ORNL/TM-5892

Design and Construction of a Resistive Energy Dump Device for Bipolar Superconducting Magnet Systems

Martin J. Mohan

OAK RIDGE NATIONAL LABORATORY

OPERATED BY UNION CARBIDE CORPORATION FOR THE ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

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FUSION ENERGY DIVISION

DESIGN AND CONSTRUCTION OF A RESISTIVE ENERGY DUMP DEVICE FOR BIPOLAR SUPERCONDUCTING MAGNET SYSTEMS

Martin J. Mohan

Date Published: May 1977

NOTICE This document contains information of a preliminary nature. It is subject to revision or correction and therefore does not represent a final report.

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ABSTRACT

When superconducting magnets quench, the resistance of the conductor material rises rapidly to its normal value. This increase in resistance can result in catastrophic heating in the magnet unless stored field energy is quickly removed from the system.

Phase inversion is the normal mode of energy removal. SCR's in the power supply are phased back, the output of the supply is inverted, and magnetic field energy is directed back into the utility grid.

Under certain conditions, however, the power supply may fail to invert properly, and an alternate energy removal scheme must protect the superconducting magnet system. Composed of an isolation switch, a semiconductor switching module, and a dump resistor, the resistive dump device provides a viable protection scheme.

Operationally, several conditions are capable of activating the isolation switch and triggering the bipolar SCR switching module. Manual dump commands, for instance, permit the operator to dump field energy in the event of observed abnormalities. A special voltage tap quench detector senses the aforementioned abnormal power supply output inversion and also fires the dump circuit.

Regardless of the nature of the trigger input, however, activation of the energy dump device diverts coil current through the dump resistor. I^2R losses over time then safely dissipate stored magnetic field energy.

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ACKNOWLEDGMENTS

The author would like to thank Mr. R. E. Schwall, of the Superconducting Magnet Development Division at Oak Ridge National Laboratory, for his help in defining design parameters and providing technical information on superconductor theory. Mr. E. W. Pipes, of the Y-12 Plant Electrical Engineering Department, also deserves special recognition for his tireless assistance and seemingly limitless technical expertise. Mr. Pipes developed the semiconductor switching circuit at the heart of the dump device.

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LIST OF FIGURES

1. INTRODUCTION

Superconducting materials are bounded in their resistanceless behavior by critical values of temperature, magnetic field and current density (See Figure 1) which, if exceeded, cause the superconductor to quench or return to its normal conducting state.[1] When present in magnet systems, the quenched superconductor creates a serious problem in dealing with energy stored in the field of the magnet. Unless current in normal portions of the magnet is shunted to a highly conductive normal conductor (usually copper) surrounding the superconductor and field energy is quickly and safely removed from the system, catastrophic heating may result.[2] In the event of failure of phase inversion techniques where field energy is fed back into the utility grid, energy dissipation in the superconducting magnet system described must occur through an appropriate energy dump device.

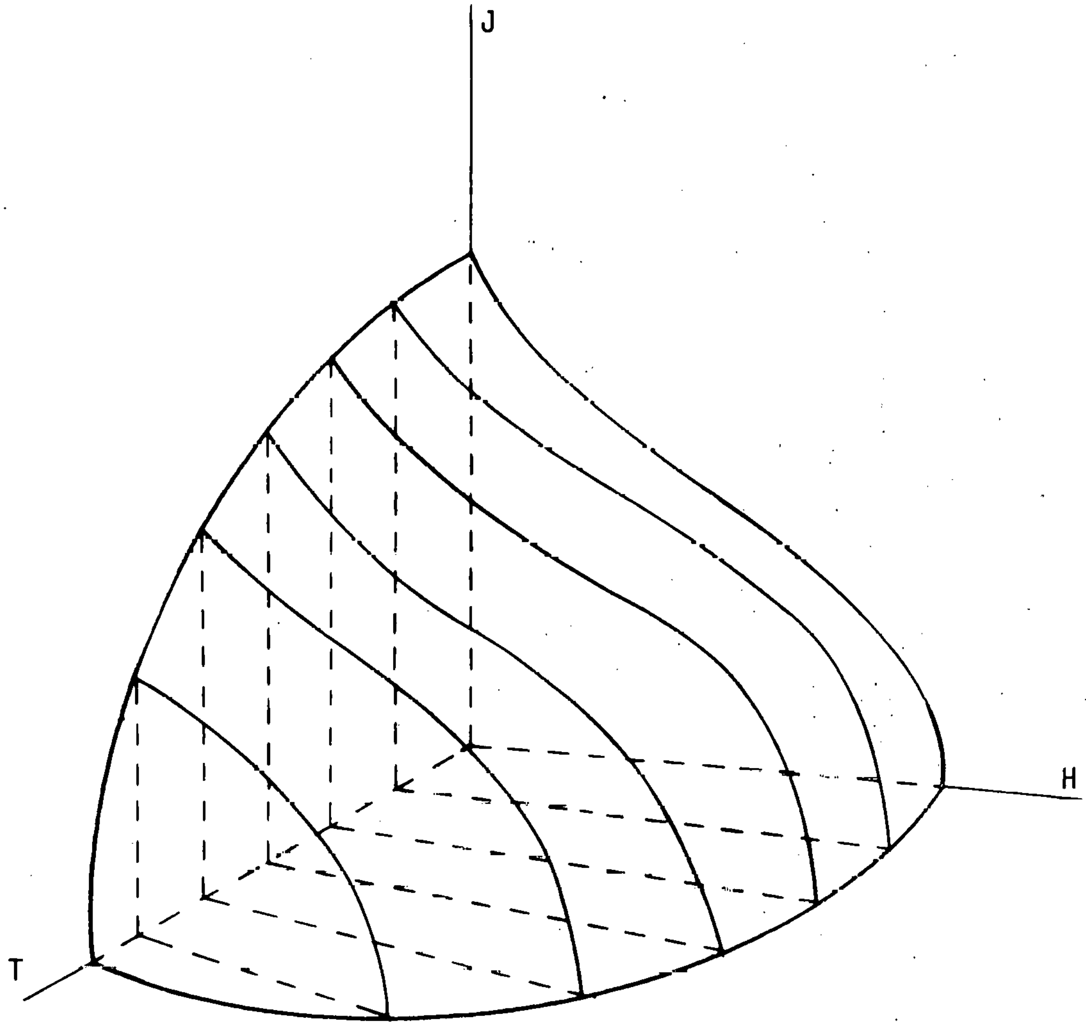

Fig. 1. Superconducting region bounded by critical J-H-T surface. Superconducting region below surface, resistive "normal" region above surface. (From Ref. 3)

2. THE ENERGY DUMP DEVICE

The circuit described is designed for use with a 2 kA, 300 V bipolar power supply. The three major elements of the dump device are a semiconductor switch, a dump resistor, and a 13.8 kV ac circuit breaker used as an isolation switch. (See Figure 2)

2.1 THE SEMICONDUCTOR SWITCHING MODULE

2.1.1 Design Considerations

The purpose of the semiconductor switch is to provide a path for coil current through the dump resistor. See Figure 3. Because of the bipolar nature of the power supply, the switch must be capable of accommodating current in two directions but not short the output of the supply under normal operating conditions. Also, the switch must have a minimum forward blocking voltage greater than 300 V and be capable of enduring a current decaying exponentially from 2000 A at a maximum time constant of 3 seconds.

The switching device chosen was a Westinghouse Type T920 Pow-R-Disc SCR, manufacturer's number T920121003 DW.* Data sheets are contained in Appendix A.

The rated 1200 V maximum forward blocking voltage of the device well exceeds minimum design requirements. It will be noted, however, that the device is rated for 1000 A average and 1570 A RMS forward current. It was therefore necessary to determine whether or not the junction temperature of the SCR would rise unacceptably during a dump procedure.

A worst case estimate of temperature rise was made by converting the power input curve shown in Figure 4a to the series of pulses shown in Figure 4b as described in reference 4. Next, the transient thermal impedance of the SCR and thermal impedance between the SCR case and heat-sink were determined from manufacturer's data.

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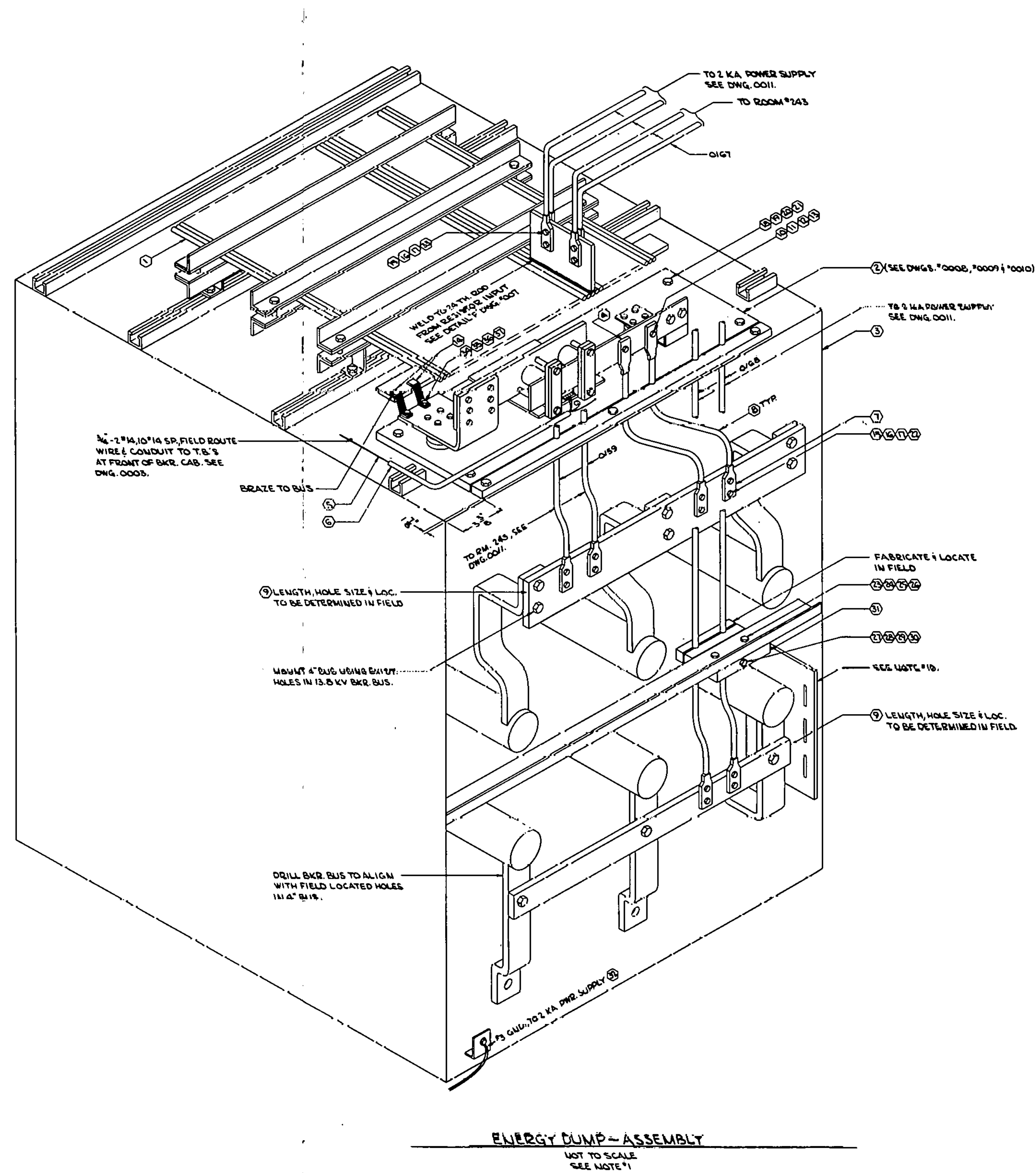
*Reference to a company or product name does not imply approval or recommendation of the product by Union Carbide, the Oak Ridge National Laboratory, or the U. S. Energy Research and Development Administration to the exclusion of others that may be suitable, equal, or superior.



NOTES:

1. PERFORM THE FOLLOWING WORK ON THE 13.8 KV BKR. CABINET:

   A. DISCONNECT P.T. LEADS ON P.T. COMPARTMENT SIDE; COIL LEADS IN BKR. COMPARTMENT AND LEAVE INTACT

   B. DISCONNECT BUS WHERE IT IS PRESENTLY JOINED TO VERTICAL BUS BARS LEADING TO THE LOWER ROW OF BKR. RECEPTACLES.

   C. REMOVE THE P.T. COMPARTMENT AND GND. BAR.

   D. BOLT INSULATING BUS BAR SUPPORT PNL. AT REAR OF BKR. COMPARTMENT INTO PLACE.

   E. DISCONNECT EXISTING BUS AT THE JOINT IMMEDIATELY TO THE POTHEAD SIDE OF THE C.T.'S.

   F. REMOVE THE POTHEAD AND ATTACHED BUS.

   G. SHORT C.T. OUTPUT TERMINALS AT THE TRANSFORMER AND AT THE CORRESPONDING TERMINAL BLOCK LOCATIONS AT THE FRONT OF THE BKR. COMPARTMENT.

   H. REMOVE JUNCTION BOX AT FRONT RIGHT HAND SIDE OF BKR. COMPARTMENT.

   I. MOVE THE BKR. COMPARTMENT TO THE LOCATION INDICATED ON DWG. #0011.

2. INSTALLATION SHALL COMPLY WITH ES 1.4-5.

3. FOR LEGEND AND REFERENCE DWGS., SEE DWG. #0001.

EQUIPMENT LIST

ITEM	DESCRIPTION
1	RESISTOR, DUMP, TAPPED AT .15 OHM PER DWG. 0006, ON HAND
2	DUMP LOGIC & SWITCHING MODULE, SUPPLIED BY UCC-ND
3	13.8 KV BKR. & CABINET, ON HAND
4	LUG, CABLE, ALUMINUM, ONE HOLE, FOR 1000 MCM CABLE, T & B CAT. NO. 60184
5	WIRE, COPPER, #14, SOLID, TFE INSULATION
6	CONDUIT, EMT, 3/4"
7	LUG, CABLE, ALUMINUM, TWO HOLE, FOR 1000 MCM CABLE, T & B CAT. NO. 60284
8	CABLE, COPPER, 1000 MCM, 61 STRAND, 600 V., FURNISHED BY UCC-ND
9	BUS, COPPER, 4 IN. WIDE X 1/2 IN. TH.
10	SCREW, CAP, HEX, SILICONE BRONZE (S.B.), 5/8-11 X 2 IN. LONG
11	WASHER, FLAT, S.B., TYPE A WIDE SERIES PER ANSI STD. B27.2, FOR 5/8 IN. DIA. BOLT
12	WASHER, LOCK, S.B., FOR 5/8 IN. DIA. BOLT
13	NUT, HEX, S.B., 5/8-11 THD.
14	BRAID, COPPER, FLEXIBLE, BURNDY CAT. NO. B4D12
15	WASHER, FLAT, S.B., TYPE A, WIDE SERIES PER ANSI STD. B27.2, FOR 1/2 IN. DIA. BOLT
16	WASHER, LOCK, S.B., FOR 1/2 IN. DIA. BOLT
17	NUT, HEX, S.B., 1/2-13 THD.
18	SCREW, CAP, HEX, S.S., 1/2-13 X 2 IN. LONG
19	WASHER, FLAT, S.S., FOR 1/2 IN. DIA. BOLT
20	WASHER, LOCK, S.S., FOR 1/2 IN. DIA. BOLT
21	NUT, HEX, S.S., 1/2-13 THD.
22	SCREW, CAP, HEX, S.B., 1/2-13 X 2 IN. LONG
23	SCREW, CAP, HEX, S.S., 3/8-16 X 1-1/2 IN. LONG
24	WASHER, FLAT, S.S., FOR 3/8 IN. DIA. BOLT
25	WASHER, LOCK, S.S., FOR 3/8 IN. DIA. BOLT
26	NUT, HEX, S.S., 3/8-16 THD.
27	BOLT, HEX HEAD, S.S., 1/4-20 BY LENGTH AS REQ'D
28	WASHER, FLAT, S.S., FOR 1/4 IN. DIA. BOLT
29	WASHER, LOCK, S.S., FOR 1/4 IN. DIA. BOLT
30	NUT, HEX, S.S., 1/4-20 THD.
31	SHEET, MICARTA, 3/4 IN. TH.
32	WIRE, COPPER, #3, SOLID
33	SCREW, CAP, S.B., HEX HEAD, 1/2-13 X 2-1/2" LONG
34	SCREW, CAP, S.B., HEX HEAD, 3/8-16 X 1-1/2" LONG
35	NUT, HEX, S.B., 3/8-16 THD.
36	WASHER, FLAT, S.B., FOR 3/8" DIA. BOLT
37	WASHER, LOCK, S.B., FOR 3/8" DIA. BOLT
38	BUSHING, INSULATING, END, FOR 3/4" EMT

Fig. 2. Assembly of the dump device.

UNION CARBIDE CORPORATION · NUCLEAR DIVISION

SUPERCONDUCTING MAGNET DEVELOPMENT
2 KA POWER SUPPLY
ENERGY DUMP ASS'Y

SMD 2KA PS ENERGY DUMP

DES M. MOHAN 2-77
DRW R. PENLAND JR. 2-77

PLANT Y-12 · BLDG 9204-1 · SCALE NONE · E2E 14390 0006 · REV 0

O — FOR APPROVAL

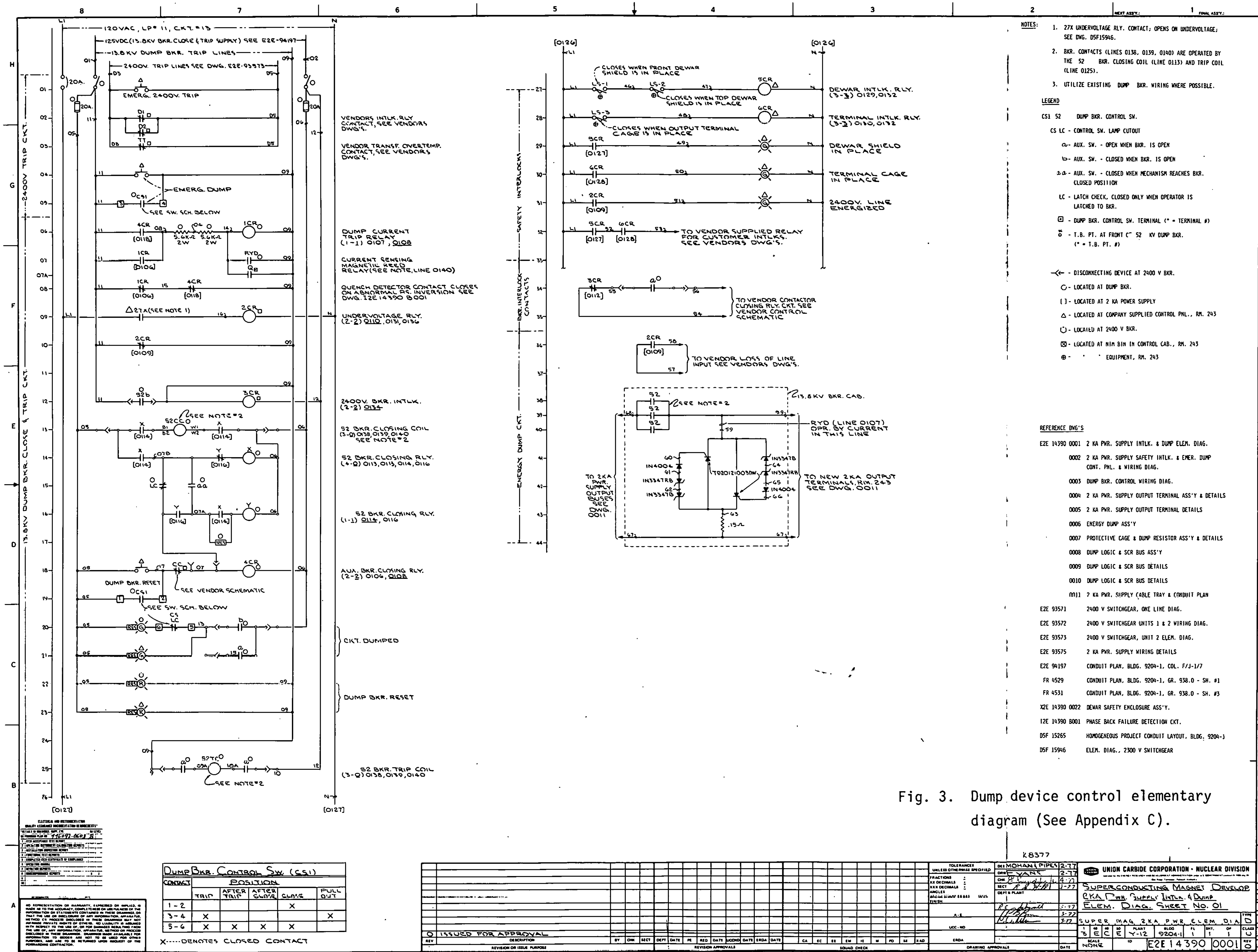
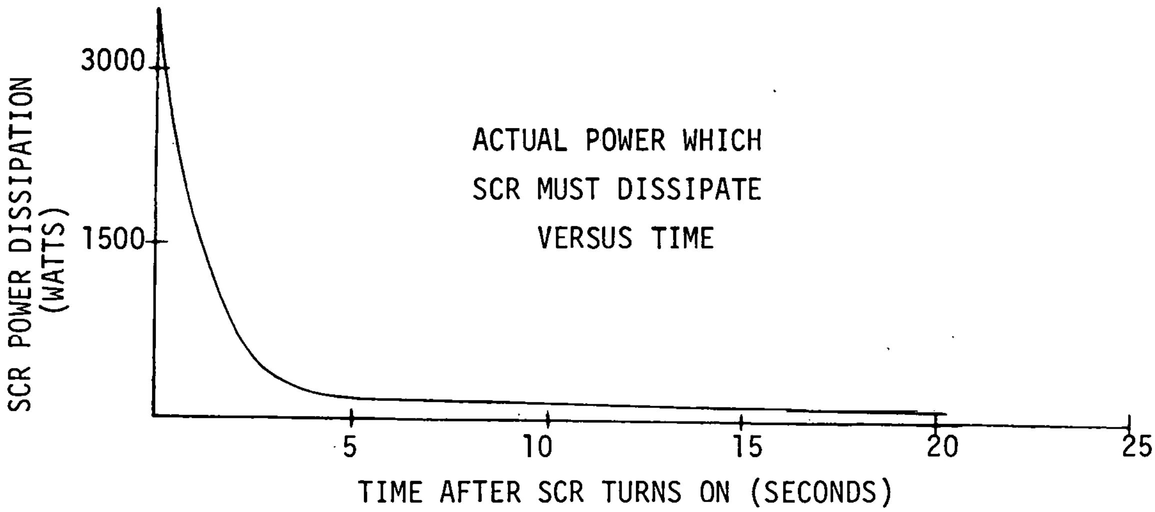
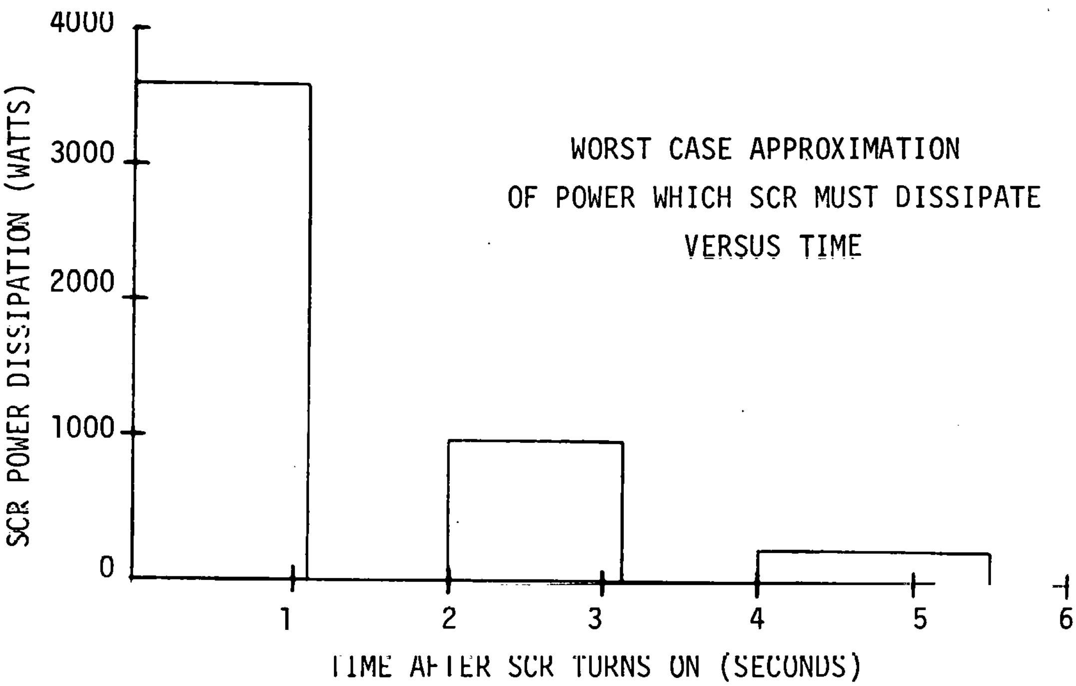


Fig. 3. Dump device control elementary diagram (See Appendix C).



(a)



(b)

Fig. 4. Actual and Approximated SCR Power Dissipation Versus Time.

In order to complete the thermal circuit of the SCR and to calculate a junction temperature rise, characteristics of the heatsink were considered. Transient thermal impedance of the heatsink, $\theta_{(t)F}$, was calculated from the expression:

$$\theta_{(t)F} = \frac{1}{hxA} \left(1-e^{-t/RC}\right) \ {}^{o}C/Watt,$$

where h is the total heat transfer coefficient of the heatsink in watts/in^2 - ^oC, A is the sink's surface area in in^2 and RC is the thermal time constant of the system in seconds. Substituting known values for A and RC, $\theta_{(t)F}$, was expressed as a function of h. A graph of the relation, however, indicates $\theta_{(t)F}$ varies only approximately 1 x 10^{-5} ^oC/Watt while h varies from 10^{-8} to 10^{-2} watt/in^2 -^oC. The short electrical time constant of the circuit thus limits the significance of heatsink configuration. After approximating h from nomographs in reference 4 to insure $10^{-8} < h < 10^{-2}$, $\theta_{(t)F}$ was estimated at 1.5 x 10^{-3} ^oC/Watt.

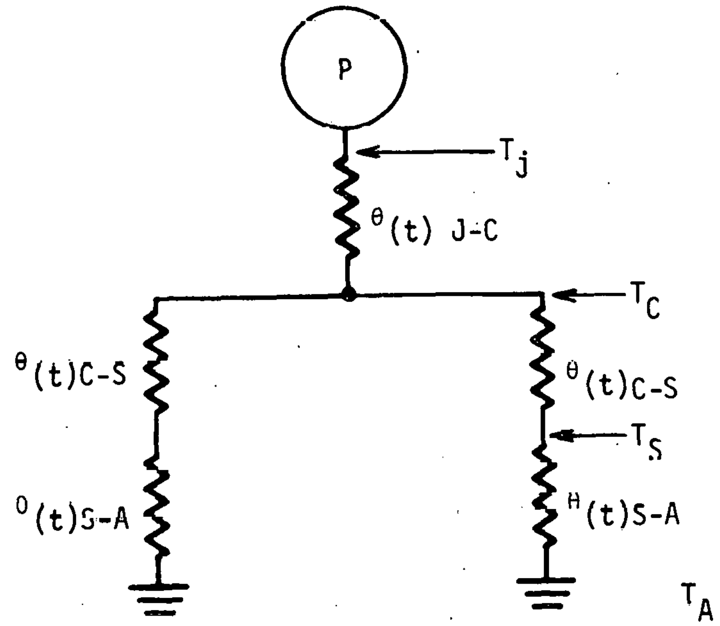
The complete thermal circuit is shown in Figure 5. Calculation indicates that with $T_{ambient} = 25^oC$, the SCR junction temperature will rise to a maximum of 122.4^oC. No junction overheating difficulties are therefore foreseen as maximum rated junction temperature is 125^oC and the estimate is based on a worst case.

Finally, a symmetrical switch assembly, described more fully under "Description of Circuit Operation", allows the required bidirectional dump current.

2.1.2 Construction

An assembly view of the SCR switch is shown in Figure 6. A modular concept was adopted so that the device could be assembled and tested under controlled conditions.

The base of the switching module is one inch thick laminated phenolic board. The L shaped end brackets are held by 6 inch high



P = SCR power dissipation, Watts; See Fig. 3b.

$\theta(t)_{J-C}$ = Transient thermal impedance between SCR junction & case See Appendix A.

$\theta(t)_{C-S}$ = Transient thermal impendance between case & heatsink $\approx 0.01\ ^{\circ}C/Watt$.

$\theta(t)_{S-A}$ = Transient thermal impedance between heatsink & ambient $\approx 0.0015^{\circ}C/Watt$.

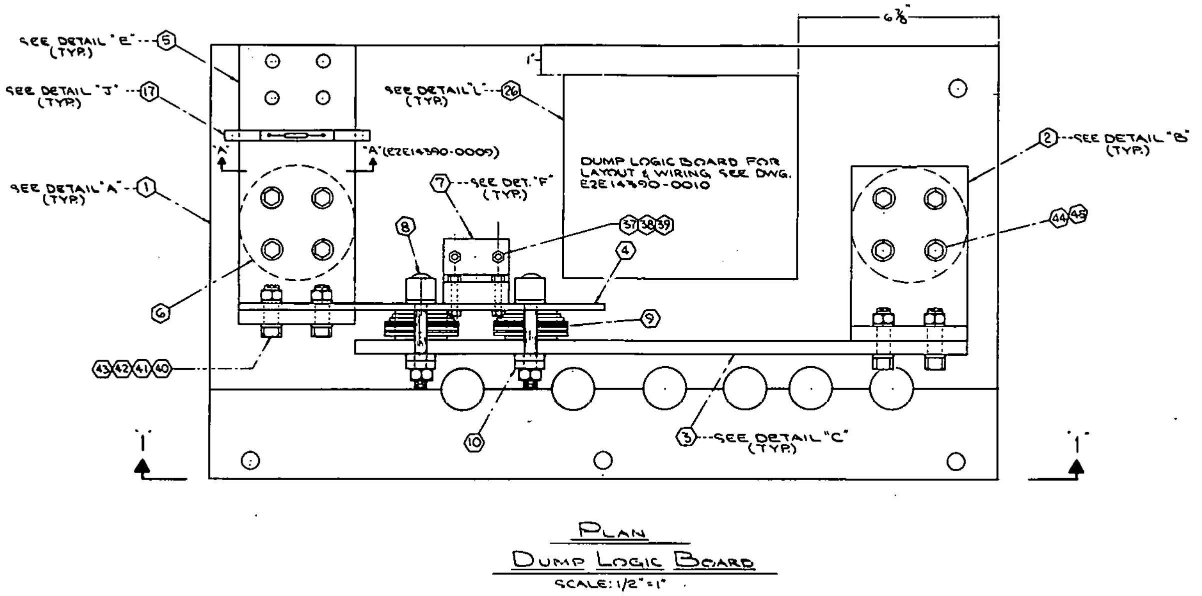
T_j = junction temperature, °C

T_C = SCR case temperature, °C

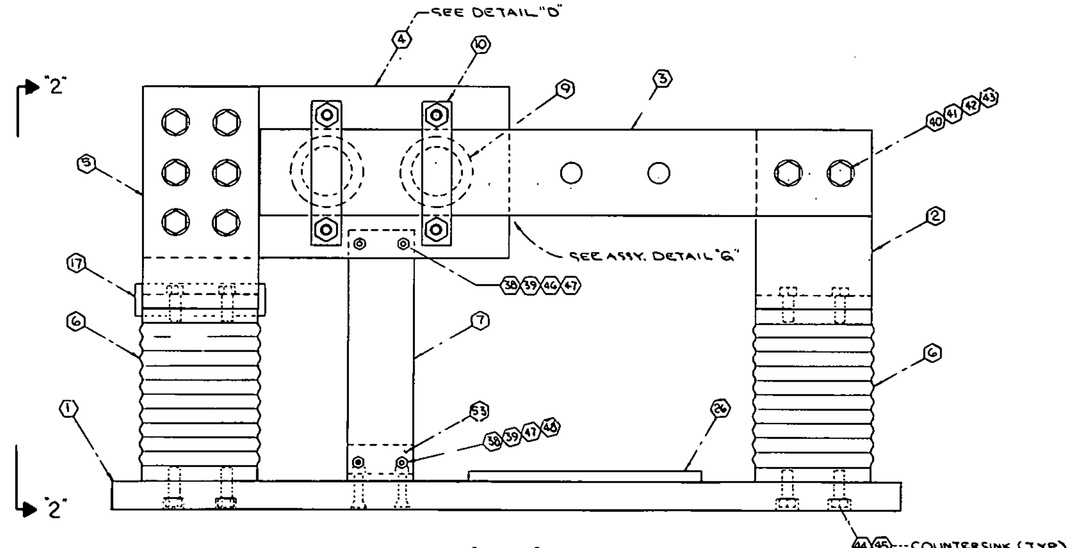
T_S = heatsink temperature, °C

T_A = ambient temperature, °C

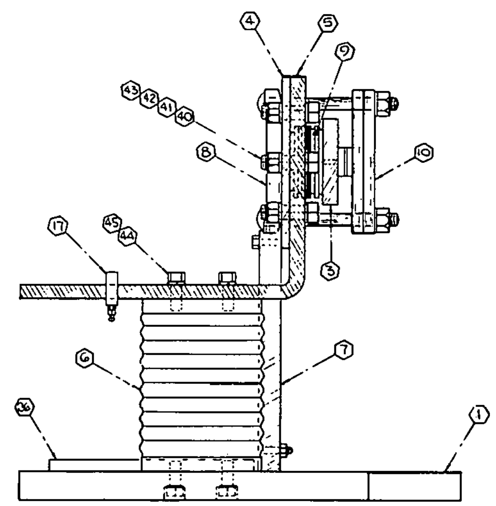
Fig. 5. SCR Thermal Circuit.



PLAN
DUMP LOGIC BOARD
SCALE: 1/2"=1"



"1 – 1"
SCALE: 1/2"=1"
(SEE NOTE #7)



"2 – 2"
SCALE: 1/2"=1"

EQUIPMENT LIST

ITEM	DESCRIPTION
1	BOARD, PHENOLIC, LAMINATED (MICARTA), 27" X 15" X 1" TH.
2	BUS, COPPER, 4" WIDE X 1/2" TH.
3	BUS, COPPER, 4" WIDE X 1/2" TH., CUT TO 3" WIDTH
4	BUS, COPPER, 6" WIDE X 1/4" TH.
5	BUS, COPPER, 4" WIDE X 1/2" TH.
6	STANDOFF, BUS, 4" DIA. X 6" HIGH, ON HAND
7	BOARD, PHENOLIC, LAMINATED (MICARTA), 2-1/2" X 3/4" TH.
8	BAR, STUD, WAKEFIELD CAT. NO. 139-E, ON ORDER
9	SCR, 1200 V, 1000 A, WESTINGHOUSE CAT. NO. T920121003 DW, ON ORDER
10	CLAMP, MOUNTING, SPRING ASSEMBLY, WAKEFIELD CAT. NO. 139-2, ON ORDER
11	NUT, HEX, SUPPLIED WITH ITEM #10
12	TERMINAL, CRIMP, FOR #22 WIRE, ON HAND
13	SCREW, MACHINE, S.S., ROUND HEAD, FOR ITEM #12, ON HAND
14	WASHER, LOCK, S.S., FOR ITEM #13, ON HAND
15	NUT, HEX, S.S., FOR ITEM #13, ON HAND
16	BOARD, PHENOLIC, LAMINATED (MICARTA), 3/8" X 1/4" TH.
17	STEEL, CARBON, COLD ROLLED, 3/8" WIDE X 1/4" TH.
18	RELAY, REED, MAGNETIC, HAMLIN CAT. NO. MSRR-2, ON ORDER
19	PIN, TERMINAL, BENDIX NO. 10-40569
20	WIRE, HOOKUP, #22, ON HAND
21	NUT, HEX, S.S., #10-24
22	SCREW, MACHINE, S.S., ROUND HEAD, #10/24 X 3/4" LONG
23	SCREW, MACHINE, S.S., FLAT HEAD, #4/40 X 3/4" LONG
24	WASHER, LOCK, S.S., FOR #4 MACHINE SCREW
25	NUT, HEX, S.S., FOR #4/40 SCREW
26	BOARD, PHENOLIC, LAMINATED (MICARTA), 7" X 8" X 3/8" TH.
27	DIODE, ZENER, 160 V, 50 W, 5% TOLERANCE, CATHODE CONNECTION VIA STUD, TYPE NO. 1N3347RB, ON ORDER
28	DIODE, ZENER, 160 V, 50 W, 5% TOLERANCE, ANODE CONNECTION VIA STUD, TYPE NO. 1N3347B, ON ORDER
29	INSULATOR, STANDOFF, 3/8" X 1" HIGH
30	SCREW, MACHINE, S.S., ROUND HEAD, #6-32 X 1/2" LONG
31	STRIP, TERMINAL, 6 POINT, CINCH-JONES CAT. NO. 6-141
32	DIODE, RECTIFIER, TYPE 1N4004
33	STRIP, TERMINAL, 16-1/2" LONG X 1-3/4" WIDE
34	PLATE, ALUMINUM, 1" X 1/8" TH.
35	WASHER, FLAT, S.S., FOR 1/4" DIA. BOLT
36	NUT, HEX, S.S., 1/4-28 THD.
37	SCREW, MACHINE, S.S., FLAT HEAD, 1/4-20 X 2" LONG
38	WASHER, LOCK, STEEL, FOR 1/4" DIA. BOLT
39	NUT, HEX, S.S., 1/4-20 THD.
40	SCREW, CAP, SILICONE BRONZE, HEX HEAD, 1/2-13 X 2" LONG
41	WASHER, LOCK, S.B., FOR 1/2" DIA. BOLT
42	NUT, HEX, S.B., 1/2-13 THD.
43	WASHER, FLAT, S.B., TYPE A, WIDE SERIES PER ANSI STD. B27.2, 1-3/8" O.D., .109" TH., FOR 1/2" DIA. BOLT
44	SCREW, CAP, S.S., HEX HEAD, 3/8-16 X 1-1/4" LONG
45	WASHER, LOCK, S.S., FOR 3/8" DIA. BOLT
46	SCREW, CAP, S.S., HEX HEAD, 1/4-20 X 1-1/2" LONG
47	WASHER, FLAT, S.S., FOR 1/4" DIA. BOLT
48	SCREW, MACHINE, S.S., FLAT HEAD. 1/4-20 X 1-1/2" LONG
49	WASHER, FLAT, S.S., FOR #6 SCREW
50	SCREW, MACHINE, S.S., FLAT HEAD, #6-32 X 3/4" LONG
51	WASHER, BELLEVILLE, FOR 1/4" DIA. BOLT
52	LUBRICANT, THERMAL, ALCOA #2
53	ANGLE, ALUMINUM, 1-1/2" X 1-1/2" X 1/4" TH.

REF. DWG'S
E2E 14390-0009
E2E 14390 0010

NOTES:

1. BOLT CHASSIS TO 1" MICARTA APPROXIMATELY AT LOCATION SHOWN.
2. SURFACE MUST BE CLEANED OF OXIDES, FILM, ETC., OR WITH ZINC CHROMATE CONVERSION ON ALUMINUM.
3. THE SEMICONDUCTOR DEVICES MUST BE MOUNTED USING A THERMAL LUBRICATING COMPOUND (52) AS FOLLOWS.
   A. DISPENSE THE COMPOUND FROM A TUBE OR USE A SOLID APPLICATOR. OTHER APPLICATORS LEAVE LINT AND GRIT AND SHALL NOT BE USED.
   B. APPLY COMPOUND IN THE GEOMETRIC CENTER OF EACH CONTACT AREA FOR ITEM #9 AND AROUND THE STUD FOR ITEM #'S 27 AND 28.
   C. ROTATE THE DEVICE, SPREADING THE COMPOUND OVER THE MOUNTING SURFACES.
   D. CHECK TO INSURE DEVICE IS POSITIONED AS ILLUSTRATED.
   E. FOR ITEM #9: MOUNT WITH A FORCE OF 5000 LBS. EXTREME CARE MUST BE TAKEN TO TIGHTEN OPPOSITE ENDS OF ITEM #10 EVENLY. OTHERWISE, AN UNACCEPTABLE INTERFACE RESULTS. USE CAUTION; ITEM #10 BECOMES VERY BRITTLE NEAR 5000 LBS. APPLIED FORCE.

      FOR ITEM #'S 27 AND 28: TIGHTEN BELLEVILLE NUT FINGER TIGHT PLUS 1/2 REVOLUTION.
   F. IF DEMOUNTING IS REQUIRED, CLEAN ALL SURFACES AND REPEAT STEPS A THRU E.
4. THE THERMAL LUBRICANT IS AN INSULATOR. CARE MUST BE TAKEN TO PROVIDE A THIN FILM OF COMPOUND AND APPROPRIATE MOUNTING PRESSURE AT ALL JOINTS.
5. HOLE MUST BE DRILLED AT 90° TO MOUNTING SURFACE.
6. LOCATE CONNECTION IN THE FIELD.
7. COUNTERSINK BOLT HEADS ON REVERSE SIDE OF BOARD TO MAINTAIN FLAT MOUNTING SURFACE.
8. LOCATE HOLES FOR STANDOFFS AFTER ALL OTHER PORTIONS OF THE SCR AND BUS DEVICE HAVE BEEN ASSEMBLED. THE DEVICE MUST NOT BE PLACED UNDER STRESS DUE TO IMPROPERLY LOCATED BUS SUPPORTS.
9. CENTER REED SW. ON ITEM #16 AND SOLDER LEADS TO FIELD LOCATED TERMINAL PINS. REED LEAF FACES MUST BE PARALLEL TO THE BUS SURFACE AND LOWER ENDS OF PINS MUST NOT TOUCH BUS.
10. USE #22 HOOKUP WIRE UNLESS OTHERWISE SPECIFIED.
11. SEE DWG. 0001 FOR LEGEND AND REFERENCE DWG'S.

ALL WORK SHOWN ON THIS DRAWING TO BE PERFORMED BY UCC-ND

Fig. 6. Assembly of the switching module.

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SUPERCONDUCTING MAGNET DEVELOP. DUMP LOGIC & SCR BUS ASSEMBLY
DUMP LOGIC+SCR BUS ASSY
E2E 14390 0008

porcelain bus supports. The vertical bus bars which make electrical and thermal connection to the SCR's are prepared per Figure 7. Assembly procedures are extremely important and manufacturer's recommendations must be followed to prevent excess thermal and electrical impedance at the SCR case to heatsink junction.

2.2 THE DUMP RESISTOR

2.2.1 Operating Parameters

Actual dissipation of energy in the dump circuit is seen as heat in a stainless steel resistor. Since at maximum coil current it is desired to see only approximately 300 volts across the dump resistor, the resistance value required is 0.15Ω. Also, the temperature of the resistor must not rise to an unacceptable level when maximum dump energy input is 1 MJ.

Performing the conversion on the curve shown in Figure 8a to obtain the pulses shown in Figure 8b and determining the transient thermal impedance of the resistor as described earlier, a maximum resistor temperature of 92°C is expected when $T_{ambient} = 25°C$. Since the insulation of cables attached to the resistor is rated for 75°C, the conductors have been attached far enough away from the resistor to prevent overheating as described below.

2.2.2 Construction

The resistor used in the 300 V, 2 kA application was an existing device constructed of parallel four foot lengths of 1/2 inch diameter 304 stainless steel rods welded in series. Twenty-four such rods are required for 0.15Ω total resistance. See Reference 5.

Electrical connections are made via 1/2 inch thick stainless steel plates welded to the rods. The entire device is insulated thermally and electrically from aluminum angle support members by 1/2 inch thick strips of Marinite inserted between 2" x 2" x 1/4" sections of aluminum angle. See Figure 9.

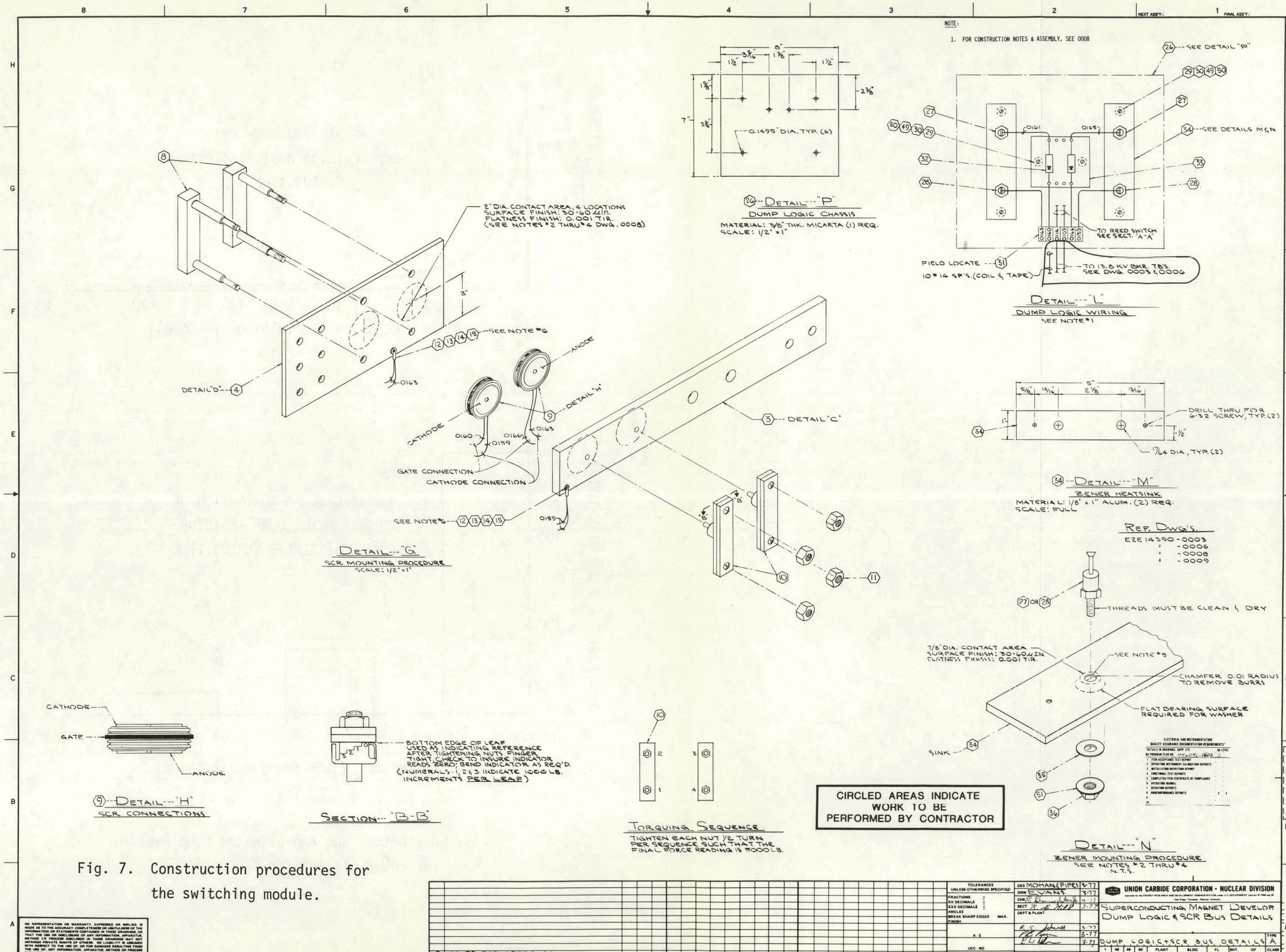
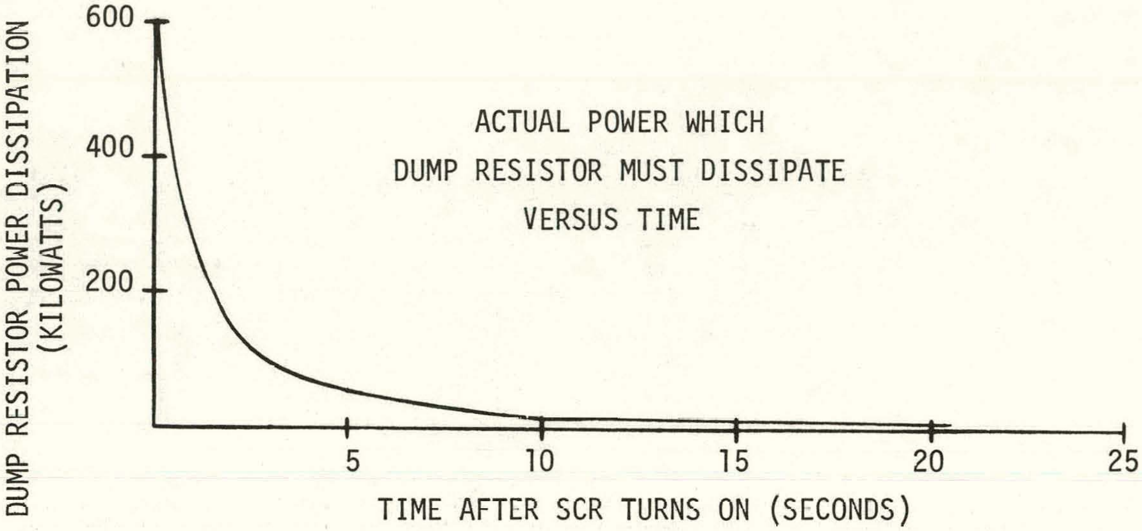
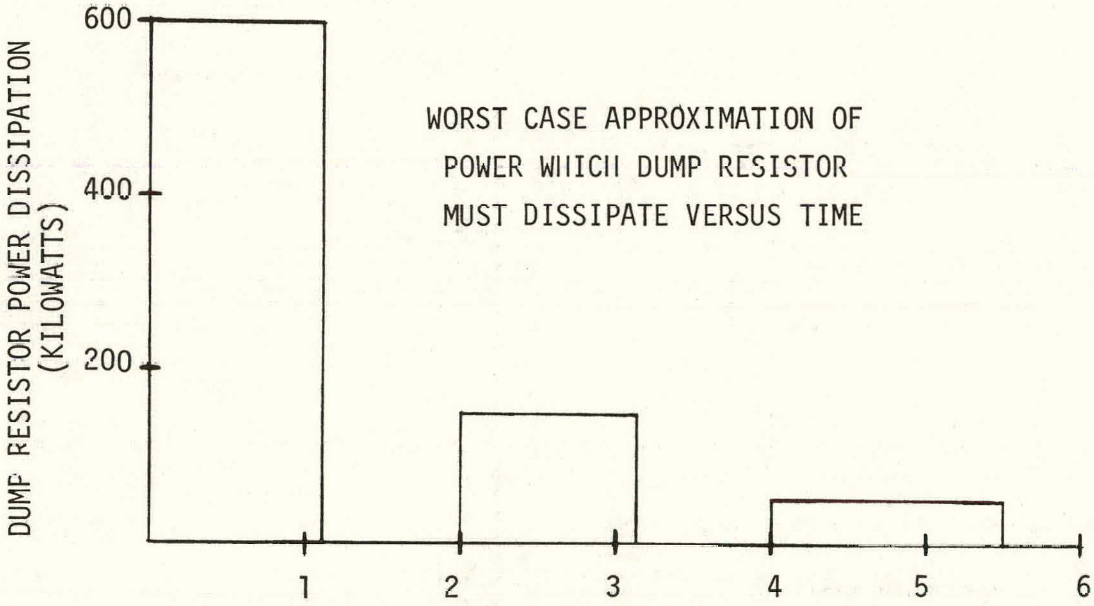


Fig. 7. Construction procedures for the switching module.



(a)



(b)

Fig. 8. Actual and Approximated Dump Resistor Power Dissipation Versus Time.

ORNL-DWG 76-1612

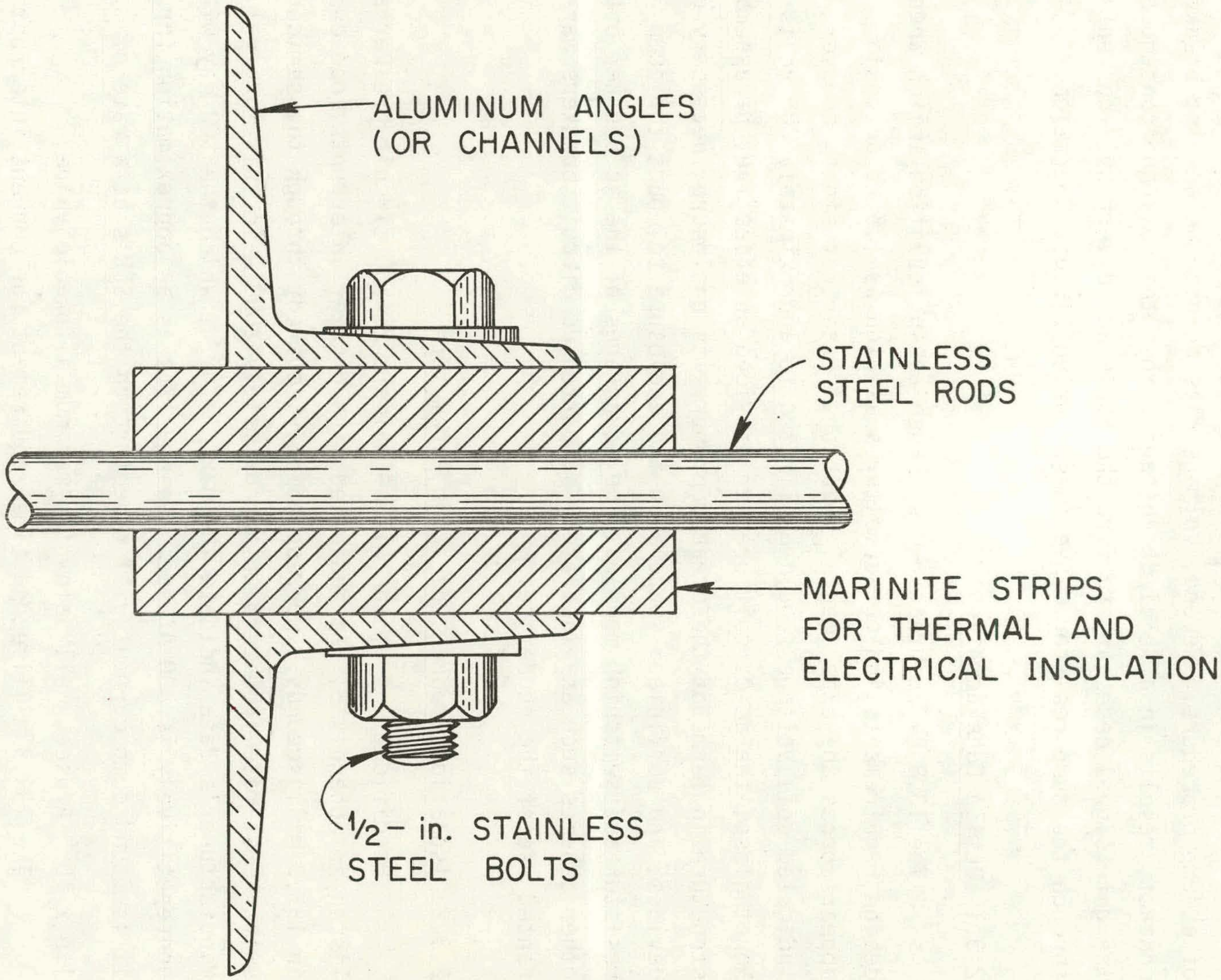


Fig. 9. Dump Resistor Support Detail.

2.3 THE ISOLATION BREAKER

In the present application, the role of the dump breaker is twofold. First, it isolates the power supply from the loadside conditions of a dump procedure. Second, voltage rise across the opening breaker contacts results in a -L di/dt voltage across the coil and consequently the gate signal necessary to fire the SCR's and divert coil current through the dump resistor. See "Description Circuit Operation."

2.3.1 Design Considerations

The 13.8 kV ac breaker was chosen as an isolation switch when design requirements indicated voltages as high as 1.5 kV dc could appear across the experimental inductor. Later revisions, however, indicated coil voltage should be limited to approximately 300 volts dc. Nonetheless, the ac circuit breaker provided an effective, preassembled structure in terms of the breaker proper, its enclosure, necessary control devices, and sufficient space atop the enclosure to mount the dump resistor and switching module. The advantages of the ac breaker over other schemes such as elaborately supported dc circuit breakers warranted use of the ac device.

2.3.2 Isolation Breaker Operating Parameters

Specifications of the Allis-Chalmers MC-500 circuit breaker are listed in Appendix B. As indicated, the breaker interrupts load current in 133.3 milliseconds. Correspondingly, current through the semiconductor switch must rise from zero to approximately 2000 A in this interval. Manufacturer's data indicate the maximum di/dt which the SCR may withstand nonrepetitively is 800 A/μsec. Using $\Delta i/\Delta t$ as an approximation for di/dt, it is found dump current will rise through the SCR's at a rate of 1.5×10^{-2} A/μsec, well below the maximum allowable value.

The 133.3 millisecond time requirement for current interrupt also implies field energy dissipation before experimental coils are damaged by hot spot formation. For example, the time scale describing magnet heating characteristics during a quench depends upon the current density, magnetic field, and heat transfer characteristics of the magnet. Choosing the low representative values of maximum field B_m = 1.8 tesla and current density J = 1.7 kA/cm^2, magnet temperatures will reach 100°K in four minutes and 300°K in 7.4 minutes when adiabatic heating at constant current is assumed. Higher representative values such as B_m = 8 tesla and J = 4.2 kA/cm^2 suggest a temperature of 100°K in only 24 seconds.[6] Higher values for B_m and J therefore indicate sufficient isolation switch operating speed, but illustrate the need for automatic dump signals as described in the next section.

3. DUMP STAGING

3.1 TRIGGER INPUTS

Consideration of operating contingencies led to a list of conditions which, if existing, should initiate a signal to dump stored magnetic energy. The first condition is based on operator judgment. Should abnormal operation be observed, a manual switch may trigger the energy dump device. Second, should power supply output inversion fail to discharge a quenched inductor, the dump mechanism is automatically activated. Third, loss of primary power must initiate a dump command as line loss implies no utility grid for the inversion process. Finally, a current sensing magnetic reed relay located at the semiconductor switching module insures full dump staging in the event a short current pulse passes through the SCR switches or device failure permits excess leakage current through the dump device.

3.2 DESCRIPTION OF CIRCUIT OPERATION

Circuit operation during a dump procedure is characterized first by the opening of the isolation switch, second by consequent - Ldi/dt inductor voltage rise, and third by energy dissipation in the dump resistor. Considering dump breaker operation, Figure 3 indicates all the previously described trigger inputs provide a low resistance path across the trip lines of the 13.8 kV dump breaker. The manual switches located at a remote control panel and at the dump breaker tie the trip coil (line 25) directly across the 125 VDC battery supply, opening the circuit breaker.

Operation of the reed relay is more subtle, however. First, as shown in Figure 10, the relay is positioned so as to be activated by field lines created by dump current. The relay used is designed to pull in 17.5 ± 7.5 ampere-turns magnetomotive force. Considering the bus in section A-A, Figure 10, as a single turn, the relay may not operate until a dump current of 25 amperes flows. To increase the sensitivity of the device, the field shunt (item 17, Figure 10) may be

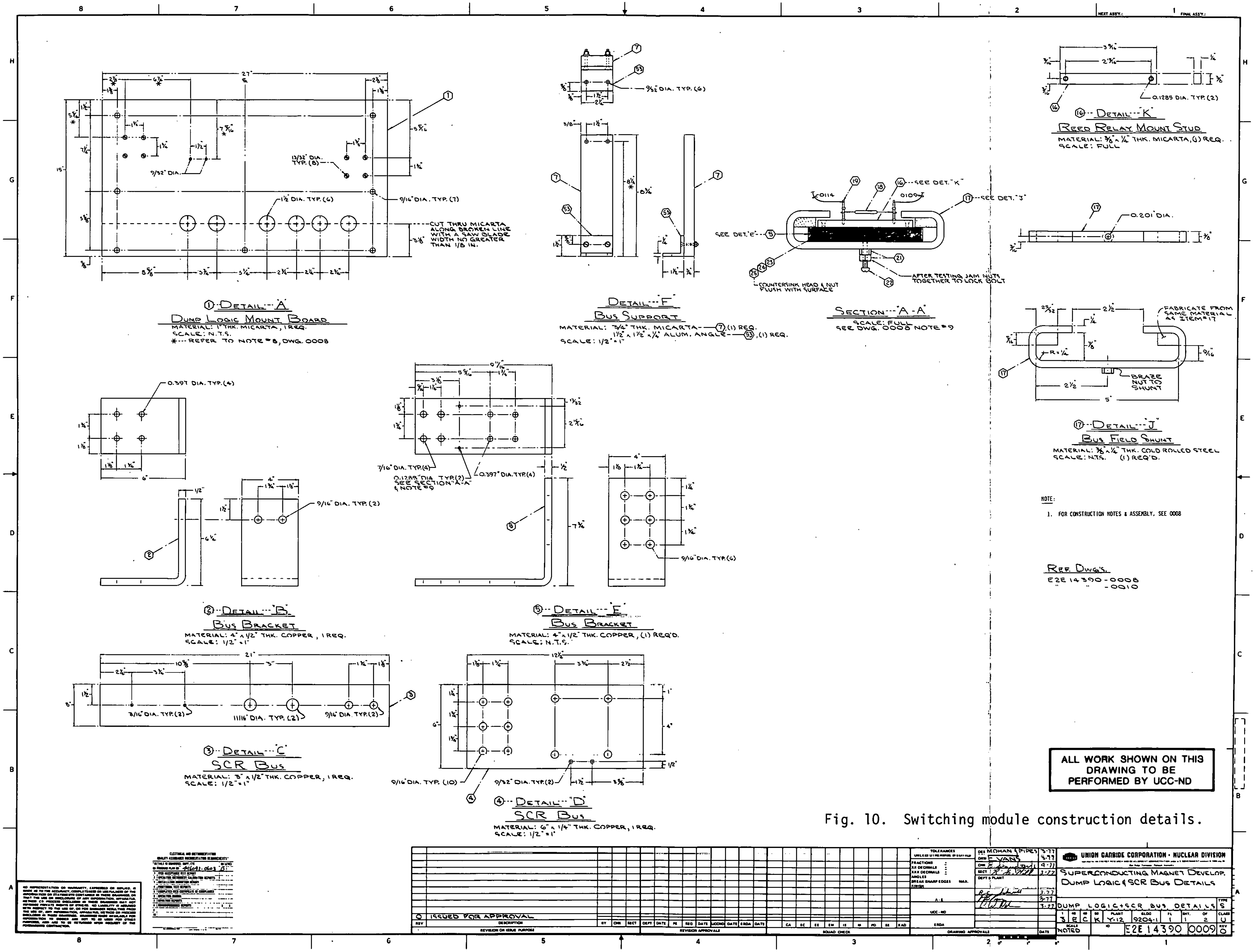


Fig. 10. Switching module construction details.

adjusted to control magnetization of the reed leaves and thus the current level necessary for operation. At required current, the reed relay contacts (RYD) touch, shorting out 1 CR, de-energizing the normally closed 1 CR relay contact in line 08, Figure 3 and tripping the dump breaker.

Third, loss of 2400 V utility power is detected by an undervoltage relay which opens the 27 X relay contact in line 09, Figure 3. Control relay 2 CR de-energizes and the dump breaker is opened.

Fourth, a specially designed quench detector circuit may open the dump breaker. See Figure 11. By monitoring resistive voltage across an experimental inductor,[7] the detector circuit senses a quenching coil and commands power supply SCR's to phase back and route magnetic field energy back into the utility grid. If however, coil voltage does not lie between 270 V and 330 V within a period of 80 milliseconds, the power supply is assumed to have failed to invert and contact Q in line 07A closes. Subsequent dump staging is then identical to that in the event of an RYD contact closure. Next, should the 2400 V primary power circuit breaker open, the 52b contact in line 12 closes and trips the dump breaker.

Finally, if the integral contactor in the power supply is opened under load conditions, manufacturer provided circuits detect abnormal inductive voltage rise internal to the power supply and provide an output appropriate to activate the energy dump device.

Considering next semiconductor switch operation, assume wire number 68 (Figure 3) is the positive leg and wire number 67 is the negative leg of the power supply. When the breaker contacts are closed, a very low voltage, positive on top, is seen across the inductor and both SCR's are in the off state. When the breaker contacts begin to open as a result of some trigger input, however, voltage on the coil reverses polarity and rises as the inductor attempts to maintain constant current. Voltage will continue to rise across the dump device and at 320 V, the left hand series combination of IN3347, 160 V, zener diodes will break over and gate current will be drawn in the left hand SCR. The gate signal is limited, however, by the 180Ω impedance of the

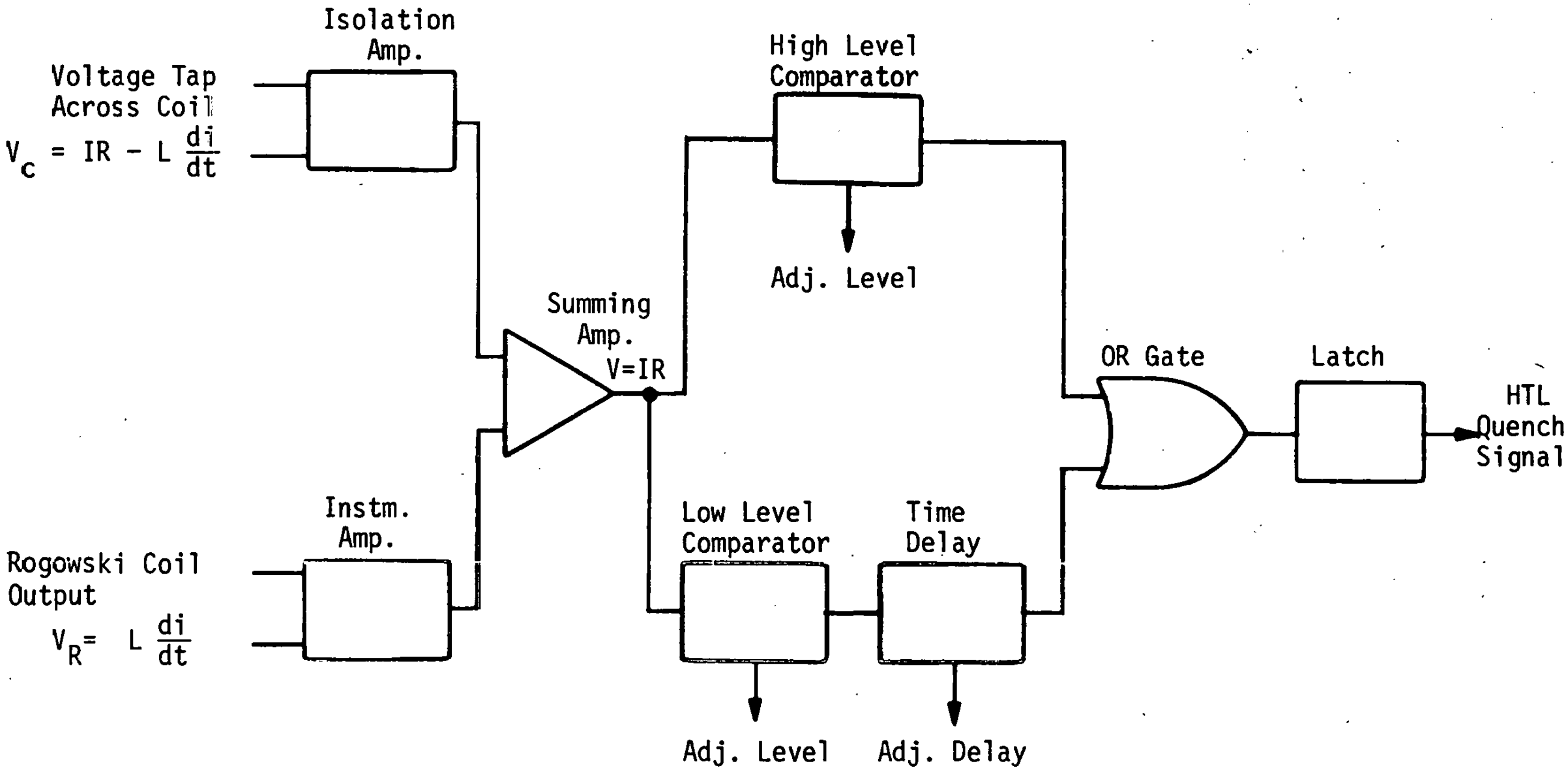


Fig. 11. Block Diagram of Voltage Tap Quench Detection Circuit (From Ref. 10)

gate circuit.

Since the SCR will trigger over a gate signal range from 100 to 200 mA (V_D = 12 V), worst case calculations indicate the left hand SCR will switch to the on state for coil voltages between 338 V and 356 V.

As the SCR begins conducting, coil current is diverted through the 0.15Ω dump resistor and magnetic field energy is converted to heat. Dissipation continues until dump current falls below the 150 mA holding current of the SCR.

Should the polarity of the power supply be reversed, an identical analysis of the right hand SCR and gate circuit is applicable.

4. CONCLUSION

The problem of dealing with stored energy in a normal going superconducting magnet is significant. Unless coil current is shunted around the superconductors or energy is quickly removed from the system, coil damage is likely. In the case of energy removal schemes, failure of the primary discharging technique requires a reliable energy dump device to insure maximum operating safety.

In the 300 V, 2 kA design, magnetic field energy is dissipated as heat on signal from a variety of inputs ranging from manual triggering to line loss indication. The device effectively deals with the bipolar power supply by using a symmetrical semiconductor switching module in conjunction with a modified circuit breaker isolation switch and a stainless steel dump resistor. Reliability of the dump device is increased by the capability of the circuit to provide its own gate signal via voltage rise across the isolation switch.

Considerable streamlining, however, is possible in the design. For instance, commercial heatsinks could be used in place of the bus bars shown in Figure 7 so that less chance of improper assembly would exist. Simpler bus supports and connections could also be incorporated with a commercial heatsink installation.

As a final consideration, the dump device does not trigger immediately when a dump signal is received since isolation switch voltage rise is not instantaneous. Delayed operation, however, is not severe enough to compromise design effectiveness because of the comparatively long time scale associated with temperature rise in a quenched superconducting magnet.[6]

The dump system described meets design requirements for the 300 V, 2 kA installation and modification can permit other applications where rapid magnetic field energy removal is required.

Technical Data 54-568

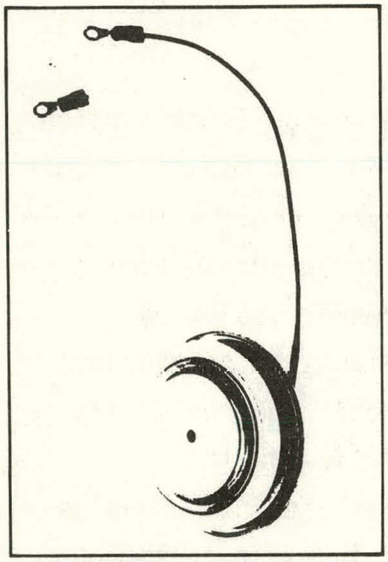
APPENDIX A

SCR Data

Westinghouse

*di/*namic Gate
Pow-R-Disc Thyristor
Silicon Controlled Rectifiers
Type T920

Forward Current 1415 to 1570 Amps RMS
900 to 1000 Amperes Half-Wave Average
Forward Blocking Voltages to 1600 Volts



Features

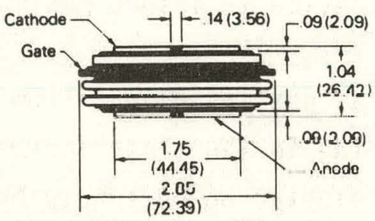
- *di/*namic Gate design
- All diffused design
- Guaranteed dv/dt (300v/μs)
- Low gate current witn soft gate control
- Low V_{TM}
- Low Thermal Impedance
- High surge current capability
- Compression Bonded Encapsulation
- I^2t package rating

Pow R Disc thyristor package offers:

- Single or double-sided cooling
- Reversible mounting polarity
- Compact size and weight
- Long creepage & strike paths
- Hermetic seal

Westinghouse Lifetime Guarantee
Westinghouse warrants to the original purchaser that it will correct any defects in workmanship or material, by repair or replacement, F.O.B. factory or, at its option, issue credit at the original purchase price, for any silicon power semiconductor bearing this symbol ✚ during the life of the equipment in which it is originally installed, provided said device is used within manufacturer's published ratings and applied in accordance with good engineering practice.

Dimensions in Inches (and Millimeters)



Approximate Weight 16 oz. (454 gms.)

Outline T92

Air-cooled and water-cooled heat exchangers are available.

Ordering Information

Type	Voltage		Current		Turn off		Gate current		Leads	
Code	V_{DRM} and V_{RRM} (V)	Code	$I_{T(av)}$ (A)	Code	tq μsec	Code	I_{GT} (ma)	Code	Case	Code
T920	100	01	900	00	150 (typical)	0	200	3	T92	DW
	200	02								
	300	03	1000	10						
	400	04								
	500	05								
	600	06								
	700	07								
	800	08								
	900	09								
	1000	10								
	1100	11								
	1200	12								
	1400	14								
	1600	16								

Example

Obtain optimum device performance for your application by selecting proper order code.

Type T920 rated at 1000 A average with V_{DRM} = 1000V, I_{GT} = 200 ma, and standard 12 inch leads—order as:

Type				Voltage		Current		Turn Off	Gate Current	Leads	
T	9	2	0	1	0	1	0	0	3	D	W

February 1975
Supersedes TD 54-568
pages 39-42, dated
October 1974

Technical Data 54-568

di/namic Gate
Pow-R-Disc Thyristor
Silicon Controlled Rectifiers
Type T920

Forward Current 1415 to 1570 Amps RMS
900 to 1000 Amperes Half-Wave Average
Forward Blocking Voltages to 1600 Volts

Voltage

Blocking State Maximums ($T_J = 125°C$)

	Symbol														
Repetitive peak forward blocking voltage, V	V_{DRM}	100	200	300	400	500	600	700	800	900	1000	1100	1200	1400	1600
Repetitive peak reverse voltage②, V	V_{RRM}	100	200	300	400	500	600	700	800	900	1000	1100	1200	1400	1600
Non-repetitive transient peak reverse voltage, $V \leq 5.0$ msec	V_{RSM}	200	300	400	500	600	700	800	900	1000	1100	1200	1300	1500	1700
Forward leakage current, mA peak	I_{DRM}	◄— 50 —►													
Reverse leakage current, mA peak	I_{RRM}	◄— 50 —►													

Current

Conducting State Maximums ($T_J = 125°C$)	Symbol	T920—09	T920—10
RMS forward current, A	$I_{T(rms)}$	1415	1570
Ave. forward current, A	$I_{T(av)}$	900	1000
One-half cycle surge current③, A	I_{TSM}	25,000	27,000
3 cycle surge current③, A	I_{TSM}	18,700	20,200
10 cycle surge current③, A	I_{TSM}	15,400	16,700
I^2t for fusing (t=8.3 ms) A^2sec	I^2t	2,600,000	3,040,000
Max I^2t of package (t=8.3 ms), A^2sec	I^2t	90×10^6	90×10^6
Forward voltage drop at $I_{TM} = 1500A$ and, $T_J = 25°C$, V	V_{TM}	1.55	1.35

Switching

($T_J = 25°C$)	Symbol	Min	Typ	Max
Turn-off time, $I_T = 250A$ $T_J = 125°C$, $di_R/dt = 50$ A/μsec reapplied dv/dt = 20V/μsec linear to 0.8 V_{DRM}, μsec	t_q		150	
Turn-On and Delay Time $I_{TM} = 1000A$④, $t_p = 450$ μsec	t_{on}		2.5	
$V_D = 600V$, μsec	t_d		1.0	
Critical dv/dt exponential to V_{DRM} $T_J = 125°C$, V/μsec⑤	dv/dt	300	1000	
di/dt④non-repetitive, JEDEC Std. #7 Sec. 5.1.2.4, Aμsec	di/dt			800
Latching Current④ $V_D = 75V$, mA	I_L		300	500
Holding Current④ $V_D = 75V$, mA	I_H		150	250

Gate

($T_J = 25°C$)	Symbol	Min	Typ	Max
Gate current to trigger at $V_D = 12V$, mA	I_{GT}		100	200
Gate voltage to trigger at $V_D = 12V$, V	V_{GT}		1.5	3.0
Non-triggering gate voltage, $T_J = 125°C$, and rated V_{DRM}, V	V_{GDM}			.15
Non-triggering Gate Current at $V_D = 12V$, mA	I_{GNT}		20	
Peak forward gate current, A	I_{GTM}			4
Peak reverse gate voltage, V	V_{GRM}			5
Peak gate power, Watts	P_{GM}			16
Average gate power, Watts	$P_{G(av)}$			3

Thermal and Mechanical

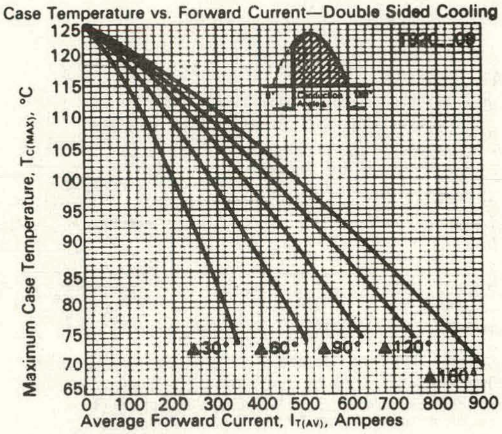
	Symbol	Min	Typ	Max
Oper. junction temp., °C	T_J	—40		125
Storage temp., °C	T_{stg}	—40		150
Mounting force, lb.①		5000		5500
Thermal resistance with double sided cooling①				
Junction to case, °C/Watt	$R\theta JC$		.028	.03
Case to sink, lubricated, °C/Watt	$R\theta CS$		.008	.01

① For information on Mounting Procedures and Techniques refer to AD 54-050.
② Applies for zero or negative gate voltage.
③ At 60 Hertz., with V_{RRM} after Surge.
④ With recommended gate drive, 20 volts, 40 ohms, rise time—1.0 . sec.
⑤ JEDEC Standards 6.201.1.6 and 6.201.1.7.

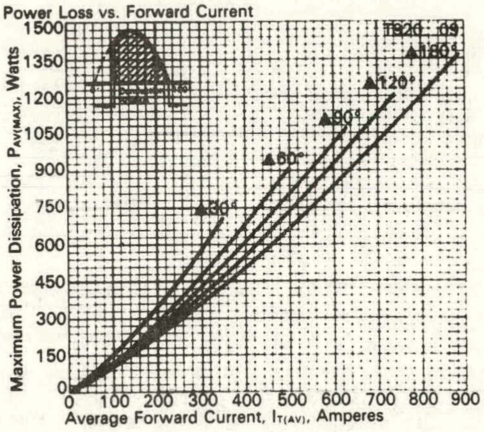
dI/namic Gate
Pow-R-Disc Thyristor
Silicon Controlled Rectifiers
Type T920__09

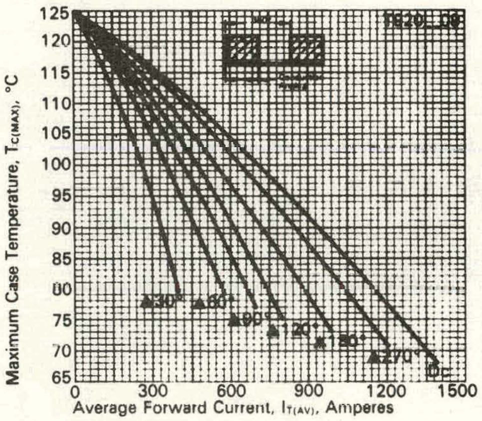
Forward Current 1415 Amps RMS
900 Amperes Half-Wave Average
Forward Blocking Voltages to 1600 Volts

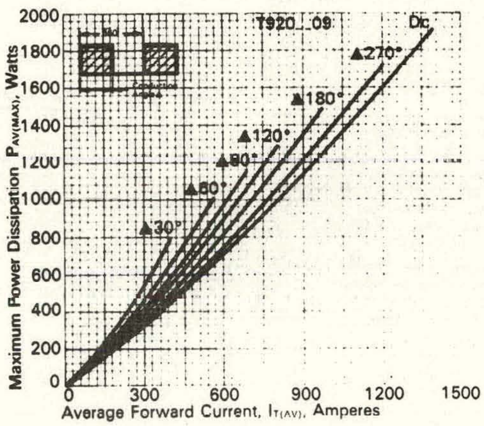
Case Temperature vs. Forward Current—Double Sided Cooling

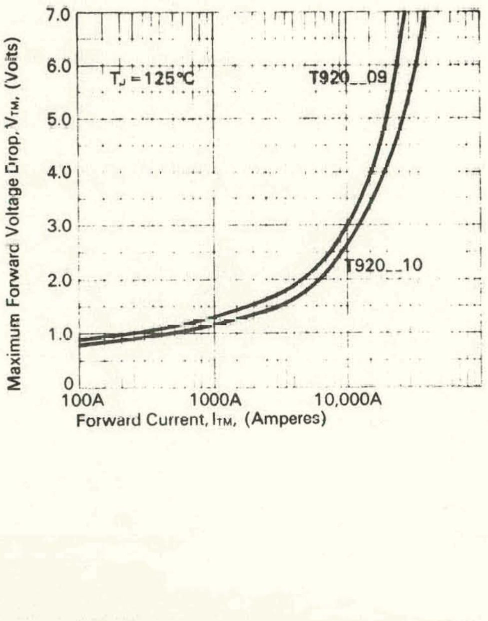


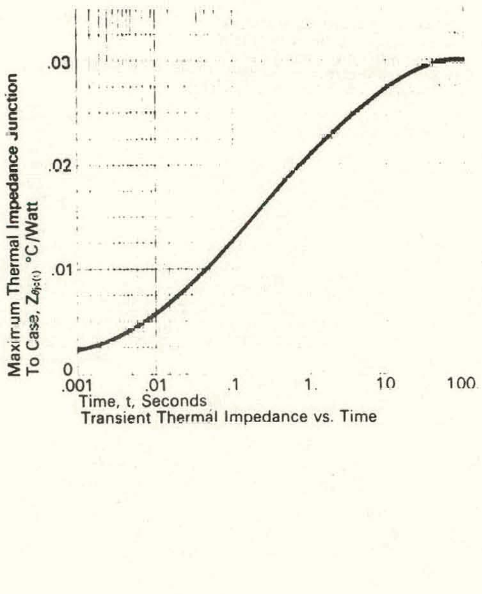
Power Loss vs. Forward Current











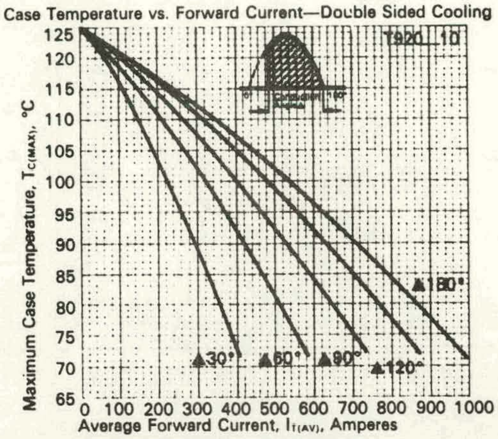
Transient Thermal Impedance vs. Time

Technical Data 54-568

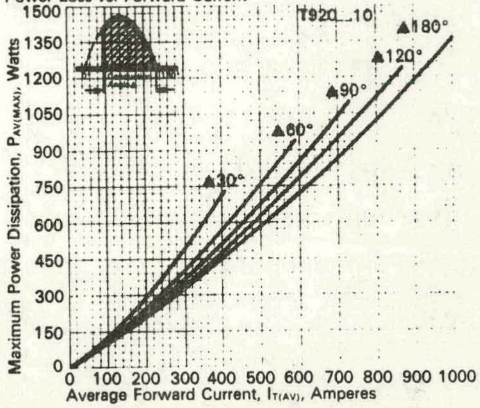
di/namic Gate
Pow-R-Disc Thyristor
Silicon Controlled Rectifiers
Type T920__10

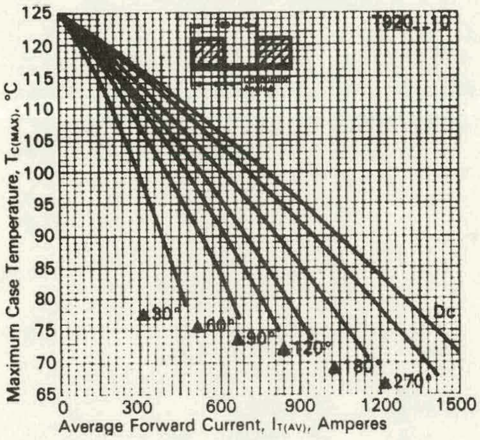
Forward Current 1570 Amps RMS
1000 Amperes Half-Wave Average
Forward Blocking Voltages to 1600 Volts

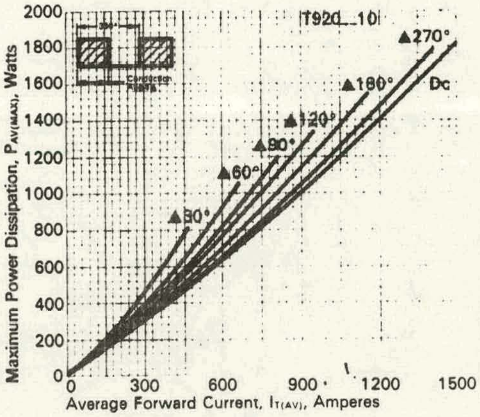
Case Temperature vs. Forward Current—Double Sided Cooling

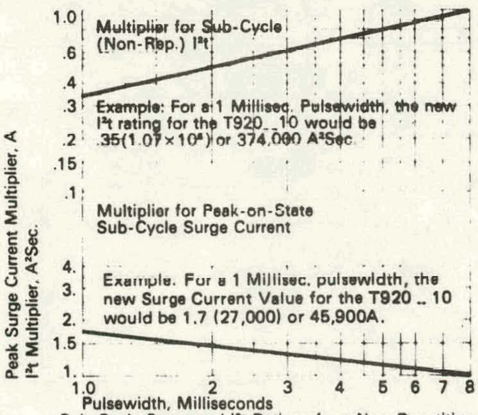


Power Loss vs. Forward Current





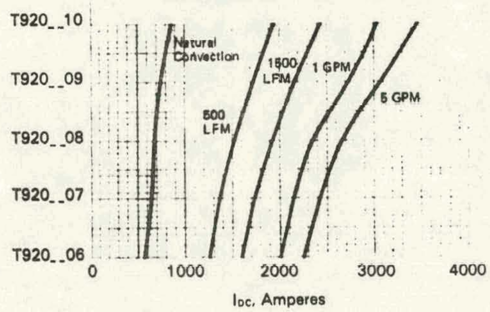




Sub-Cycle Surge and I²t Ratings for a Non-Repetitive Half-Sine Wave

WESTINGHOUSE T920 CURRENT RATINGS

Three Phase Full Control Bridge Circuit
On A9 Heatsink @ $T_A = 40°C$
On W9 Heatsink @ $T_{H2O} = 25°C$



Westinghouse Electric Corporation
Semiconductor Division, Youngwood, Pa. 15697

Printed in U.S.A.

APPENDIX B

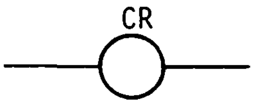
Allis-Chalmers Circuit Breaker Data

Type	MC 500
Rated Volts	13,800
Rated amps,	
3Ø at 13,800 volts	1,200
MVA	500
Max. design volts	15,000
Interrupt amps at rated volts	21,000
Rated interrupting time, cycles	8
Weight, Lbs.	1,650

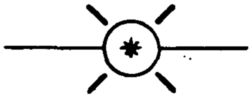
APPENDIX C

Elementary Diagram Symbol Legend and Numbering System

SYMBOL LEGEND



CONTROL RELAY COIL



PILOT LIGHT (* = CAP COLOR)

RELAY CONTACT, NORMALLY OPEN (N.O.)

RELAY CONTACT, NORMALLY CLOSED (N.C.)

PUSH BUTTON SWITCH, MOMENTARY, N.O.

PUSH BUTTON SWITCH, MOMENTARY, N.C.

SWITCH, N.O.

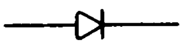
LIMIT SWITCH, N.O.

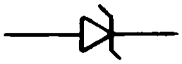
RESISTOR, FIXED, VALUE (IN OHMS) ADJACENT TO SYMBOL

SILICON CONTROLLED RECTIFIER

APPENDIX C (continued)

SYMBOL LEGEND

 DIODE

 ZENER DIODE

WIRE NUMBERING SYSTEM

WIRE NUMBERS ARE SHOWN ON EACH SHEET AS TWO-DIGIT NUMBERS: (E.G. 01, 02, 10, 42, ETC.). IN ALL CASES, THE COMPLETE WIRE NUMBER (WHICH APPEARS ON THE ACTUAL WIRES IN THE EQUIPMENT AND ON THE TERMINAL BOARDS) IS A 4-DIGIT NUMBER. THE FIRST TWO DIGITS INDICATE THE NUMBER OF THE ELEMENTARY DIAGRAM SHEET ON WHICH THE WIRE ORIGINATES AND THE LAST TWO DIGITS INDICATE THE WIRE ON THAT SHEET. THUS 0342 INDICATES WIRE NUMBER 42 ORIGINATING ON SHEET 03 OF THE DIAGRAM.

MAPPING SYSTEM

1. IN THE MARGIN OF THE DIAGRAM, BESIDE EACH DEVICE OPERATING COIL, TWO NUMERALS SEPARATED BY A DASH AND ENCLOSED IN PARENTHESES ( ) ARE SHOWN. THE FIRST NUMBER GIVES THE TOTAL NUMBER OF NORMALLY OPEN CONTACTS ON THE DEVICE. THE SECOND NUMBER (UNDERSCORED) GIVES THE TOTAL NUMBER OF NORMALLY CLOSED CONTACTS ON THE DEVICE.

2. AGAIN, IN THE MARGIN OF THE DIAGRAM, ONE OR MORE 4-DIGIT NUMBERS ARE SHOWN. THESE NUMBERS GIVE THE LOCATION OF THE DEVICE CONTACTS. THE FIRST TWO DIGITS INDICATE THE SHEET NUMBER AND THE LAST TWO DIGITS, THE LINE NUMBER WHERE THE CONTACT WILL BE FOUND. IF THE 4-DIGIT NUMBER IS UNDERSCORED, IT INDICATES THE CONTACT IS NORMALLY CLOSED; IF NOT UNDERSCORED, THE CONTACT IS NORMALLY OPEN, THUS:

   0362 INDICATES A NORMALLY OPEN CONTACT, LOCATED ON LINE 62 OF SHEET

3 OF THE ELEMENTARY DIAGRAM.

0364 INDICATES A NORMALLY CLOSED CONTACT, LOCATED ON SHEET 03, LINE 64.

3. UNDER EACH CONTACT, A 4-DIGIT NUMBER IS SHOWN IN BRACKETS. THIS NUMBER INDICATES THE SHEET AND LINE NUMBERS WHERE THE OPERATING COIL OF THE DEVICE WILL BE FOUND.

4. WHERE A WIRE IS CONTINUED FROM ONE DIAGRAM SHEET TO ANOTHER, A 4-DIGIT NUMBER IN BRACKETS IS SHOWN AT THE END OF THE WIRE. AGAIN, THIS NUMBER INDICATES THE SHEET AND LINE NUMBERS WHERE THE WIRE CONTINUES.

REFERENCES

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9. Westinghouse SCR Designer's Handbook, second edition, 1970, pp. 10-10 & 10-11.
10. J. Goddard, ORNL, private communication.

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