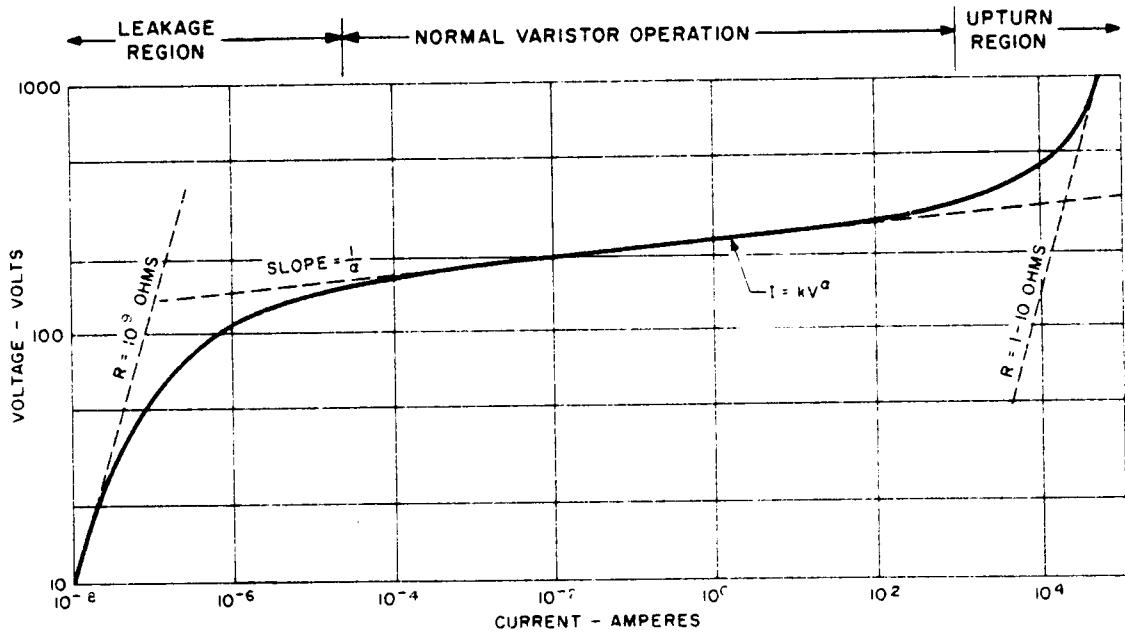
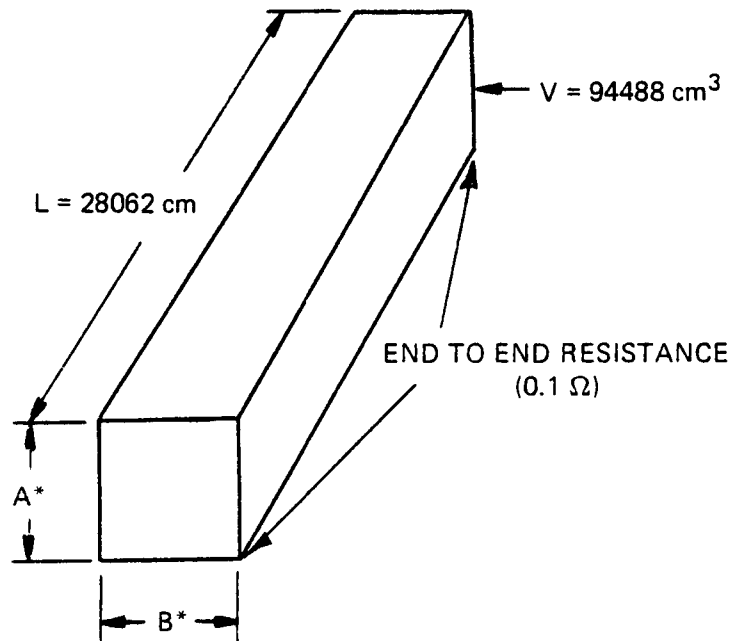
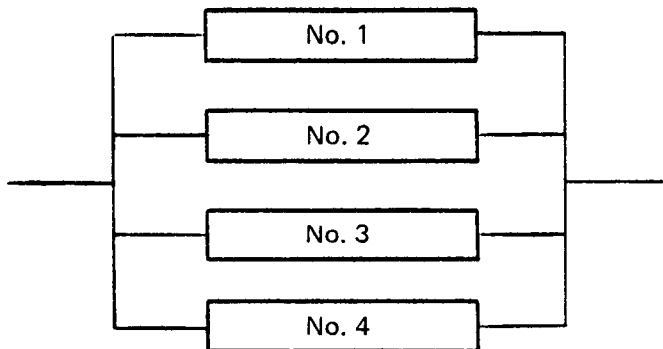


Fig. 27. Typical varistor V-I curve.



*NOTE $A \times B = 3.37 \text{ cm}^2$



VOLUME/MODULE = $23,622 \text{ cm}^3$

LENGTH/MODULE = $28,062 \text{ cm}$

RESISTANCE/MODULE = 0.4Ω

Fig. 28. Volume/area/length for 200-MJ dump resistor.

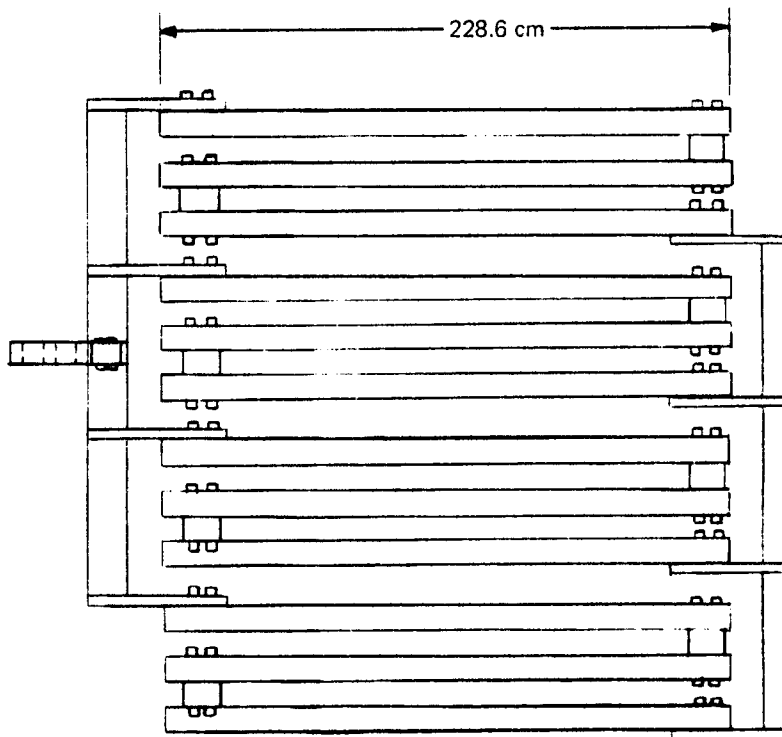
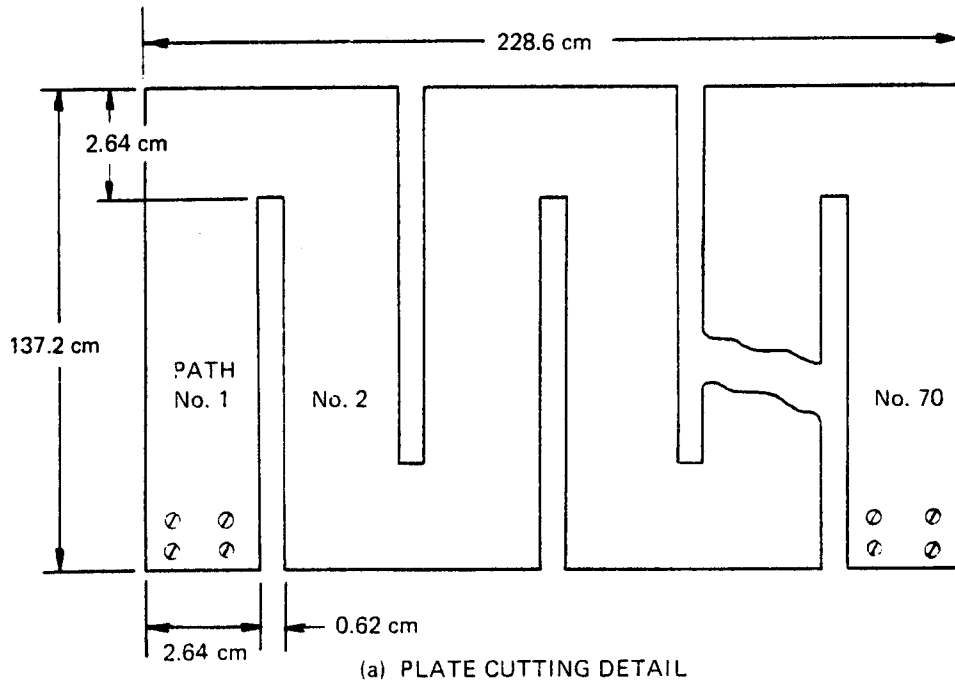


Fig. 29. Plate cutting and final connection details.

APPENDIX B

Transients without Suppression

Appendix B presents the computer printed results of the model without a snubber. These printed outputs show the following calculated variables during the breaker interruption:

- voltage across coil (VL4)
- voltage across breaker (VR6)
- current in breaker (IR6)
- watts in breaker (DPBKR)
- watts in dump resistor (DPBKR)
- joules deposited in breaker (PBKR)
- joules deposited in dump resistor (PDMP)

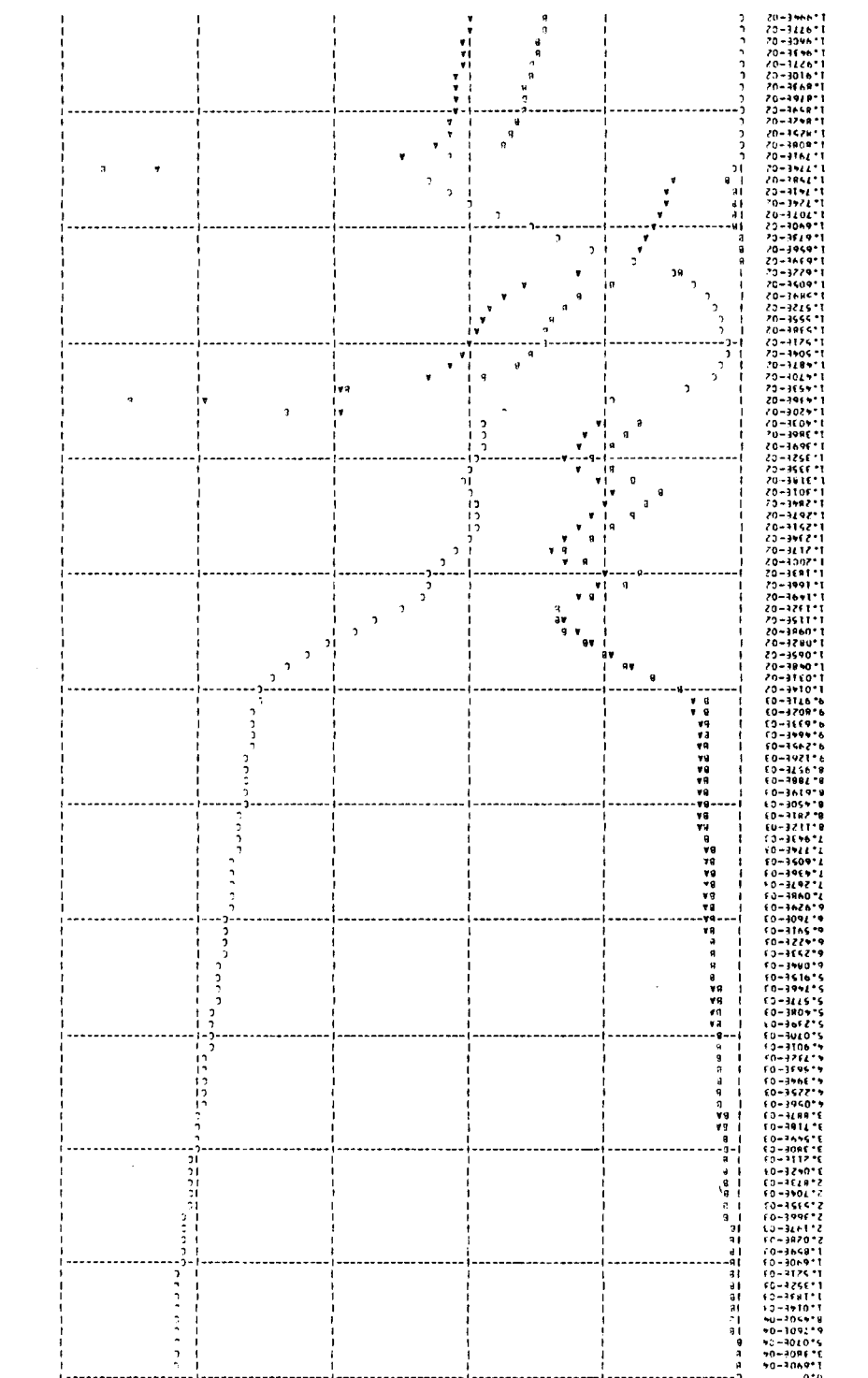


Fig. 30. Voltage and current transient profiles (computer simulation, no snubber).

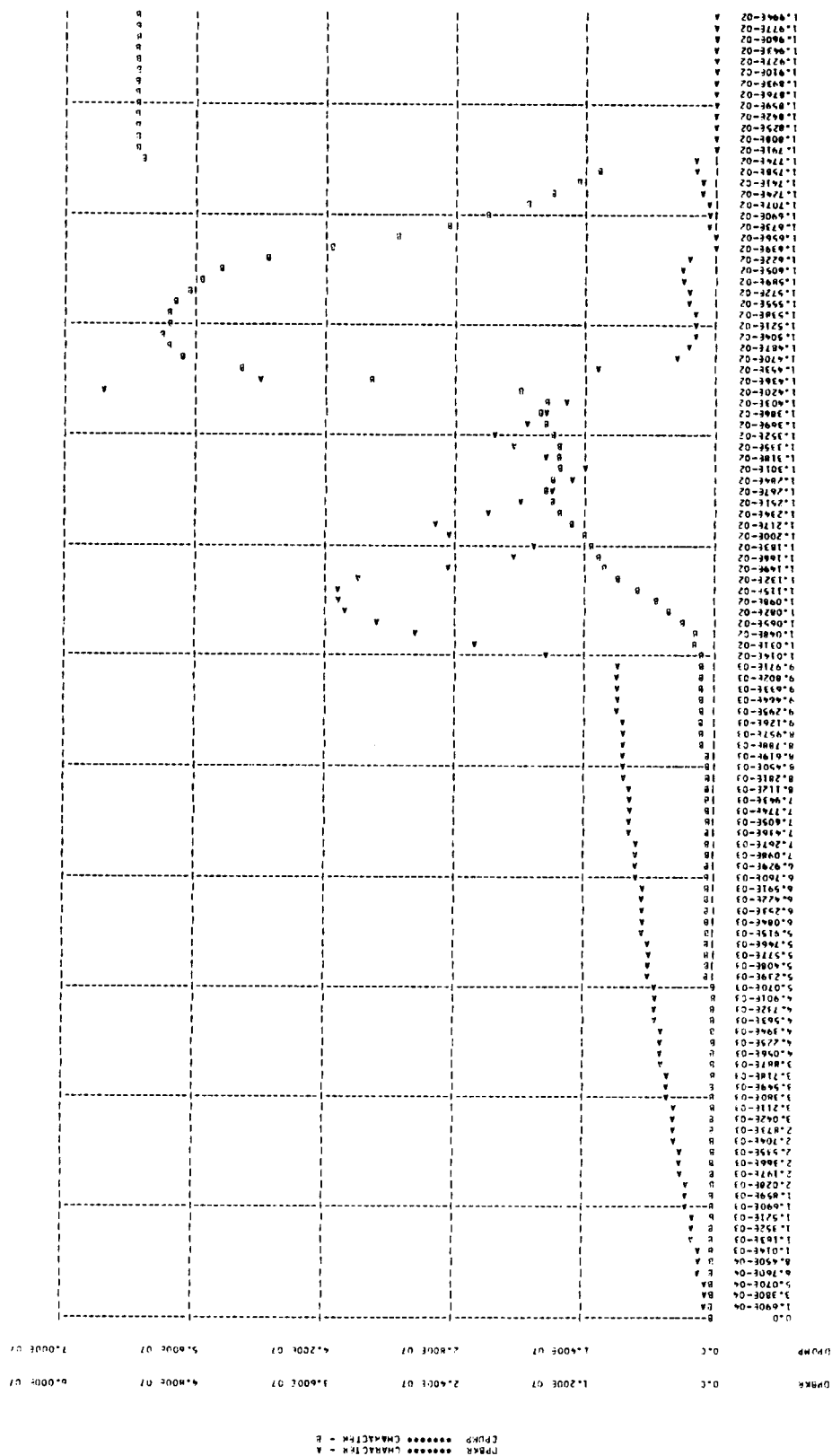
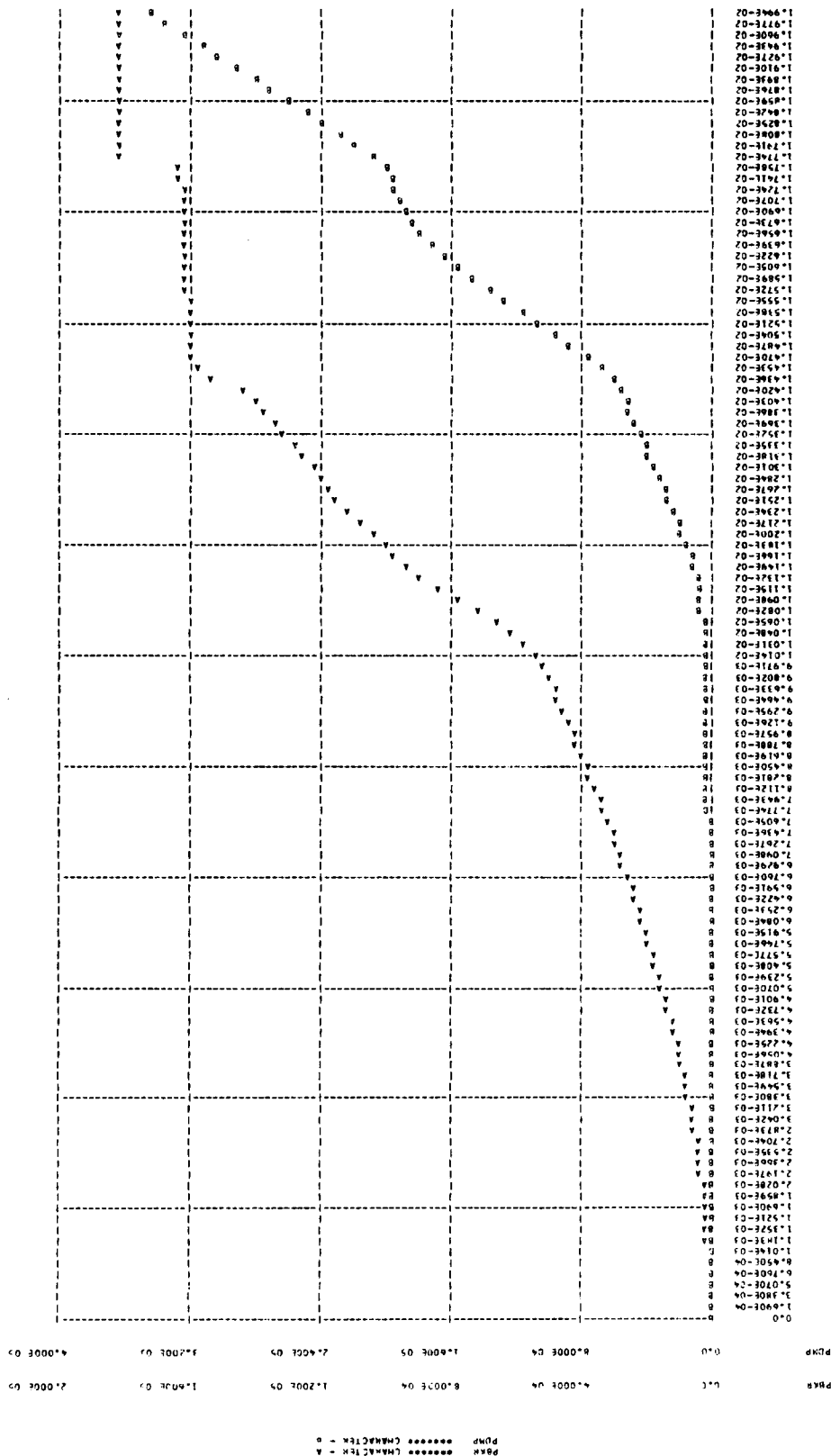


Fig. 31. Watt profiles (computer simulation, no snubber).



APPENDIX C

Transients with R-C Snubber Network

Appendix C presents the computer printed results of the R-C snubber network. The following plots are shown:

- Voltage across coil (VL4)
- Voltage across coil (VR6)
- Current in breaker (IR6)
- Watts in breaker (DPBKR)
- Watts in dump resistor (DPDMP)
- Watts in snubber capacitor (DPCAP)
- Joules deposited in breaker (PBKR)
- Joules deposited in dump resistor (PDMP)
- Joules deposited in snubber capacitor (PCAP)

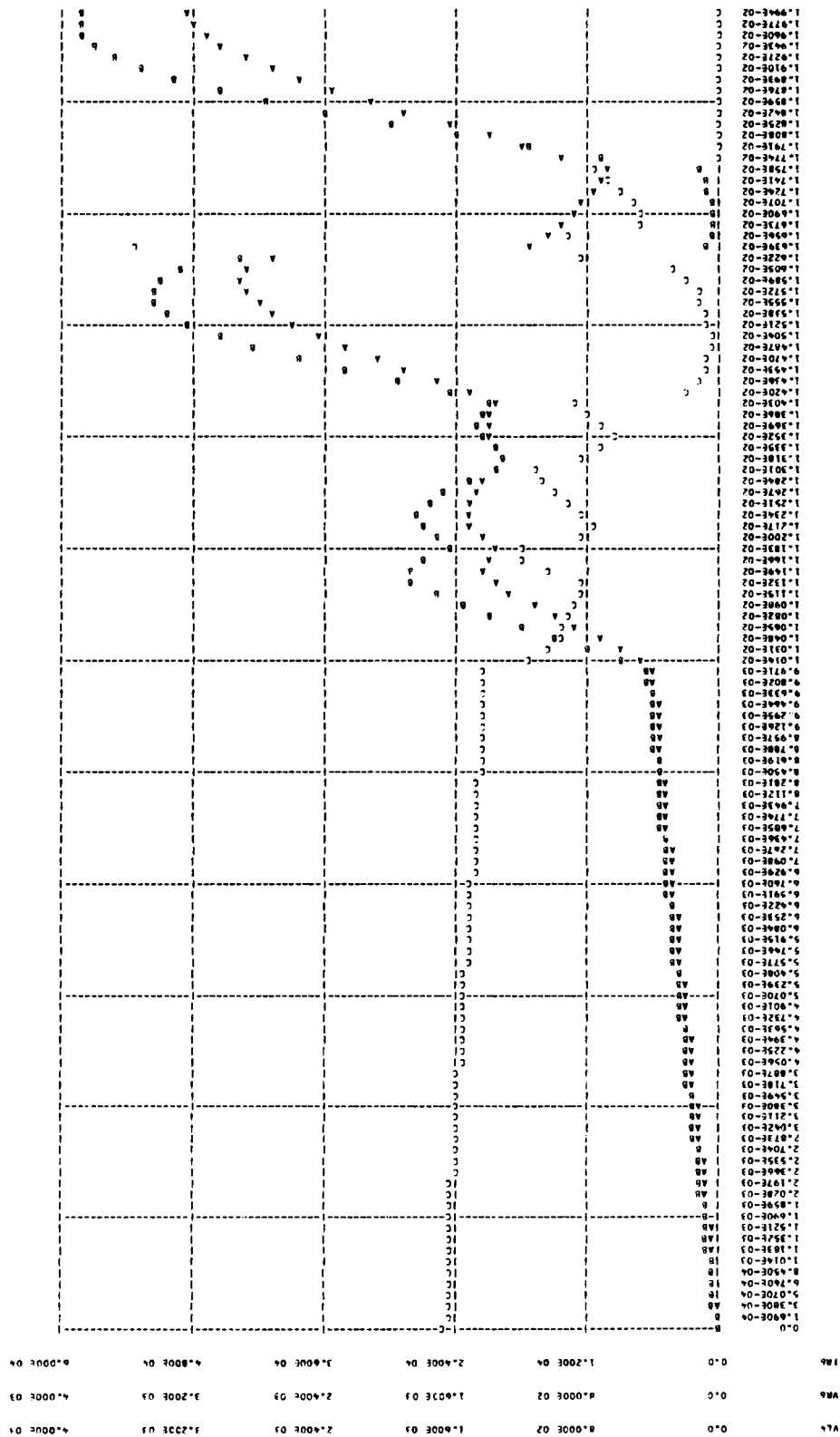


Fig. 33. Voltage and current transient profiles (computer simulation, R-C snubber).

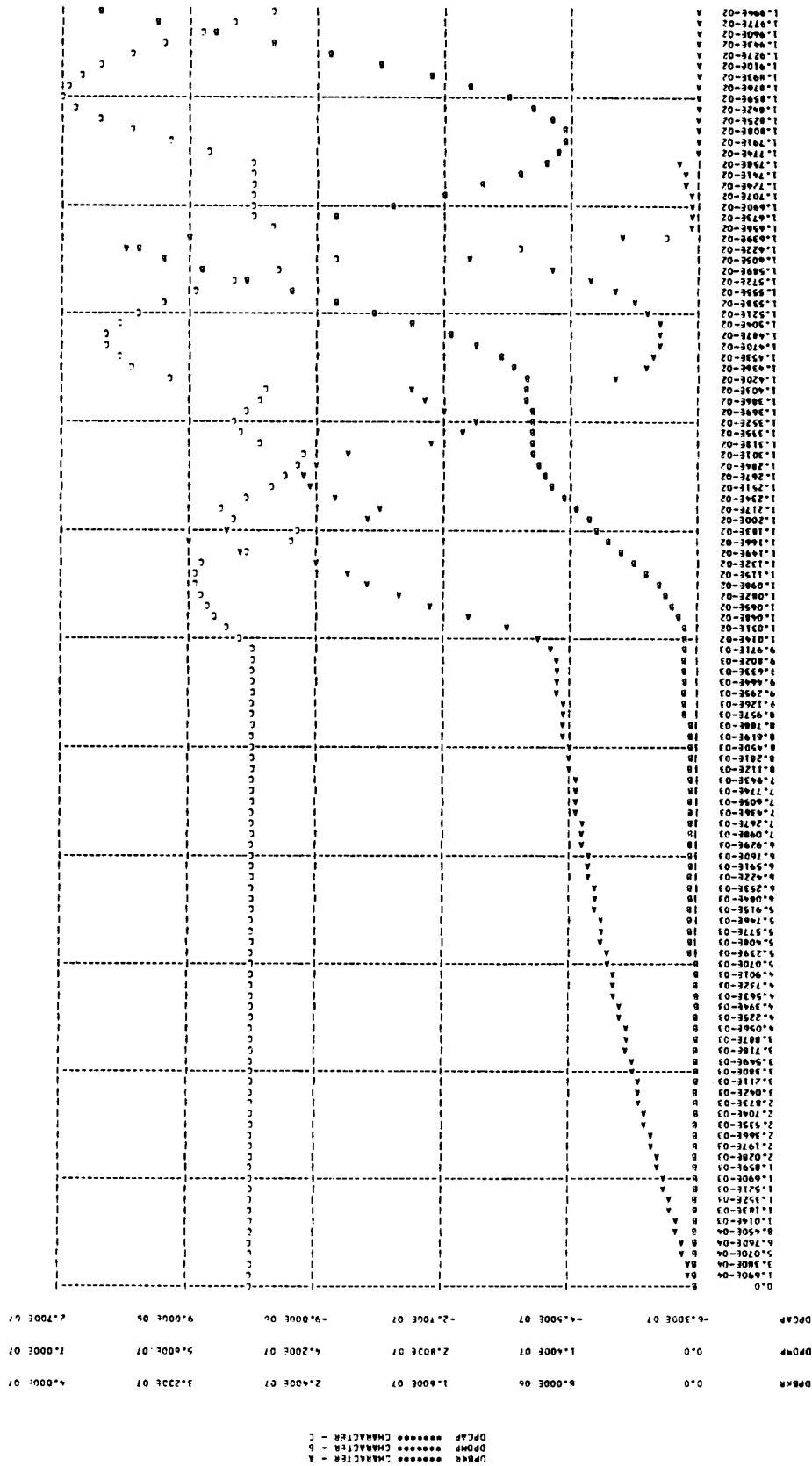


Fig. 34. Watt profiles (computer simulation, R-C snubber).

APPENDIX D

Transients with Varistor Snubber Network

Appendix D shows the printed computer results of the Zn-O varistor snubber network. The printed output shows the following calculated variables:

- voltage across coil (VL4)
- voltage across breaker (VR6)
- current breaker (VR6)
- current in varistor (IRX)
- watts in varistor (DPVAR)
- watts in breaker (DPBKR)
- watts in dump resistor (DP DMP)
- joules deposited in varistor (PVAR)
- joules deposited in breaker (PBKR)
- joules deposited in dump resistor (PDMP)

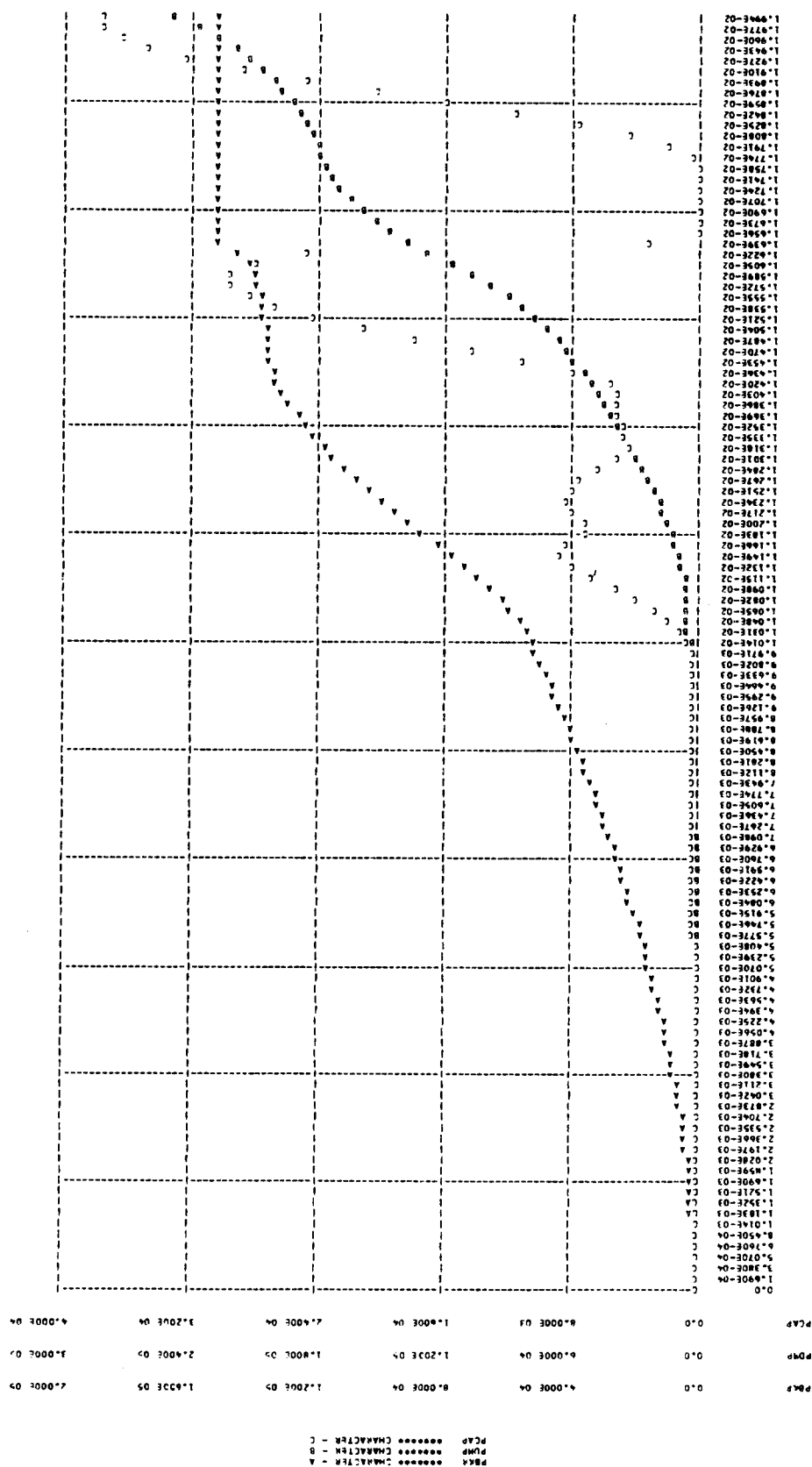


Fig. 35. Joules deposited profiles (computer simulation, R-C snubber).

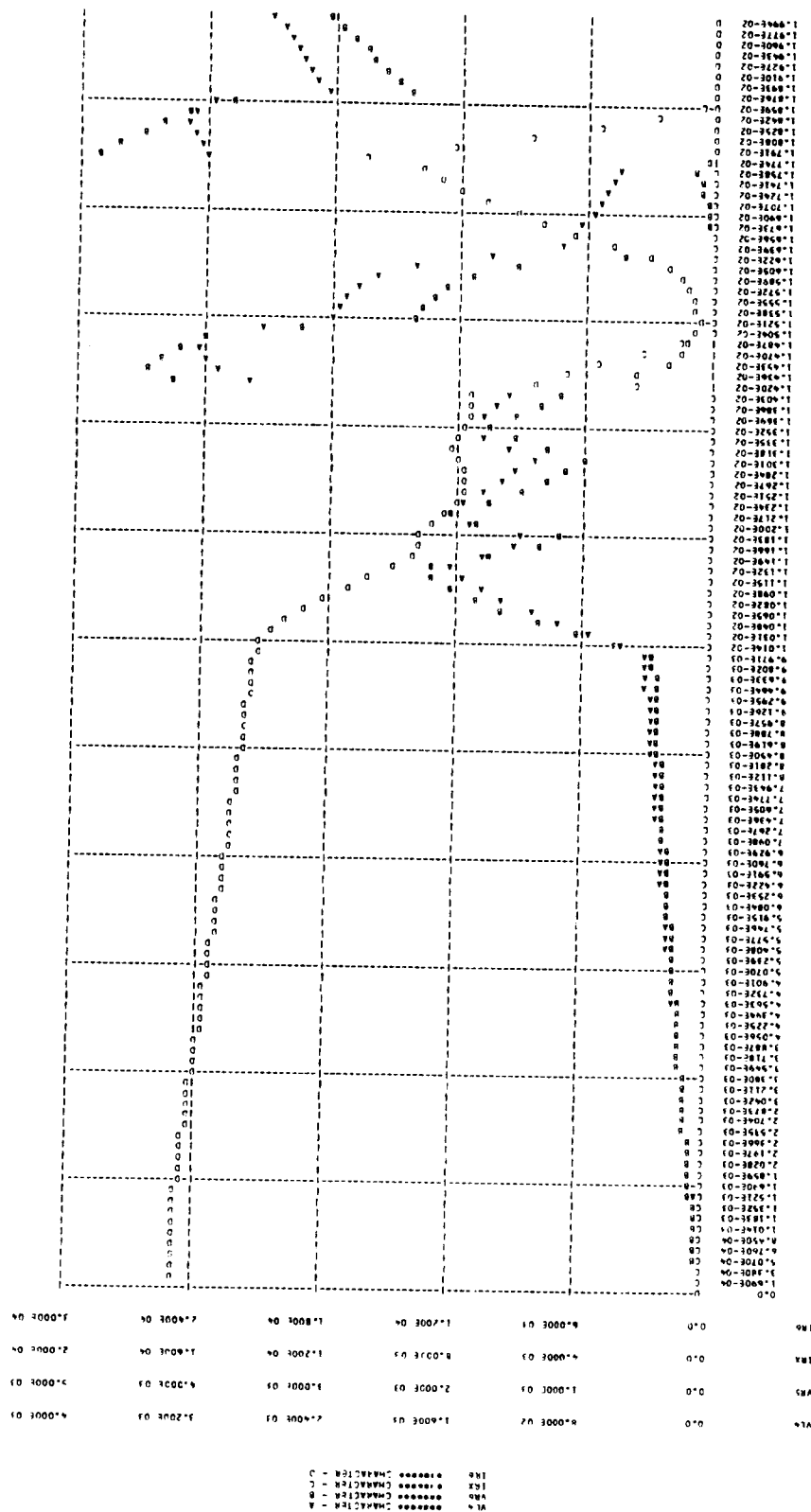


Fig. 36. Voltage and current transient profiles (computer simulation, Zn-0 snubber).

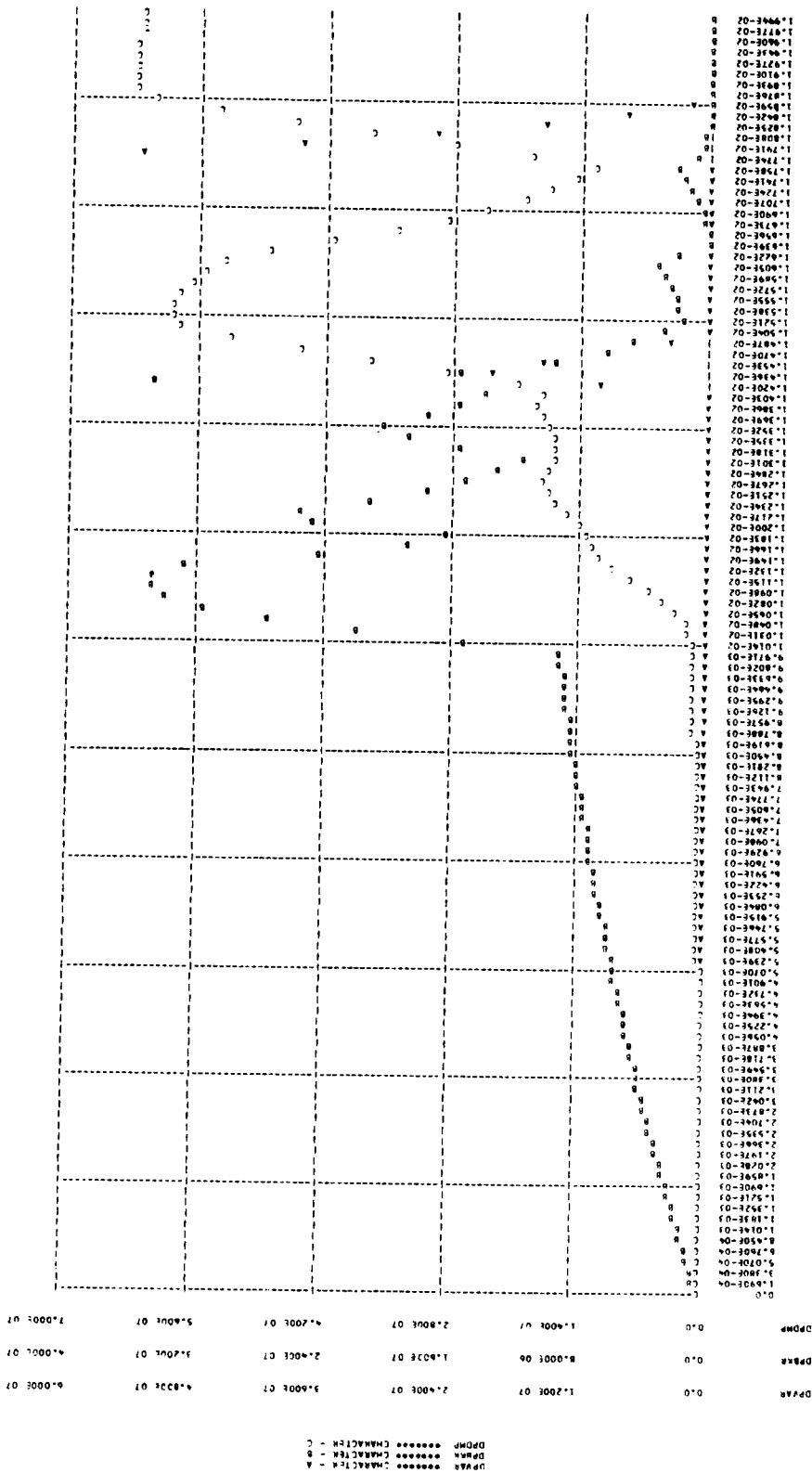


Fig. 37. Watt profiles (computer simulation, Zn-0 snubber).

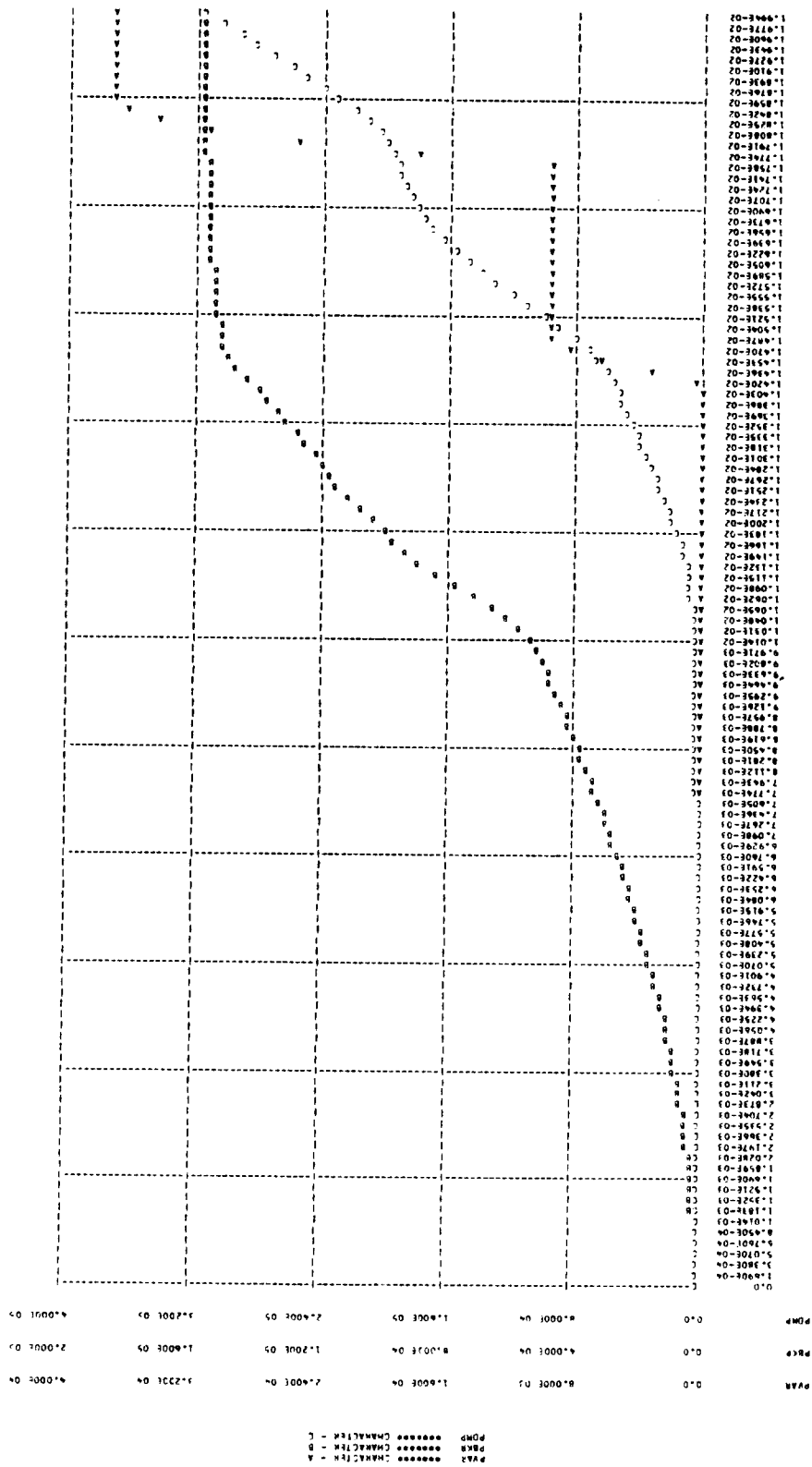


Fig. 38. Joules deposited profiles (computer simulation, Zn-0 snubber).

VITA

Randall Jay Wood was born in Huntingdon, Tennessee, on May 16, 1950. He attended elementary school in Wildersville, Tennessee, and high school at Lexington High School in Lexington, Tennessee. He graduated from high school in May 1968. He enrolled at The University of Tennessee, Knoxville, in September 1968 and received a Bachelor of Science degree in electrical engineering in June 1972.

After graduation he began work in Cincinnati, Ohio, as an electrical engineer whose work responsibilities included reliability assessment and electrical power system design. He moved to the Knoxville area and began work with Union Carbide Corporation Nuclear Division at Oak Ridge, Tennessee, in February 1977. In September 1978 he began work on a master's degree in electrical engineering at The University of Tennessee, Knoxville and received the degree in March 1983.

He is married to Shelia Diana (Grogan) Wood formerly of Clarksburg, Tennessee.