MASTER

ORMAK Upgrade Ohmic Heating Coil Generator Protection

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Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22161
Price: Printed Copy \$5.25; Microfiche \$3.00

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Contract No. W-7405-eng-26

FUSION ENERGY DIVISION

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Date Published - January 1978

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Prepared by the
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
operated by
UNION CARBIDE CORPORATION
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A. INTRODUCTION

Four existing generators are to provide power to the ohmic heating coils during a shot on the ORMAK Upgrade tokamak. Each generator is rated 3 MW at 350 V dc, with two generators connected in series and two in parallel to supply 20,000 amps at 700 V to the coils. A discharge capacitor can be switched into the circuit, with no generator excitation present, in order to provide for discharge cleaning between shots, as well as liner baking when experiments are not under way.

During a shot, the voltage across the ohmic heating coil reaches 20 kV when a 1 ohm series resistor is switched into the circuit at a coil current of 20 kA. In the case of discharge cleaning, a 200 μ F series capacitor charged to 20 kV is switched into the circuit to provide a high voltage pulse across the ohmic heating coil.

A study involving the use of the computer was initiated to investigate the effects of these high circuit voltages on the generators during normal operation and under various fault conditions. This was necessary because the maximum voltage which the generators can tolerate is 400 V per machine or 800 V across the dc bus. In addition, the maximum voltage which can be tolerated from either generator output terminal to ground is 800-1000 V. A generator, unlike other types of solid state equipment, has an inherent low voltage capability to ground.

This report will describe methods which can be used to limit the voltage across the generator for normal operation and various ground faults. It will also contain quantitative information, obtained from the computer study, which can be used for evaluating the protection methods cost-wise.

The stored energy in the ohmic heating coil during a shot is approximately 4.6 megajoules. In addition, depending on the protection scheme used, there are 2 to 4 megajoules contributed by the generator, making a total of 6.6 to 8.6 megajoules. For discharge cleaning, the 200 μ F capacitor at 20 kV stores 40 kilojoules, while the generator contributes no energy. Since the energy is much higher during a shot,

initial efforts were made to find a suitable protection scheme for the shot mode. Then either no modification or only a slight modification would be required for discharge cleaning faults.

Two general methods of protection were considered: a) voltage suppression to absorb the energy with static devices without exceeding the generator voltage limits, and b) switching devices with static suppression devices to divert the current from the ohmic heating coil and the generator while switching the generator out of the circuit. The first method involved the use of resistors, resistors with steering diodes, capacitors, and avalanche devices such as metal oxide varistors (MOV's).

Results of the computer runs and study affected the protective circuitry as follows (refer to Appendix C):

- a) Capacitors - This approach was investigated primarily as a solution for the shot mode. Capacitance in the discharge cleaning mode resulted in voltage oscillations across the generator terminals.
- b) Resistors - This was an actively pursued solution because it was the least expensive, the smallest size, and the most readily available device. Because a resistor was required from each generator terminal to ground, steering diodes were also required to prevent excessive currents during normal shots. However, the unidirectional path for current flow through the resistors wasn't adequate for all fault conditions which could exist. It became apparent that bipolar impedance was required to satisfy all fault conditions.
- c) Metal Oxide Varistor (MOV) - Computer runs were made utilizing these devices both alone and along with capacitors and a crowbar. The capacitors and crowbar were necessary to limit the generator terminal voltage during a shot when the 1 ohm resistor was switched in, while the MOV's were used to limit the bus voltage to ground during a fault. These particular

bipolar devices were selected because their voltage vs. current curve is extremely flat. Avalanche devices, such as thyrite or selenium, do not have this flat characteristic. The joule rating (250 joules) of individual suppressors is low, therefore large banks of them are required to do a satisfactory job.

- d) Switching - The intent of this study was to disconnect the generator from the circuit just prior to a shot or discharge cleaning. In this case, high voltages would not be present when the generator is in the circuit, and so high voltages at the generator terminals would not be produced during a ground fault. A typical disconnect circuit will produce high voltages when an inductive current is interrupted. To prevent this from happening, both the generator and the coil circuit are shunted with a crowbar which also serves as a free wheeling thyristor. Then a high voltage vacuum breaker is commutated open in each generator bus to disconnect it from the circuit. Once the circuit has been opened, the vacuum breakers prevent high voltages from appearing at the generator terminals. This is a straightforward approach which allows the low voltage generators (or a low voltage thyristor power supply with inversion capability) to be used.

The figures in Appendix C show some of the various methods of protection studied. There are others which could be added, but the problems associated with them are similar to those analyzed in this report.

B. RESULTS OF THE STUDY

1. Shot Mode

The circuit configuration for the shot mode is shown in Fig. 1.

Fig. 1. Ohmic Heating Circuit: Shot Mode

Prior to the initiation of a shot, both vacuum circuit breakers are closed, and the ignitrons on the 1 ohm resistor and commutation capacitor are open. The generator terminal voltage is then driven to 700 V, establishing a current of 20 kA through the breakers and ohmic heating coil in about 3.5 sec. Approximately 100 msec prior to this point, the secondary breaker is opened and thereafter serves as a crowbar to protect the main breaker in case it fails to interrupt.

The "shot" occurs when the main breaker is opened and then commutated to interruption by firing the ignitrons on the

commutation capacitor and 1 ohm resistor. The purpose of the saturable reactor is to help minimize the rate of fall of interrupted current (RFIC), and the RC snubber across the breaker holds down the rate of rise of restored voltage (RRRV). Keeping the magnitudes of the RFIC and RRRV as low as possible helps to assure reliable interruption. This interruption of current in the vacuum circuit breaker diverts the 20 kA into the 1 ohm resistor, creating across the ohmic heating coil an initial voltage of 20 kV with a 25 msec time constant. A voltage is induced in the plasma by transformer action, bringing about the desired plasma current of 400 kA.

The thyrite is triggered into the circuit approximately 25 msec into the response in order to linearize the decay of current in the ohmic heating coil after that point. By the time it is activated, however, 80 to 90% of the coil energy is already dissipated, and so the addition of the thyrite has little effect upon the concerns of this report. It will therefore be omitted from the circuit model.

When the 1 ohm resistor is switched into the circuit, a voltage spike appears not only across the ohmic heating coil, but across the generator armatures as well. The magnitude of this spike exceeds the capabilities of the generators, and can be calculated as follows:

$$\begin{aligned} R/L &= 1.035/0.026 \approx 40, \\ di/dt|_{t=0^+} &= (40) (20 \text{ K}) = 8.0 \times 10^5, \\ V_{\text{Iarm}}|_{t=0^+} &= (8.0 \times 10^5) (700 \text{ } \mu\text{H}) = 560 \text{ V}. \end{aligned}$$

The armature emf is still present at this time, so the voltage across the dc bus jumps to $700 + 560 = 1260 \text{ V}$, which exceeds the 800 V limit.

Because the circuit is not grounded, there are no problems with excessive voltages to ground on the generator armatures during normal

operation. However, if a ground fault were to occur, excessive voltages to ground could easily be present, depending upon the timing and location of the fault.

Two alternatives for generator protection in the shot mode have been arrived at. They will both be discussed here, with additional details covered in the appendices.

a. C-C-MOV (Capacitor-Crowbar-Metal Oxide Varistor) Protection

This protection scheme involves the use of capacitors, a crowbar, and banks of metal oxide varistors (nonlinear resistors) as shown in Fig. 2. Also included in this figure are labels for the five points (A, B, C, D and E) to be studied as possible ground fault points.

Fig. 2. Shot Mode: C-C-MOV Protection

During a normal shot, the 0.05 F capacitor will prevent the terminal voltage from reaching 800 V for approximately 3.7 msec. At this time, a voltage sensing device triggers the crowbar into operation. The crowbar resistance is

chosen to conduct 20 kA at 800 V, and therefore will not allow the voltage across the generator armature to exceed 800 V at any time. The crowbar must be able to absorb at least 3 megajoules. The MOV's have negligible effect upon the response.

The banks of nonlinear elements are MOV's (metal oxide varistors) which have a thermal limit of 400 V and a clamping voltage in the neighborhood of 700 V. They will therefore draw negligible current during normal operation since the voltage across each bank will not exceed 400 V. However, if a ground fault occurs, they will prevent the armature terminal voltages from exceeding 800 V.

Each MOV is capable of absorbing only 250 joules. With energies of 6.6 to 8.6 megajoules to be absorbed by the circuit, and fully half of this amount to be absorbed by a single MOV bank in the case of a certain ground fault, large numbers of these elements in parallel will be necessary.

A worst case time for a fault to occur is at the instant the shot is fired. The current is at a maximum, as are the stored energy and the resultant voltage spikes. Computer (CSMP) simulations were done for the various fault locations with the assumption of a worst case time for the fault.

For the case of a ground fault at A, the 1 ohm resistor is effectively shorted out, and the MOV bank at C has to absorb approximately 3.5 megajoules, which is about half of the stored and generated energy. This energy consumption requirement necessitates the use of about 20,000 of these MOV elements in the bank at C. The crowbar does not fire in this case, for the armature voltage does not reach 800 V.

The maximum demand on the suppressor (MOV) bank at B occurs for the case of a ground fault at D, and the use of about 10,000 MOV's in parallel is necessary in order to

dissipate approximately 2 megajoules. Again, the crowbar does not trigger.

If a ground fault occurs at either point B or C, neither MOV bank is called upon to absorb more energy than in the cases already discussed. Once again, the crowbar does not activate.

Due to the near symmetry of the circuit, a ground fault at E gives a response very similar to that of a normal shot.

Some consideration should be given to the circuit response in case of a fault which occurs at some moment other than the instant the shot is made. If the fault occurs prior to the shot, while the armature voltage is being built up, then a ground fault detector should reverse the amplidyne voltage immediately in order to reduce the generator voltage and abort the shot. If the fault occurs just after the shot is made and the crowbar triggers, then different things happen, depending upon the location of the fault. If the fault is at E, the response is unchanged. If the fault is at A, B, C or D, the effect is that of adding another crowbar. The armature voltage drops momentarily as it experiences a surge of current, and the amount of generated energy rises. In no case, however, is the energy to be absorbed by the suppressors or the crowbar any greater than it is for the worst case faults already discussed.

This first alternative deliberately avoids the use of any device which actually switches the generator out of the circuit. It appears that without such a device it is necessary to employ rather extensive numbers of passive elements in order to protect the generators. This is not the case in the second protection scheme, a discussion of which follows.

b. C-VCB (Crowbar-Vacuum Circuit Breaker) Protection

This alternative employs devices to effectively separate the generator circuit from the ohmic heating coil circuit. It consists of two crowbars, four vacuum circuit breakers with associated commutation circuits, and an SCR switch which is closed in order to provide a current path during discharge cleaning. Refer to Fig. 3.

Fig. 3. Shot Mode: C-VCB Protection

In this scheme, when the armature current has been driven to 20,000 A and the shot is ready to be made, the vacuum circuit breaker contacts are parted. Then the crowbar SCR's and commutating capacitors are triggered by ignitrons, extinguishing the VCB arcs and diverting the current into two separate loops. A small inductance

($\sim 10 \mu\text{H}$) is placed in the load crowbar in order to limit the rate of current increase in the SCR's. Once the generators have been isolated from the coil circuit, the shot is ready to be made. If the arcs fail to extinguish, parallel vacuum circuit breakers close, shorting out the arcing breakers and thereby extinguishing the arcs.

Since the generators are now isolated from the remainder of the circuit, the di/dt spike due to the opening of the vacuum circuit breaker across the 1 ohm resistor does not appear at the generator terminals. If ground faults occur at any of points B, C or E, the stress on the separation is no different than for a normal shot. However, if a ground fault occurs at point A the instant the shot is made, then it becomes apparent that the vacuum circuit breakers must both be rated at 20 kV , as shown in Fig. 4. Also, the ignitrons must be able to withstand 20 kV plus whatever voltage is left on the capacitors. If a fault occurs at D, the voltage stresses are not nearly so severe.

Fig. 4. Shot Mode C-VCB Configuration: Voltages for a Fault at A.

The generator emf decays to zero approximately 0.6 seconds after the amplidyne field voltage is reversed (which coincides with the firing of the shot). The decay of this armature emf is nearly linear and is approximated by the equation $V_{emf} = (700 - 1167 t) \text{ V}$.

A Laplace analysis of the isolated generator circuit (see Appendix C) shows that the generator crowbar must be able to absorb 3 megajoules, and so should probably have a capacity of 4 megajoules. The energy absorbed by the load crowbar will be determined by its resistance, but will be small. For instance, if the resistance of the SCR's is taken to be $100 \mu\Omega$, the energy absorbed would be approximately 500 J.

The generator crowbar will be shut off when the armature voltage goes negative (it undershoots slightly before returning to zero volts). The load crowbar will shut off either when the coil current goes to zero, or when the first discharge cleaning pulse reverse-biases the device.

A discussion of both protection alternatives for the discharge cleaning mode follows.

2. Discharge Cleaning Mode

The circuit configuration for discharge cleaning is shown in Fig. 5.

Fig. 5. Ohmic Heating Circuit: Discharge Cleaning Mode

To prepare for a discharge cleaning pulse, the $200\mu\text{F}$ capacitor is charged to 20 kV with its ignitron open. A pulse is initiated when the ignitron is fired, discharging the capacitor and creating a peak current in the ohmic heating coil of approximately 2000 A. This induces a relatively low current in the plasma, which helps to sustain a "low grade" plasma for the purpose of "cleaning" impurities out of the liner. When the capacitor is fully discharged, it charges to about 19.4 kV in the opposite direction due to the oscillatory nature of the circuit. Then the current reverses, the ignitron shuts off, and current flows back through the parallel diode, recharging

the capacitor to another peak of about 18.7 kV. When the current tries to reverse again, it is blocked by the ignitron and diode. The charging supply restores the lost charge to the capacitor until a voltage of 20 kV is reached and the circuit is ready to be fired again.

This same circuit also provides for liner baking during periods when experiments are not under way. It does this by using the same capacitor bank, switched appropriately. The general problems and solutions discussed here are also applicable to liner baking.

Because there is no armature emf in this circuit, the voltage across the armature for a normal pulse does not exceed prescribed limits. However, if a ground fault were to occur, excessive voltages could be present, depending upon the location of the fault.

The same two alternatives for generator protection were considered for the discharge cleaning mode.

a. C-C-MOV Protection

The capacitor-crowbar-MOV protection circuit needs to have the capacitor removed for discharge cleaning so that ringing between the generator armature and the capacitor can be avoided. The MOV's and crowbar are sufficient protection both for normal operating and fault conditions. The circuit is shown in Fig. 6.

For a normal discharge cleaning pulse, excessive voltages across the armature or from the terminals to ground do not occur, and so the MOV's and crowbar make little contribution to the response. For certain ground fault conditions, however, the MOV's and crowbar are quite necessary.

A worst case ground fault would be one which occurs at the moment the capacitor discharge is triggered. If the fault occurs prior to the initiation of a pulse, a ground

fault detector system would prevent the discharge. If the fault were to occur in the middle of a pulse, circuit voltages and di/dt 's would all be lower than they are initially. Therefore, the fault conditions to be discussed are those which would exist if the fault occurred at the time the pulse is initiated.

Fig. 6. Discharge Cleaning Mode: C-C-MOV Protection

If a ground fault were to occur at A without the protection of the MOV's, the voltages at B and C would both jump to -20 kV when the discharge capacitor is fired. The suppressors keep both of these voltages within the limits of ± 700 V, and the crowbar prevents an overvoltage across the armature.

For the case of a ground fault at D without MOV protection, the voltages at B and C would go to -20 kV in the first instant, followed by a positive surge at both points. The suppressors hold these voltages within the limits of ± 600 V. The armature voltage does not reach 800 V, and so the crowbar remains inactive in this case.

For ground faults at points B, C or E, the response differs very little from that for a normal discharge cleaning pulse. Excessive voltages to ground or across the armature do not occur.

b. C-VCB Protection

If the crowbar and vacuum circuit breaker protection is to be employed, then the circuit breakers would simply be left open for discharge cleaning. Two SCR crowbars are used to provide a bidirectional current path for the discharge cleaning pulse. Refer to Fig. 7.

Fig. 7. Discharge Cleaning Mode: C-VCB Protection

The generators are protected for both normal and fault conditions with this configuration. For faults at A and D, the VCB's and ignitrons need to be rated at 20 kV, the same as for the shot mode.

C. SUPPLEMENTAL SPARK GAP PROTECTION

In case of the failure of protective equipment for either scheme, it is desirable to have the security provided by spark gaps. A maximum of three could be used, with one across the armature itself and one at each terminal to ground.

In the C-C-MOV protection scheme, if the crowbar failed to conduct, a spark gap across the armature could be used to short out the generator before excessive voltages occurred. Spark gaps from either terminal to ground would probably not be necessary, for the chance of an MOV bank failure occurring simultaneously with a fault at A or D is remote.

In the C-VCB protection scheme, one spark gap would probably be desirable. A spark gap across the armature could protect the generators in case the generator crowbar failed to fire. Again, spark gaps from the terminals to ground would probably be overprotective. A fault at A or D along with the failure of one of the VCB's or ignitrons is also remote.

D. CONCLUSION

It can be concluded that the energy of the system must either be suppressed during a ground fault, or the generators must be disconnected from the system, or the equipment must be designed to withstand the high voltages. The latter solution requires equipment other than the existing generators.

A preliminary cost estimate indicates that the use of suppressors is expensive compared to a generator disconnect scheme. The use of equipment designed to withstand the voltage to ground involves the procurement of new equipment, which is very expensive compared to using existing equipment. If a low voltage (700 V) thyristor power supply were used it would require disconnects, similar to those used for the generator, to protect it from the resulting high circuit voltages. No cost savings would result from this approach. If a high voltage (20 kV) thyristor supply were used, it could eliminate the need for the 1 ohm resistor and its switches, or the thyrite for discharging the ohmic heating coil during normal shots, and possibly the discharge cleaning capacitor-switch circuit. This is possible because the SCR power supply is fast, programmable, and can rectify or invert. It has the capability of doing the complete job. However, at 20 kV, it is 28.6 times larger than a 700 V supply and its cost will be considerably higher unless the rms current can be reduced by using the additional forcing voltage to build up the current faster in the ohmic heating coil. While the versatility of an SCR power supply may justify its use, it wasn't pursued in depth because it represents a new capital expenditure that will cost more than the proposed system.

Of the alternatives studied, the scheme considered most favorable is that which involves disconnecting the generators. First, the generators and ohmic heating coil are crowbarred by diverting the 20 kA through SCR's in order to maintain normal current flow in the inductive circuits so that high di/dt 's and the resulting high voltages can be prevented. This allows the generators to be disconnected from the circuit with vacuum circuit breakers just before the shot is made. The high voltage capability of the vacuum circuit breakers prevents excessive

voltages to ground from appearing at the generator terminals in the event of a ground fault.

The complete circuit is shown in Fig. 8.

Fig. 8. Ohmic Heating Circuit With Recommended Generator Protection

E. APPENDIX A: COST ANALYSIS

1. C-C-MOV Configuration

<u>Item</u>	<u>Description</u>	<u>Cost Estimate</u>
1	<u>MOV's:</u> Panasonic EPZ-C32EK431 Quantity: 30,000	Elements are priced at \$5 each. In this large quantity the per unit price would surely drop. However, the costs associated with constructing the banks would probably cancel out any volume savings on the elements themselves. \$150,000
2	<u>Capacitors:</u> 0.05 F electrolytic @ 1000 V Quantity: 1 (or equivalent)	A 4500 μ F capacitor @ 250 V dc costs about \$15. This particular bank would require 45 parallel paths of 4 of these capacitors in series, a total of 180. Adding a cost of \$1500 for the mounting racks gives a total of \$ 4,200
3	<u>Resistors:</u> a) 180 Ω @ 40 joules in 0.5 sec. Quantity: 20,000 (or equivalent, such as 0.18 Ω @ 40,000 joules in 0.5 sec. Quantity: 20)	\$ 1,500
	b) 85 Ω @ 40 joules in 0.5 sec. Quantity: 10,000 (or equivalent, such as 0.17 Ω @ 20,000 joules in 0.5 sec. Quantity: 20)	\$ 750

c) 50 Ω @ 10,000 joules in
0.5 sec. +9000 joules in
3.5 sec.
Quantity: 1 \$ 100

d) 50 Ω @ 5000 joules in
0.5 sec. +9000 joules in
3.5 sec.
Quantity: 1 \$ 75

e) 0.04 Ω @ 4 megajoules in
0.7 sec. (crowbar)
Quantity: 1 \$ 4,000

4 Switch:

For switching out capacitor
during discharge cleaning.

800 V and 20 kA

Quantity: 1 \$ 10,000

5 SCR Crowbar and Crowbar Trigger Circuit:

Able to trigger crowbar at
specified voltage level.

Must be able to trigger
within 0.1 msec.

Quantity: 1 \$ 3,000

6 Spark Gap:

800 V, 20 kA

Quantity: 1 \$ 2,000

TOTAL \$176,625

2. C-VCB Configuration

<u>Item</u>	<u>Description</u>	<u>Cost Estimate</u>
1	<u>Vacuum Circuit Breakers:</u>	
	20 kA and 20 kV	
	Quantity: 4	\$50,000
2	<u>Resistor:</u>	
	0.035 Ω @ 4 megajoules in	
	0.7 sec. (generator crowbar)	
	Quantity: 1	\$ 4,000

3 Crowbar SCR's and SCR Switch (Discharge Cleaning):

800 V, 20 kA - load crowbar
insulated for 20 kV to ground
Quantity: 1 \$ 9,000

4 Shot Triggering Circuit:

To open vacuum circuit breakers
and trigger both crowbars and
commutating capacitors into
operation when desired current
(20 kA) is reached. Must
include current sensing devices
in vacuum circuit breakers and
ignitrons, with provision for
initiating the shot once the
generator is isolated. \$ 1,000

5 Capacitor Bank:

For VCB commutation.
200 μ F @ 10 kV
Quantity: 2 \$20,000

6 Ignitron:

For firing of commutation
capacitors.
30 kV, 30 kA
Quantity: 2 \$ 2,000

7 Saturable Reactor:

For aiding VCB commutation.
Quantity: 2 \$ 2,000

8 Switches:

For disconnecting charging
supply from commutation
capacitors.
Quantity: 2 \$ 2,000

9 Spark Gap:

800 V, 20 kA
Quantity: 1 \$ 2,000

TOTAL \$92,000

F. APPENDIX B: OHMIC HEATING COIL EQUIVALENT CIRCUIT COMPUTATION

1. Shot Mode

The ohmic heating coil resistance is chosen so as to carry 20 kA at the terminal voltage of the generators. Previous ohmic heating coil simulation studies indicate that a maximum terminal voltage will be 660 V before the shot is made. The protective circuits in this study are designed to protect the generator for the case where the maximum generator terminal voltage for the shot is 700 V. The proper ohmic heating circuit resistance is therefore $700 \text{ V} / 20 \text{ kA} = 35 \text{ m}\Omega$. With $2 \text{ m}\Omega$ in the bus work this leaves $33 \text{ m}\Omega$ for the ohmic heating coil itself. The coil inductance has previously been determined to be 23.3 mH . Therefore, the equivalent circuit for the ohmic heating coil in the shot mode consists of $33 \text{ m}\Omega$ in series with 23.3 mH .

2. Discharge Cleaning Mode

An equivalent circuit for the model in Fig. B-1 was developed.

Fig. B-1. Circuit Model for Ohmic Heating Coil

$$\omega \approx 470 \text{ rad/sec}$$

$$\begin{aligned} X_{eq} &= 33 \text{ m} + j 470 (23.3 \text{ m}) + \frac{(81.8 \text{ } \mu)^2 (470)^2}{(10^{-4}) + j 470 (1.89 \text{ } \mu)} \\ &= 33 \text{ m} + j 10.95 + 0.185 - j 1.643 \\ &= 0.218 + j 9.307 \end{aligned}$$

Therefore, the equivalent circuit for the ohmic heating coil in the discharge cleaning mode consists of 0.218 ohms in series with 20 mH.

G. APPENDIX C: DETAILED DEVELOPMENT OF VARIOUS SCHEMES

Various protection configurations were investigated leading up to the development of the C-VCB configuration. These are listed here, and their failings and successes pointed out.

1. Capacitors to Ground (See Fig. C-1)

Fig. C-1. Capacitive Protection

For the shot mode, capacitors can hold down the voltage spike across the generators, but only for a limited time, such as a few milliseconds at 0.1 F. An additional device, such as a spark gap or crowbar, would have to be employed at every shot. Even then, if certain ground faults occur, such as a fault at A, excessive voltages to ground occur at the generator terminals. In addition, capacitor C2 may charge in a negative direction, ruling out the possibility of using an electrolytic capacitor. Figures C-2 and C-3 show the main currents for a fault at A before and after the triggering of a crowbar.

Fig. C-2. Shot Mode Capacitor Protection:
Fault at A Before Crowbar Triggers
(See Table D-1)

Fig. C-3. Shot Mode Capacitor Protection:
Fault at A After Crowbar Triggers
(See Table D-2)

In the situation of Fig. C-2, C1 starts charging very rapidly. At 0.1 F, the armature voltage reaches 800 V in 1.22 msec. (The voltage across C1 is 450 V and the voltage across C2, having discharged very little, is still 350 V.) The crowbar is then triggered and the currents are shown in Fig. C-3.

This situation presents two problems. First of all, the voltages from B and C to ground are rising rapidly and the voltage from C to ground reaches 800 V before 10 msec have passed. Secondly, it is seen that C2 starts charging to a negative polarity which will not only cause excessively high voltage to ground eventually, but will rule out the possibility of using an electrolytic capacitor in this position.

One way to solve these two problems is to remove the ground between the two capacitors and place suppressors to ground at either generator terminal, which is the C-C-MOV configuration discussed later in this appendix as Item 4.

For the discharge cleaning mode, a capacitance placed across the generator terminals gives rise to oscillations between it and the armature inductance. Also, the initial charging action would be in the incorrect direction for the electrolytic capacitors to hold. Therefore, if capacitors are to be used, it would be best to switch them out in the discharge cleaning mode.

2. Resistors With Steering Diodes (See Fig. C-4)

This particular protection method is designed to prevent excessive voltages to ground at the generator terminals in the case of a ground fault.

For the shot mode, this configuration obviously will not help to hold down the di/dt spike which appears across the armature in the course of a normal shot. Also, for ground faults at C or D, terminal B is not protected from the large negative voltage to ground that will occur.

For the discharge cleaning mode, the problem is that certain ground faults, such as at A, cause large negative voltages to ground at the generator terminals that cannot be protected against by a polarized protection scheme.

3. Metal Oxide Varistors (See Fig. C-5)

This protection scheme can work well for ground fault conditions at points A-D, provided the correct fixed resistors are placed in series and in parallel with the MOV's. It also is acceptable for use during a normal discharge cleaning pulse. However, during a normal shot or one in which E is grounded, they will not protect against overvoltage across the armatures. Each MOV bank has about half of the armature voltage across it, and since the high impedance

limit of the devices is in the vicinity of 400 V, the armature voltage reaches 800 V before the MOV's can begin to suppress it.

Fig. C-5. MOV Protection
(See Table D-3)

4. C-C-MOV Configuration (See Fig. C-6)

This configuration is able to hold down the voltages to ground, as well as the voltage across the armature for normal operating conditions, and all ground fault conditions as well. Quantitative results from computer runs for the various conditions are included at this point. (Ref. Appendix D.)

Fig. C-6. C-C-MOV Protection
(See Tables D-4 and D-5)

a. Shot Mode Ground Faults

1. At "E", or Normal Shot

The 0.05 F capacitor prevents the armature voltage from reaching 800 V until 3.7 msec after the shot is made. The generator current at this time is still nearly 20 kA, and when the crowbar triggers, it causes the armature voltage to drop suddenly and then climb back to about 780 V before it begins a steady decline as the response subsides. The MOV banks have negligible effect upon the response, for the voltage across either has a maximum of 400 V.

The crowbar must be able to absorb most of the energy put out by the generator. CSMP results indicate that the energy to be absorbed by the crowbar is 2.9 megajoules. Also, for the time after the shot is triggered, the energy absorbed by the ohmic heating coil is 0.17 megajoules, and

that absorbed by the 1 ohm resistor is 5.2 megajoules, making a total of approximately 8.3 megajoules.

2. At "A" (See Fig. C-7)

Fig. C-7. Shot Mode C-C-MOV Protection:
Main Current Path for a Fault at A

The 1 ohm resistor is shorted out by the MOV bank at C. The MOV bank at B carries very little current and the voltage across it drops as the voltage to ground at C rises. This simultaneous voltage rise at C balances with the change in voltage at B in such a way that the voltage across the armature does not exceed 800 V. Therefore the crowbar does not trigger.

The MOV bank at C absorbs approximately 3.5 megajoules, which calls for at least 14,000 of the elements in parallel. If a safety margin is to be included, roughly 20,000 of these MOV's would be necessary. The coil resistance accounts for the absorption of 2.7 megajoules and the 1 ohm resistor absorbs 0.51 megajoules.

The suppressor configuration actually used in the computer simulation consists of a particular number of MOV's in parallel, with a fixed resistance in series with each MOV, and an additional fixed resistance across the entire bank. The purposes of the series resistors are to help equalize the current in each MOV and to raise the clamping voltage to the maximum allowable level in order to absorb as much energy as possible. This helps to minimize the amount of energy which must be absorbed by the ohmic heating coil. The purpose of the parallel resistor is to provide stability at low bank voltages and help slow the rate of voltage rise.

For the case of a fault at A, the series resistors absorb 0.7 megajoules, while the parallel resistors absorb a negligible amount. So the total energy absorbed by the suppressor bank, ohmic heating coil, and 1 ohm resistor is approximately 7.4 megajoules.

The values for the series resistors were arrived at by formulating V-I curves for the paralleled MOV's from a V-I curve for a single device. The series resistances were then chosen so as to raise the voltage across each bank to 800 V at 20,000 A. For the case of 20,000 parallel MOV's, this resistance is 180 ohms in series with each MOV (or an equivalent arrangement). For the case of 10,000 parallel MOV's, it is 85 ohms.

The value for the parallel resistor was chosen to be small enough to accomplish its stated purpose while carrying only negligible current during normal operating conditions. Fifty ohms across each bank is suitable for this purpose. It helps provide for a stable response during fault conditions and will carry a maximum of only 7-8 A across the bus for a normal shot.

3. At "D" (See Fig. C-8)

Fig. C-8. Shot Mode C-C-MOV Protection:
Main Currents for a Fault at D

This is the fault point which demands the most energy consumption of the MOV bank at B. As in the case of a fault at point A, the fault at D does not result in an overvoltage across the armature, and so the crowbar does not trigger.

The energy dissipated in the MOV's at B is 1.9 megajoules, which calls for at least 7,600 in parallel, or about 10,000 if a safety factor is to be included. The series resistors (85 ohm) absorb 0.4 megajoules, the coil resistance 0.16 megajoules, and the 1 ohm resistor 4.9 megajoules, so the total energy absorbed is approximately 7.4 megajoules.

4. At "B" or "C" (See Fig. C-9)

Since there is only one MOV bank across the generators in this case, the armature voltage will not exceed 800 V, and so the crowbar will not trigger. The MOV bank in question absorbs only 1 megajoule, which is less than in the previous fault cases, so no additional elements are

required. The series resistors absorb 0.17 megajoules, the coil 0.16 megajoules, and the 1 ohm resistor 4.9 megajoules, for a total of approximately 6.1 megajoules.

Fig. C-9. Shot Mode C-C-MOV Protection:
Main Currents for a Fault at B or C

Before proceeding to a discussion of discharge cleaning, it should be noted that a variation on this configuration was considered that would attempt to minimize the energy absorption requirements of the MOV bank at C. The scheme is shown in Fig. C-10.

In this arrangement the crowbar across the MOV bank at C is set to trigger at about 700 V. A ground fault at A or B are situations which will bring about this condition. In this way the extra crowbar can be used to absorb energy that would otherwise have to be absorbed by the MOV's, and so the quantity of MOV's in this bank could be considerably reduced. However, this scheme was not pursued to any great lengths, for the C-VCB protection scheme had already been selected as the most promising method.

Fig. C-10. Variation on C-C-MOV Protection for Shot Mode with a Fault at A

b. Discharge Cleaning Mode Ground Faults

1. At "E", or Normal Shot

Since the 0.05 F capacitor is to be switched out for discharge cleaning, only the MOV's and crowbar remain across the armature. The maximum voltage across the armature can be determined by a voltage division between the inductances of the circuit. The 20 mH of the coil, 2 mH of the bus, and 0.7 mH of the generator all carry the same current and divide a maximum of 20 kV between them. This means that the maximum voltage across the armature is about 620 V. The maximum current is roughly 2,000 A, which gives an IR drop of 1.4 V across the armature, and so the $L \frac{di}{dt}$ term clearly dominates.

This maximum voltage of 620 V indicates that the crowbar will not trigger and the MOV's do not contribute to the response in this case.

2. At "A" (See Fig. C-11)

Fig. C-11. Discharge Cleaning Mode C-C-MOV Protection:
Main Currents for a Fault at A Before the Crowbar Triggers
(See Table D-6)

If the MOV's were not in the circuit, the voltage at both points B and C would go to -20 kV at the instant of discharge, for the voltage from C to ground would be equivalent to the voltage across the discharge capacitor, and the voltage from B to ground would be equal to the di/dt spike on the coil inductance. The presence of the MOV's limits the maximum voltage to ground at both points to within ± 700 volts.

Due to the fault, the capacitor discharges very quickly. When the current attempts a reversal at 1.4 msec, the sudden change causes the armature voltage to reach 800 V, at which time the crowbar triggers.

3. At "D" (See Fig. C-12)

Fig. C-12. Discharge Cleaning Mode C-C-MOV Protection:
Main Currents for a Fault at D

Once again, if the MOV's were not in the circuit, the voltages at B and C would both go to -20 kV at the instant of discharge, for the voltage from C to ground is equivalent to the voltage across the saturable reactor, while the voltage from B to ground is again equal to the di/dt spike on the coil inductance. Then, in a very short time ($\sim 60 \mu\text{sec}$) both of these voltages would go to a positive 5,000 V as the di/dt across the saturable reactor reverses and the voltages across the snubber elements come into play. The presence of the MOV's limits these voltages to within ± 600 V. The crowbar does not trigger.

4. At "B" or "C"

In this case, an inductive voltage division shows that 620 V will try to appear across a single MOV bank at the moment of capacitor discharge. However, a single bank will conduct over 2,000 A at 620 V, and so this voltage is not reached. Instead, the maximum voltage is approximately 500 V.

5. C-VCB Configuration (See Fig. C-13)

This protection scheme protects the generators by completely isolating them from the remainder of the circuit before the shot is made or discharge cleaning is initiated.

In the shot mode, when the OH coil current reaches 20 kA, the breaker contacts are parted. Then the crowbars and commutating capacitors are fired. The breaker arcs are thereby extinguished, and the current is diverted into two separate loops. The shot is then ready to be made.

In the discharge cleaning mode, the circuit breakers are simply left open and both load SCR crowbars are closed in order to give the discharge cleaning current a bidirectional path.

A more detailed account of the circuit behavior follows.

Fig. C-13. C-VCB Protection

a. Shot Mode

Time "zero" is taken to be the time at which the crowbars and commutating capacitors are fired. Note that the load crowbar will be reverse biased at first and so will not be conducting, as shown in Fig. C-14.

The magnitude of each commutation capacitor was chosen to be 200 μF, and at this capacitance the release of a 10 kV charge causes the breaker currents to go to zero amps in 46 μsec. The purpose of the saturable reactors is to bring about lower di/dt's at low currents so that the breaker arcs will extinguish when the currents reach zero. The value at the zero crossover for

this circuit is $\sim 65 \text{ A}/\mu\text{sec}$. At the time the breakers open, the generator crowbar voltage is under 1 V.

Fig. C-14. Shot Mode C-VCB Protection:
Time 0-46 μsec
(See Table D-7)

The di/dt value of $65 \text{ A}/\mu\text{sec}$ is probably not low enough to give reliable cutoff of the arc. Various values ranging from $5 \text{ A}/\mu\text{sec}$ to $40 \text{ A}/\mu\text{sec}$ have been postulated as being desirable. Once the equipment is set up, however, adjustments of the capacitance and peak voltage could be experimented with in order to determine a desirable operating point. For instance, if the peak voltage were lowered and/or the capacitance increased, the effect would be to reduce the value of di/dt at the zero-crossing point.

It must also be noted that the value of $65 \text{ A}/\mu\text{sec}$ was obtained by a computer simulation based upon an approximation of the V-I curve for the saturable reactor, and is therefore only a rough estimate itself. The capacitance of $200 \mu F$ with an initial charge of 10 kV was used only as a basis for obtaining general information concerning the behavior of the

circuit, and all of the following information must be viewed in that light.

The circuit covering the response up until the time when the load crowbar begins to conduct is shown in Fig. C-15. After the breakers open, the capacitors continue to conduct until the current in them reverses, at which time the ignitrons will block. But before this happens, the voltage polarity on the capacitors reverses, and the load crowbar becomes forward biased. This occurs at about 112 μsec . The generator voltage is still below 1 V at this time.

Fig. C-15. Shot Mode C-VCB Protection:
Time 46-112 μsec
(See Table D-8)

The circuit covering the response from the time the load crowbar starts to conduct up until the time the ignitrons shut off is shown in Fig. C-16. The inductor in the load crowbar prevents too rapid a rate of current rise. This rate of rise is limited to 600 A/ μsec if 10 μH is used, and the same rate of rise applies to the generator crowbar. The capacitors reach their peak reverse voltage of 3300 V at 164 μsec . When the

current tries to reverse, the ignitrons block. During the time elapsed, the generator voltage goes to 700 V.

Fig. C-16. Shot Mode C-VCB Protection:
Time 112-164 μ sec
(See Table D-9)

The circuit has now been divided into two separate loops, each carrying an initial current of 20 kA. The shot is ready to be made. The vacuum circuit breakers must be able to hold off 20 kV in case of ground faults, and the ignitrons must be able to hold off 20 kV plus the reverse voltage remaining on the capacitors. A 30 kV capability is enough in this case. Note that if both ignitrons were to fail and allow a current reversal, the capacitors would discharge through the generator crowbar, quickly causing overvoltage across the armature.

It is possible that the breaker arcs will not extinguish at the first current zero, but will delay until the second current zero is reached. If the breakers continue to conduct after the first current zero at 46 μ sec, then the capacitors will reverse polarity at 107 μ sec, putting a forward bias on the load crowbar, enabling it to take on the load current.

Again, the rate of current rise in either crowbar is about 600 A/ μ sec. The capacitors reach their maximum reverse charge of about 3500 V at 157 μ sec, and when the currents attempt to reverse, the ignitrons block. The generator voltage reaches a maximum of 740 V at this time.

At about 250 μ sec the breaker current reverses again and the arcs have another opportunity to be extinguished. If they do not extinguish, then the extra breakers in parallel are closed in order to short out the arcing breakers and extinguish the arc.

Following are current and energy calculations for the generator and ohmic heating coil loops after the shot is made.

1. Generator Loop (See Fig. 3.)

The armature resistance and inductance are 700 $\mu\Omega$ and 700 μ H, and the crowbar resistance is 35 m Ω . The armature emf, as a function of time, is approximately (700-1170 t) V.

Therefore, the loop equation is:

$$\begin{aligned} V_{\text{GEN}} - R_G I_G - L_G \dot{I}_G - 0.035 I_G &= 0 \\ 700 - 1170 t - 0.0357 I_G - 0.0007 \dot{I}_G &= 0. \end{aligned}$$

Taking the Laplace transform gives:

$$\frac{700}{s} - \frac{1170}{s^2} - 0.0357 I_G(s) - 0.0007 (s I_G(s) - 20 \cdot k) = 0,$$

$$I_G(s) = \frac{20 \cdot k (s^2 + 50 s - 83.4)}{s^2 (s + 51)} = 20 \cdot k \left(\frac{1.01}{s} - \frac{1.63}{s^2} - \frac{0.01}{s + 51} \right).$$

Taking the inverse transform gives:

$$I_G(t) = 20 \cdot k \left(1.01 - 1.63 t - 0.01 e^{-51 t} \right) \text{ A.}$$

The energy consumption of the crowbar resistance can be found by integration of $I_G(t)^2 R$ over the period of 0 to 0.7 seconds.

$$\begin{aligned}
 E_{\text{CROWBAR}} &= \int_0^{0.7} (20 \text{ k})^2 (0.035) (1.01 - 1.63 t + 0.01 e^{-51 t})^2 dt \\
 &= 1.4 \times 10^7 \left[\int_0^{0.7} 1.02 dt + \int_0^{0.7} 2.67 t^2 dt \right. \\
 &\quad + \int_0^{0.7} 0.0001 e^{-102 t} dt + \int_0^{0.7} 3.3 t dt \\
 &\quad \left. - \int_0^{0.7} 0.0202 e^{-51 t} dt + \int_0^{0.7} 0.0327 t e^{-51 t} dt \right].
 \end{aligned}$$

The third, fifth, and sixth terms are small compared to the others, and so:

$$E_{\text{CROWBAR}} \approx 1.4 \times 10^7 \left[0.714 + 2.67 \frac{0.343}{3} - 3.3 \frac{0.49}{2} \right] = 2.95 \text{ MJ.}$$

2. Ohmic Heating Coil Loop (See Fig. 3.)

In this loop, the total resistance is 1.035 ohms and the total inductance is 25.3 mH. This gives an R/L of 40.9, therefore the coil current is expressed by the following equation:

$$I_C \approx 20 \text{ k} e^{-40.9 t} \text{ A.}$$

The energy consumption in the coil is:

$$\begin{aligned}
 E_{\text{COIL}} &= \int_0^{\infty} (20 \text{ k})^2 e^{-81.8 t} (0.033) dt \\
 &= \frac{(20 \text{ k})^2 (0.033)}{81.8} = 0.16 \text{ MJ.}
 \end{aligned}$$

The energy consumption of the $1\ \Omega$ resistor is:

$$E_{1\ \Omega} = \frac{1}{0.033} (0.16\ \text{MJ}) = 4.85\ \text{MJ}.$$

The energy consumption of the SCR device, assuming a resistance of $0.1\ \text{m}\Omega$, is:

$$E_{\text{SCR}} \approx 0.0001 (4.85\ \text{MJ}) = 485\ \text{J}.$$

b. Discharge Cleaning Mode

For the discharge cleaning mode, the generator vacuum circuit breakers are left open, and both load crowbar SCR's are gated on in order to provide a bidirectional current path as shown in Fig. C-17.

Fig. C-17. Discharge Cleaning Mode C-VCB Protection

As can be seen, both the vacuum circuit breakers and the ignitrons which separate the generators from the OH coil current must be able to hold off 20 kV in case of a fault at A. A fault at D is not as severe as one at A, and faults at B or C cause no strain on the devices.

As for the energy calculations, if the snubber is ignored, the capacitor sees a resistance of 0.22 ohms and an inductance of 0.022 H.

$$\frac{R}{2L} = 5,$$

$$\frac{1}{\sqrt{LC}} = 477,$$

$$V_{\text{cap}}|_{t=0} = 20 \text{ kV},$$

$$I_{\text{max}} \text{ without damping} = \frac{V_{\text{max}}}{\sqrt{L/C}} = \frac{20 \text{ k}}{\sqrt{22 \text{ m}/200 \mu}} = 1910 \text{ A}.$$

Therefore,

$$I = e^{-5 t} (1910 \sin 477 t) \text{ A},$$

$$V_{\text{cap}} \approx 20 e^{-5 t} \cos (477 t) \text{ kV}.$$

After the completion of one cycle, the voltage on the capacitor will be:

$$V_{\text{cap}} = 20 \text{ k} e^{-5 (0.0132)} = 18.7 \text{ kV}.$$

The energy stored at the end of the cycle is:

$$E = 1/2 CV^2 = 35.0 \text{ kJ},$$

as compared to the 40 kJ stored initially. Therefore, the energy absorbed in the equivalent coil resistance is 5.0 kJ. Since the reflected impedance of the plasma makes up approximately 85% of this equivalent resistance (see Appendix B), the energy transferred

to the plasma is 4.25 kJ. If a discharge cleaning pulse is made every second, then the average power is 4.25 kW. The repetition rate could easily be adjusted to provide the required power output. Since only 1.3 kV of recharging are needed between each pulse, a 5 A constant current supply could do the recharging in 0.05 sec. An alternative to this scheme would be to have a holding anode on the ignitron which would allow the response to go through several cycles at a time rather than a single cycle.

H. APPENDIX D: TYPICAL COMPUTER RESULTS

This section includes typical output from the computer studies, analysis of which led to the various circuit configurations described. Numerous computer printouts are on file to support this document and are available for review. However, the use of all the printouts would substantially increase the size of this document. Therefore, only samples of typical output are included.

1. Capacitors to Ground Configuration (See Figs. C-1 through C-3.)

The output shown in Tables D-1 and D-2 outlines the circuit response for the case of a shot with a ground fault at point A. C1 and C2 are each 0.1 F. The various voltages and currents are labeled on Figs. C-2 and C-3.

As can be seen in Table D-1, the immediate problem is that the armature voltage (V_{ARM}) exceeds 800 V in approximately 1.2 msec. Table D-2 shows the response if a generator crowbar is triggered at this time. The crowbar prevents excessive armature voltage, but the voltage from C to ground (VC) exceeds 800 V within another 8 msec. Also, the voltage across C2 (VB) changes to a polarity opposite to that which would occur during a normal shot, which rules out the use of an electrolytic capacitor in this position.

2. Metal Oxide Varistors Configuration (See Fig. C-5.)

The output in Table D-3 shows the circuit response for a normal shot. The MOV banks do a good job of holding down voltages to ground at points B and C. However, they are unable to limit the armature voltage adequately.

3. C-C-MOV Configuration (See Fig. C-6.)

a. Shot Mode

The output in Tables D-4 and D-5 show the circuit response for a normal shot. E_{COIL} and E_{CROW} are energy dissipations in the ohmic heating coil and generator crowbar, respectively.

The capacitor across the armature is able to hold the voltage below 800 V for 3.7 msec, as shown in Table D-4. Then, skipping to Table D-5, the effect of deploying the crowbar can be seen. The armature voltage immediately drops off and does not exceed 800 V at any time. The MOV's contribute very little to the response, as evidenced by the low current levels.

b. Discharge Cleaning Mode (See Fig. C-11.)

The output shown in Table D-6 is for the case of a ground fault at A at the instant of capacitor discharge. Note that the MOV's successfully suppress the negative voltage surges at points B and C. Then, at 1.4 msec, the armature voltage reaches 800 V, at which time the crowbar will deploy.

4. C-VCB Configuration (See Figs. C-13 through C-16.)

Only the shot mode was programmed for this configuration. The various voltages and currents are shown in Fig. C-14. $DILS$ is the rate of change of VCB current in A/sec, and E_{CROW} is the energy dissipated in the generator crowbar.

The case in which the breakers interrupt at the first current zero is shown in Tables D-7 through D-9. Table D-7 shows the current in the breakers (I_{LS}) going to zero at 46 μ sec. Table D-8 shows that the load crowbar becomes forward biased at 112 μ sec. Table D-9 shows that the ignitrons will shut down when the commutation capacitors reach their maximum reverse charge at 164 μ sec.

Table D-1

Circuit Response for the Case of a Shot with Ground Fault
at A and 0.1 F to Ground at each Generator Terminal

(See Fig. C-2)

TIME	VB	VC	VARM	ILG	ILS	ILC	ICI	IC2
0.0	-350.00	350.00	700.00	20000.	20000.	20000.	0.0	0.0
5.0000000-05	-350.00	350.22	700.22	20000.	19083.	19999.	916.79	-0.73438
1.0000000-04	-350.00	350.90	700.90	20000.	18179.	19998.	1820.5	-1.3203
1.5000000-04	-350.00	352.02	702.02	20000.	17316.	19998.	2683.6	-1.9063
2.0000000-04	-350.00	353.56	703.56	19999.	16494.	19997.	3505.1	-2.3906
2.5000000-04	-350.00	355.51	705.51	19999.	15712.	19996.	4286.6	-2.7695
3.0000000-04	-350.00	357.83	707.83	19998.	14968.	19995.	5030.0	-2.9648
3.5000000-04	-350.00	360.52	710.52	19998.	14260.	19995.	5737.1	-2.9805
4.0000000-04	-350.00	363.55	713.55	19997.	13507.	19994.	6409.5	-2.7891
4.5000000-04	-350.00	366.91	716.91	19995.	12946.	19993.	7048.8	-2.3516
5.0000000-04	-350.00	370.58	720.58	19994.	12337.	19992.	7656.8	-1.6719
5.5000000-04	-350.00	374.55	724.55	19992.	11757.	19991.	8234.7	-0.72266
6.0000000-04	-350.00	378.80	728.80	19990.	11206.	19991.	8784.1	0.53516
6.5000000-04	-350.00	383.32	733.32	19988.	10682.	19990.	9306.2	2.1055
7.0000000-04	-349.98	388.09	738.08	19985.	10183.	19989.	9802.4	4.0039
7.5000000-04	-349.97	393.11	743.08	19982.	9708.2	19988.	10274.	6.2539
8.0000000-04	-349.96	398.35	748.31	19979.	9257.0	19988.	10722.	8.8867
8.5000000-04	-349.95	403.81	753.76	19975.	8827.9	19987.	11147.	11.893
9.0000000-04	-349.93	409.48	759.42	19971.	8419.9	19986.	11551.	15.309
9.5000000-04	-349.92	415.35	765.27	19966.	8031.9	19985.	11934.	19.141
1.0000000-03	-349.91	421.40	771.31	19961.	7662.9	19984.	12298.	23.402
1.0500000-03	-349.89	427.63	777.52	19955.	7312.2	19984.	12643.	28.098
1.1000000-03	-349.87	434.03	783.90	19950.	6978.7	19983.	12971.	33.242
1.1500000-03	-349.84	440.59	790.43	19943.	6661.8	19982.	13281.	38.863
1.2000000-03	-349.82	447.30	797.11	19936.	6360.4	19981.	13576.	44.949
1.2500000-03	-349.79	454.15	803.94	19929.	6074.1	19980.	13855.	51.531
1.3000000-03	-349.76	461.14	810.89	19921.	5801.9	19980.	14119.	58.594
1.3500000-03	-349.72	468.25	817.97	19913.	5543.2	19979.	14369.	66.184
1.4000000-03	-349.68	475.49	825.17	19904.	5297.5	19978.	14606.	74.277
1.4500000-03	-349.64	482.84	832.48	19894.	5063.9	19977.	14831.	82.887
1.5000000-03	-349.59	490.31	839.89	19885.	4842.1	19977.	15042.	92.035

Table D-2

Circuit Response for the Case of a Shot with Ground Fault at A, 0.1 F to Ground
at Each Generator Terminal, and Generator Crowbar Triggering at 1.22 msec

(See Fig. C-3)

TIME	VB	VC	VARM	ICROW	ILG	ILC	IC1	IC2
1.220000D-03	-349.84	450.02	799.86	19996.	19933.	19976.	-6307.6	20039.
1.420000D-03	-311.01	438.71	749.72	18743.	19911.	19973.	-5020.5	18804.
1.620000D-03	-274.54	429.86	704.40	17610.	19903.	19969.	-3841.0	17676.
1.820000D-03	-240.24	423.27	663.50	16588.	19907.	19965.	-2760.1	16645.
2.020000D-03	-207.90	418.75	626.65	15666.	19922.	19960.	-1769.7	15704.
2.220000D-03	-177.36	416.13	593.49	14837.	19947.	19956.	-862.22	14846.
2.420000D-03	-148.47	415.24	563.71	14093.	19981.	19951.	-30.797	14062.
2.620000D-03	-121.07	415.94	537.01	13425.	20023.	19945.	730.93	13348.
2.820000D-03	-95.035	418.11	513.14	12829.	20072.	19940.	1428.7	12696.
3.020000D-03	-70.245	421.61	491.86	12296.	20128.	19934.	2067.8	12103.
3.220000D-03	-46.588	426.34	472.92	11823.	20189.	19928.	2653.1	11562.
3.420000D-03	-23.963	432.18	456.14	11404.	20255.	19922.	3189.1	11071.
3.620000D-03	-2.2759	439.05	441.33	11033.	20326.	19916.	3679.8	10623.
3.820000D-03	18.557	446.86	428.31	10708.	20400.	19909.	4129.2	10217.
4.020000D-03	38.615	455.53	416.92	10423.	20478.	19902.	4540.4	9847.2
4.220000D-03	57.968	464.99	407.02	10176.	20559.	19895.	4916.9	9512.0
4.420000D-03	76.683	475.17	398.49	9962.2	20642.	19888.	5261.3	9208.0
4.620000D-03	94.819	486.01	391.19	9779.7	20728.	19881.	5576.4	8932.7
4.820000D-03	112.43	497.45	385.02	9625.4	20815.	19873.	5864.6	8663.5
5.020000D-03	129.57	509.44	379.87	9496.8	20904.	19866.	6128.1	8458.2
5.220000D-03	146.28	521.94	375.66	9391.5	20994.	19858.	6369.1	8254.9
5.420000D-03	162.60	534.89	372.29	9307.3	21086.	19850.	6589.3	8071.6
5.620000D-03	178.57	548.27	369.70	9242.4	21178.	19842.	6790.5	7906.6
5.820000D-03	194.24	562.03	367.80	9194.9	21270.	19834.	6974.3	7756.3
6.020000D-03	209.62	576.15	366.53	9163.3	21363.	19825.	7142.0	7625.3
6.220000D-03	224.75	590.58	365.84	9145.9	21456.	19817.	7295.2	7506.3
6.420000D-03	239.65	605.31	365.66	9141.5	21549.	19808.	7434.8	7400.0
6.620000D-03	254.35	620.30	365.95	9148.8	21642.	19799.	7562.2	7305.4
6.820000D-03	268.87	635.54	366.67	9166.7	21735.	19790.	7678.1	7221.6
7.020000D-03	283.24	651.00	367.76	9194.1	21828.	19781.	7783.7	7147.4
7.220000D-03	297.46	666.66	369.20	9230.0	21920.	19772.	7879.8	7082.1
7.420000D-03	311.56	682.50	370.94	9273.6	22011.	19762.	7967.2	7024.8
7.620000D-03	325.55	698.51	372.96	9324.0	22102.	19753.	8046.6	6974.8
7.820000D-03	339.45	714.68	375.22	9380.5	22192.	19743.	8118.6	6931.5
8.020000D-03	353.28	730.97	377.70	9442.5	22282.	19733.	8184.0	6894.3
8.220000D-03	367.03	747.40	380.37	9509.3	22370.	19724.	8243.1	6862.7
8.420000D-03	380.72	763.93	383.21	9580.4	22458.	19714.	8296.7	6836.0
8.620000D-03	394.36	780.57	386.21	9655.2	22545.	19703.	8345.0	6813.9
8.820000D-03	407.97	797.30	389.33	9733.3	22631.	19693.	8388.6	6795.9
9.020000D-03	421.54	814.11	392.57	9814.3	22715.	19683.	8427.8	6781.6

Table D-3

Circuit Response for a Normal Shot with
MOV's from Each Generator Terminal to Ground

(See Fig. C-5)

TIME	VB	VC	VARM	ILG	IBANK	ILC
0.0	-365.79	334.85	700.64	20012.	12.000	20000.
1.0000000-03	-554.41	534.43	1088.8	19514.	393.91	19120.
2.0000000-03	-570.59	550.59	1121.2	18930.	649.07	18281.
3.0000000-03	-578.36	558.38	1136.7	18313.	830.33	17483.
4.0000000-03	-582.97	563.00	1146.0	17678.	956.58	16722.
5.0000000-03	-585.36	565.50	1150.9	17032.	1035.8	15997.
6.0000000-03	-585.97	566.31	1152.3	16382.	1076.5	15305.
7.0000000-03	-586.06	566.44	1152.5	15729.	1082.8	14646.
8.0000000-03	-585.69	565.94	1151.6	15075.	1058.1	14017.
9.0000000-03	-584.76	564.79	1149.6	14423.	1005.4	13418.
1.0000000-02	-581.99	562.01	1144.0	13775.	929.57	12846.
1.1000000-02	-578.55	558.56	1137.1	13136.	835.46	12300.
1.2000000-02	-574.55	554.55	1129.1	12506.	726.05	11780.
1.3000000-02	-568.25	548.25	1116.5	11889.	606.40	11283.
1.4000000-02	-560.92	540.92	1101.8	11291.	482.61	10808.
1.5000000-02	-551.96	531.98	1083.9	10715.	360.45	10355.
1.6000000-02	-543.29	523.33	1066.6	10164.	242.18	9922.1
1.7000000-02	-533.33	505.77	1039.1	9642.4	133.96	9508.4
1.8000000-02	-509.42	484.22	993.65	9171.6	59.324	9112.3
1.9000000-02	-499.09	451.74	950.84	8775.7	43.625	8732.1
2.0000000-02	-495.91	441.72	937.63	8407.5	38.781	8368.7
2.1000000-02	-492.97	432.49	925.46	8055.9	34.320	8021.6
2.2000000-02	-490.70	422.29	912.99	7721.0	30.867	7690.1
2.3000000-02	-484.90	415.85	900.75	7402.3	28.848	7373.4
2.4000000-02	-478.26	411.90	890.17	7098.5	27.609	7070.9
2.5000000-02	-471.86	408.09	879.96	6808.4	26.414	6782.0
2.6000000-02	-465.65	404.40	870.04	6531.3	25.254	6506.1
2.7000000-02	-459.74	400.89	860.63	6266.7	24.152	6242.5
2.8000000-02	-454.09	397.52	851.62	6013.9	23.098	5990.8
2.9000000-02	-448.65	394.29	842.94	5772.5	22.082	5750.4
3.0000000-02	-443.40	391.16	834.56	5541.8	21.102	5520.7
3.1000000-02	-438.38	388.17	826.55	5321.6	20.164	5301.4
3.2000000-02	-433.54	385.30	818.84	5111.1	19.262	5091.9
3.3000000-02	-428.41	382.78	811.19	4910.2	18.473	4891.8
3.4000000-02	-422.70	381.32	804.02	4718.6	18.016	4700.6
3.5000000-02	-417.28	379.88	797.15	4535.6	17.582	4518.0
3.6000000-02	-413.03	377.53	790.56	4360.8	17.242	4343.6
3.7000000-02	-408.97	375.30	784.27	4193.9	16.918	4176.9
3.8000000-02	-405.00	373.10	778.10	4034.5	16.600	4017.9
3.9000000-02	-401.21	371.01	772.23	3882.3	16.297	3866.0
4.0000000-02	-397.56	369.00	766.56	3736.9	16.005	3720.9

Table D-4

Circuit Response for a Normal Shot with
C-C-MOV Configuration, Before Crowbar Triggers

(See Fig. C-6)

TIME	VB	VC	VARM	ECOIL	ILG	ILC	IBANK
0.0	-360.53	337.50	700.00	0.0	20012.	20000.	11.500
1.000000D-04	-360.57	337.53	700.08	1314.8	20011.	19921.	11.504
2.000000D-04	-360.69	337.63	700.31	2619.2	20011.	19843.	11.516
3.000000D-04	-360.90	337.79	700.70	3913.4	20011.	19764.	11.535
4.000000D-04	-361.19	338.02	701.25	5197.4	20011.	19686.	11.563
5.000000D-04	-361.55	338.31	701.95	6471.3	20011.	19609.	11.598
6.000000D-04	-362.01	338.67	702.81	7735.1	20010.	19532.	11.641
7.000000D-04	-362.54	339.09	703.82	8989.0	20010.	19455.	11.691
8.000000D-04	-363.15	339.58	704.98	10233.	20009.	19378.	11.749
9.000000D-04	-363.84	340.07	706.29	11467.	20008.	19302.	11.815
1.000000D-03	-364.61	340.40	707.76	12692.	20007.	19226.	11.888
1.100000D-03	-365.46	340.77	709.37	13907.	20005.	19150.	11.968
1.200000D-03	-367.15	341.50	711.13	15112.	20004.	19075.	12.130
1.300000D-03	-369.46	342.49	713.03	16308.	20002.	19000.	12.349
1.400000D-03	-370.84	343.57	715.08	17495.	20000.	18925.	12.585
1.500000D-03	-371.99	344.71	717.28	18672.	19997.	18850.	12.837
1.600000D-03	-373.21	345.94	719.62	19840.	19994.	18776.	13.106
1.700000D-03	-374.50	347.23	722.10	20999.	19991.	18703.	13.391
1.800000D-03	-375.87	348.60	724.71	22149.	19987.	18629.	13.692
1.900000D-03	-377.31	350.04	727.47	23289.	19983.	18556.	14.009
2.000000D-03	-378.73	351.46	730.36	24421.	19979.	18483.	14.320
2.100000D-03	-379.50	352.23	733.39	25544.	19974.	18410.	14.490
2.200000D-03	-380.86	353.03	736.56	26658.	19968.	18338.	14.668
2.300000D-03	-383.22	353.87	739.85	27763.	19963.	18266.	14.852
2.400000D-03	-385.67	354.75	743.28	28860.	19956.	18195.	15.044
2.500000D-03	-388.21	355.65	746.84	29948.	19949.	18123.	15.244
2.600000D-03	-390.84	356.59	750.52	31028.	19942.	18052.	15.450
2.700000D-03	-393.57	357.56	754.33	32099.	19934.	17981.	15.664
2.800000D-03	-396.38	358.57	758.27	33162.	19926.	17911.	15.885
2.900000D-03	-399.28	359.60	762.32	34216.	19917.	17841.	16.112
3.000000D-03	-402.26	360.66	766.50	35263.	19907.	17771.	16.346
3.100000D-03	-405.34	361.76	770.80	36301.	19897.	17702.	16.587
3.200000D-03	-408.49	362.88	775.21	37331.	19886.	17632.	16.835
3.300000D-03	-411.73	364.04	779.74	38353.	19874.	17564.	17.088
3.400000D-03	-415.05	365.28	784.38	39367.	19862.	17495.	17.349
3.500000D-03	-418.44	366.84	789.14	40373.	19849.	17427.	17.615
3.600000D-03	-421.92	368.43	794.00	41371.	19835.	17359.	17.888
3.700000D-03	-426.68	370.61	798.97	42361.	19821.	17291.	18.261

Table D-5

Circuit Response for a Normal Shot with
C-C-MOV Configuration, After Crowbar Triggers

(See Fig. C-6)

TIME	VB	VC	VARM	ECOIL	ECROW	ILG	ILC	ICROW	IBANK
3.700000-C3	-426.69	370.61	796.97	42461.	0.0	19821.	17291.	19974.	18.261
1.370000-C2	-218.40	214.69	426.80	1.10336E 05	30613.	24272.	11607.	10920.	4.4673
2.370000-C2	-350.94	329.91	681.79	1.41217E 05	1.23119E 05	25677.	7899.7	17045.	10.590
3.370000-C2	-399.26	359.59	762.30	1.55753E 05	2.56904E 05	24722.	5484.8	19057.	16.110
4.370000-C2	-404.14	361.33	769.13	1.62878E 05	4.04854E 05	23079.	3892.3	19228.	16.494
5.370000-C2	-389.38	356.07	748.47	1.66530E 05	5.49231E 05	21428.	2832.0	18712.	15.335
6.370000-C2	-373.57	346.29	720.30	1.68497E 05	6.84111E 05	19597.	2119.3	18008.	13.185
7.370000-C2	-356.56	334.36	692.46	1.69618E 05	8.08780E 05	18827.	1636.6	17312.	11.123
8.370000-C2	-343.44	323.97	667.46	1.70295E 05	9.24255E 05	17888.	1307.3	16687.	9.8766
9.370000-C2	-332.33	313.32	645.73	1.70730E 05	1.03193E 06	17132.	1081.1	16143.	8.8209
0.103700	-322.49	304.57	626.84	1.71025E 05	1.13265E 06	16515.	924.19	15671.	8.0740
0.113700	-315.91	296.89	610.21	1.71241E 05	1.22776E 06	15999.	814.26	15255.	7.6134
0.123700	-309.59	289.99	595.27	1.71412E 05	1.31804E 06	15554.	736.13	14882.	7.1597
0.133700	-299.15	283.67	581.56	1.71537E 05	1.40407E 06	15160.	679.61	14539.	6.8201
0.143700	-289.57	276.53	568.72	1.71662E 05	1.48627E 06	14800.	637.77	14218.	6.4786
0.153700	-285.50	270.71	556.49	1.71767E 05	1.56487E 06	14465.	605.91	13912.	6.2748
0.163700	-281.56	265.08	544.67	1.71829E 05	1.64016E 06	14146.	580.87	13617.	6.0778
0.173700	-276.35	259.73	533.15	1.71892E 05	1.71228E 06	13839.	560.45	13329.	5.8905
0.183700	-270.33	254.57	521.86	1.71954E 05	1.78135E 06	13539.	543.19	13047.	5.7098
0.193700	-263.23	249.45	510.67	1.72017E 05	1.84746E 06	13245.	528.08	12767.	5.5307
0.203700	-256.16	244.40	499.63	1.72079E 05	1.91074E 06	12956.	514.44	12491.	5.3541
0.213700	-249.16	239.34	488.59	1.72142E 05	1.97129E 06	12667.	501.80	12215.	5.1803
0.223700	-242.58	234.23	477.64	1.72204E 05	2.02917E 06	12382.	489.84	11941.	5.0269
0.233700	-236.02	229.13	466.70	1.72267E 05	2.08437E 06	12097.	478.34	11667.	4.8738
0.243700	-229.45	224.01	455.75	1.72329E 05	2.13709E 06	11812.	467.16	11394.	4.7204
0.253700	-222.92	218.73	444.87	1.72392E 05	2.18725E 06	11529.	456.17	11122.	4.5682
0.263700	-217.00	213.55	434.00	1.72454E 05	2.23500E 06	11246.	445.41	10850.	4.4387
0.273700	-211.57	209.10	423.14	1.72514E 05	2.28040E 06	10964.	434.67	10578.	4.3275
0.283700	-206.13	204.65	412.27	1.72514E 05	2.32357E 06	10681.	424.03	10307.	4.2164
0.293700	-200.70	200.21	401.40	1.72514E 05	2.36446E 06	10399.	413.53	10035.	4.1052
0.303700	-195.26	194.83	390.53	1.72514E 05	2.40318E 06	10116.	403.03	9763.2	3.9940
0.313700	-189.83	189.41	379.66	1.72514E 05	2.43977E 06	9834.1	392.53	9491.5	3.8829
0.323700	-184.40	183.99	368.79	1.72514E 05	2.47430E 06	9551.8	382.03	9219.8	3.7717
0.333700	-178.96	178.56	357.92	1.72514E 05	2.50630E 06	9269.4	371.53	8948.0	3.6606
0.343700	-173.53	173.14	347.05	1.72514E 05	2.53735E 06	8987.1	361.03	8676.3	3.5494
0.353700	-168.09	167.72	336.18	1.72514E 05	2.56606E 06	8704.8	350.52	8404.6	3.4382
0.363700	-162.66	162.30	325.31	1.72514E 05	2.59286E 06	8422.4	340.02	8132.8	3.3271
0.373700	-157.22	156.87	314.45	1.72514E 05	2.61793E 06	8140.1	329.52	7861.1	3.2159
0.383700	-151.79	151.45	303.58	1.72514E 05	2.64136E 06	7857.7	319.02	7589.4	3.1048

Table D-6

Circuit Response for Discharge Cleaning with
Ground Fault at A and C-C-MOV Configuration

(See Fig. C-11)

TIME	VB	VC	VARM	ILG	ILC	VCD	IBANK1	IBANK2
0.0	0.0	0.0	0.0	0.0	0.0	20000.	0.0	0.0
5.000000D-05	-396.23	-571.29	-175.06	16.590	0.71644	19677.	-948.98	-15.673
1.000000D-04	-465.32	-594.96	-129.64	26.877	1.7626	19323.	-1385.3	-25.114
1.500000D-04	-491.76	-607.70	-115.95	35.382	2.9111	18735.	-2798.9	-32.471
2.000000D-04	-496.58	-618.53	-121.95	43.881	4.0858	17921.	-3676.9	-39.795
2.500000D-04	-501.65	-628.77	-127.12	52.779	5.2717	16895.	-4507.8	-47.507
3.000000D-04	-506.94	-638.22	-131.28	62.012	6.4693	15667.	-5281.4	-55.543
3.500000D-04	-511.44	-646.70	-135.26	71.515	7.6785	14253.	-5988.1	-63.836
4.000000D-04	-514.85	-654.27	-139.42	81.327	8.8959	12672.	-6619.1	-72.431
4.500000D-04	-518.36	-660.84	-142.48	91.396	10.121	10942.	-7166.6	-81.275
5.000000D-04	-521.94	-666.32	-144.38	101.64	11.354	9084.7	-7623.9	-90.289
5.500000D-04	-525.55	-670.66	-145.11	111.98	12.595	7123.9	-7985.2	-99.369
6.000000D-04	-529.16	-673.79	-144.63	122.33	13.843	5083.6	-8246.2	-108.49
6.500000D-04	-530.83	-675.68	-144.85	132.66	15.098	2989.0	-8403.6	-117.56
7.000000D-04	-531.92	-676.30	-144.38	142.99	16.355	866.13	-8455.4	-126.63
7.500000D-04	-532.99	-675.65	-142.66	153.24	17.613	-1258.9	-8401.0	-135.62
8.000000D-04	-534.04	-673.73	-139.68	163.32	18.874	-3359.7	-8241.0	-144.44
8.500000D-04	-535.07	-670.57	-135.50	173.14	20.136	-5410.4	-7977.5	-153.01
9.000000D-04	-536.05	-666.20	-130.15	182.63	21.400	-7385.7	-7613.9	-161.23
9.500000D-04	-536.98	-660.69	-123.71	191.69	22.666	-9261.2	-7154.5	-169.03
1.000000D-03	-537.86	-654.10	-116.25	200.26	23.933	-11014.	-6605.2	-176.33
1.050000D-03	-538.66	-646.51	-107.85	208.26	25.201	-12622.	-5972.7	-183.06
1.100000D-03	-539.39	-638.02	-98.634	215.63	26.471	-14066.	-5264.9	-189.15
1.150000D-03	-540.04	-628.56	-88.524	222.30	27.741	-15328.	-4490.6	-194.56
1.200000D-03	-540.59	-618.31	-77.719	228.23	29.012	-16393.	-3659.4	-199.22
1.250000D-03	-541.05	-607.49	-66.434	233.37	30.284	-17247.	-2781.5	-203.09
1.300000D-03	-541.42	-594.54	-53.125	237.68	31.556	-17880.	-1867.9	-206.13
1.350000D-03	-541.62	-570.50	-28.876	240.65	32.829	-18285.	-930.56	-207.82
1.400000D-03	-541.28	347.26	888.54	239.06	34.100	-18457.	13.398	-204.96

Table D-7

Separation of the Generators from the Jhmie
Heating Coil in the C-VCB Configuration:
From Firing of Commutation Capacitors
to Reversal of Breaker Current

(0-46 μ sec, See Fig. C-14)

TIME	ILG	ILC	ILS	DILS	VCD	ECKOW	VCROW	ICROW
0.0	2CCCC.	2CCCC.	2CCCC.	-1.00000E 09	10000.	0.0	0.0	0.0
2.0000000-C6	200C2.	200C1.	18001.	-9.98982E 08	9989.8	1.42415E-08	2.73437E-02	0.78125
4.0000000-C6	200C4.	200C2.	16005.	-9.95966E 08	9959.7	1.13931E-07	5.46875E-02	1.5625
6.0000000-C6	200C6.	200C4.	14018.	-9.90957E 08	9909.6	3.84517E-07	8.20312E-02	2.3438
8.0000000-C6	200C8.	200C5.	12042.	-9.83965E 08	9839.7	9.11451E-07	0.10937	3.1250
1.0000000-C5	20010.	20006.	10083.	-9.75000E 08	9750.0	1.78014E-06	0.13672	3.9063
1.2000000-C5	20012.	20007.	8143.2	-9.64086E 08	9640.9	3.07607E-06	0.16406	4.6875
1.4000000-C5	20014.	20008.	6227.4	-9.51244E 08	9512.4	4.88470E-06	0.19141	5.4688
1.6000000-C5	20016.	20009.	4386.2	-8.11920E 08	9365.1	7.29147E-06	0.21875	6.2500
1.8000000-C5	20018.	20011.	2988.2	-6.08625E 08	9201.3	1.03818E-05	0.24609	7.0313
2.0000000-C5	20020.	20012.	2217.2	-1.86939E 08	9026.3	1.42413E-05	0.27344	7.8125
2.2000000-C5	20021.	20013.	1929.9	-1.20352E 08	8846.6	1.89546E-05	0.30078	8.5938
2.4000000-C5	20023.	20014.	1708.3	-1.02437E 08	8664.5	2.46078E-05	0.32612	9.3750
2.6000000-C5	20025.	20015.	1516.5	-9.00477E 07	8480.3	3.12864E-05	0.35547	10.156
2.8000000-C5	20027.	20016.	1340.3	-8.68210E 07	8294.2	3.90757E-05	0.38281	10.938
3.0000000-C5	20029.	20018.	1169.1	-8.43513E 07	8106.4	4.80614E-05	0.41016	11.719
3.2000000-C5	20031.	20019.	1002.8	-8.19071E 07	7916.9	5.83288E-05	0.43750	12.500
3.4000000-C5	20033.	20020.	841.45	-7.94872E 07	7725.8	6.99761E-05	0.46744	13.355
3.6000000-C5	20035.	20021.	684.86	-7.70902E 07	7533.0	8.35862E-05	0.50846	14.527
3.8000000-C5	20037.	20021.	533.05	-7.47149E 07	7338.7	9.95795E-05	0.54947	15.699
4.0000000-C5	20039.	20022.	385.97	-7.23602E 07	7142.9	1.18148E-04	0.59049	16.871
4.2000000-C5	20041.	20023.	243.58	-7.00253E 07	6945.7	1.39485E-04	0.63150	18.043
4.4000000-C5	20043.	20024.	105.84	-6.77090E 07	6747.0	1.63781E-04	0.67252	19.215
4.6000000-C5	20045.	20025.	-27.298	-6.55296E 07	6547.0	1.91230E-04	0.71354	20.387

Table D-8

Separation of the Generators from the Ohmic
Heating Coil in the C-VCB Configuration:
From Interruption of Breaker Current
to Load Crowbar Conduction

(46-112 μ sec, See Fig. C-15)

TIME	ILG	ILC	ICROW	VCE	VCUILL	ECROW
4.600000C-05	20045.	20025.	20.000	6547.0	13095.	0.0
4.800000C-05	20045.	20026.	18.828	6346.6	12694.	2.63946E-05
5.000000C-05	20044.	20027.	17.656	6146.2	12293.	4.96995E-05
5.200000C-05	20044.	20027.	16.484	5945.8	11892.	7.01076E-05
5.400000C-05	20043.	20028.	15.313	5745.4	11491.	8.78110E-05
5.600000C-05	20043.	20029.	14.141	5545.0	11091.	1.03002E-04
5.800000C-05	20043.	20030.	12.969	5344.7	10690.	1.15873E-04
6.000000C-05	20042.	20030.	12.086	5144.3	10289.	1.26800E-04
6.200000C-05	20042.	20031.	11.305	4943.9	9888.1	1.36382E-04
6.400000C-05	20041.	20031.	10.523	4743.5	9487.3	1.44727E-04
6.600000C-05	20041.	20031.	9.7422	4543.1	9086.5	1.51920E-04
6.800000C-05	20041.	20032.	8.9609	4342.7	8685.7	1.58048E-04
7.000000C-05	20040.	20032.	8.1797	4142.3	8284.9	1.63196E-04
7.200000C-05	20040.	20033.	7.3984	3942.0	7884.2	1.67448E-04
7.400000C-05	20040.	20033.	6.6172	3741.6	7483.5	1.70891E-04
7.600000C-05	20039.	20033.	5.8359	3541.3	7082.8	1.73610E-04
7.800000C-05	20039.	20034.	5.0547	3340.9	6682.0	1.75691E-04
8.000000C-05	20038.	20034.	4.2734	3140.6	6281.3	1.77218E-04
8.200000C-05	20038.	20034.	3.4922	2940.2	5880.6	1.78277E-04
8.400000C-05	20038.	20035.	2.8711	2739.9	5479.8	1.78968E-04
8.600000C-05	20037.	20035.	2.4805	2539.5	5079.1	1.79470E-04
8.800000C-05	20037.	20035.	2.0898	2339.1	4678.4	1.79836E-04
9.000000C-05	20036.	20035.	1.6992	2138.8	4277.6	1.80088E-04
9.200000C-05	20036.	20035.	1.3086	1938.4	3876.9	1.80246E-04
9.400000C-05	20036.	20035.	0.91797	1738.0	3476.1	1.80333E-04
9.600000C-05	20035.	20035.	0.52734	1537.7	3075.4	1.80370E-04
9.800000C-05	20035.	20035.	0.13672	1337.3	2674.6	1.80378E-04
1.000000D-04	20034.	20035.	-0.25391	1136.9	2273.9	1.80379E-04
1.020000D-04	20034.	20035.	-0.64453	936.58	1873.1	1.80393E-04
1.040000D-04	20034.	20035.	-1.0352	736.21	1472.4	1.80442E-04
1.060000D-04	20033.	20035.	-1.4258	535.85	1071.6	1.80548E-04
1.080000D-04	20033.	20035.	-1.8164	335.48	670.90	1.80732E-04
1.100000D-04	20033.	20035.	-2.0898	135.13	270.18	1.81010E-04
1.120000D-04	20032.	20034.	-2.0898	-65.218	-130.51	1.81315E-04

Table D-9

Separation of the Generators from the Ohmic
Heating Coil in the C-VCB Configuration:
From Load Crowbar Conduction
to Blockage by Ignitrons

(112-164 μ sec, See Fig. C-16)

TIME	ILG	ICROW	ILCRO	ILC	VCD	VCROW	VCOIL
1.120000E-04	20032.	-2.0000	0.0	20034.	0.0	-7.00000E-02	-7.00000E-02
1.140000E-04	20034.	40.210	39.966	20034.	-200.20	1.4108	-399.00
1.160000E-04	20036.	161.70	159.30	20033.	-399.60	5.6596	-793.54
1.180000E-04	20037.	361.32	356.97	20033.	-597.40	12.646	-1182.2
1.200000E-04	20039.	637.94	631.63	20032.	-792.83	22.328	-1563.3
1.220000E-04	20040.	989.92	981.66	20032.	-985.14	34.647	-1935.6
1.240000E-04	20042.	1415.3	1405.1	20032.	-1173.6	49.537	-2297.6
1.260000E-04	20043.	1912.0	1899.8	20031.	-1357.4	66.920	-2647.9
1.280000E-04	20045.	2477.4	2463.3	20031.	-1535.9	86.710	-2985.2
1.300000E-04	20047.	3108.9	3092.8	20030.	-1708.5	108.81	-3308.2
1.320000E-04	20048.	3803.5	3785.4	20030.	-1874.5	133.12	-3615.8
1.340000E-04	20049.	4557.4	4537.8	20030.	-2033.2	159.51	-3906.9
1.360000E-04	20051.	5367.7	5346.5	20029.	-2184.1	187.87	-4180.3
1.380000E-04	20052.	6230.8	6208.0	20029.	-2326.6	218.08	-4435.2
1.400000E-04	20053.	7143.2	7118.6	20028.	-2460.3	250.01	-4670.6
1.420000E-04	20054.	8100.7	8074.3	20028.	-2584.7	283.52	-4885.8
1.440000E-04	20055.	9098.8	9070.8	20027.	-2699.2	318.46	-5080.0
1.460000E-04	20056.	10134.	10104.	20026.	-2803.6	354.68	-5252.6
1.480000E-04	20056.	11201.	11170.	20025.	-2897.5	392.02	-5403.0
1.500000E-04	20057.	12295.	12263.	20024.	-2980.6	430.34	-5530.9
1.520000E-04	20057.	13413.	13380.	20024.	-3052.7	469.46	-5635.8
1.540000E-04	20058.	14550.	14515.	20023.	-3113.4	509.24	-5717.6
1.560000E-04	20058.	15700.	15664.	20022.	-3162.7	549.50	-5776.0
1.580000E-04	20058.	16859.	16823.	20021.	-3200.5	590.08	-5811.0
1.600000E-04	20058.	18023.	17986.	20021.	-3226.7	630.82	-5822.5
1.620000E-04	20058.	19187.	19149.	20020.	-3241.2	671.56	-5810.8
1.640000E-04	20058.	20346.	20307.	20019.	-3244.1	712.12	-5776.0
1.660000E-04	20058.	21496.	21457.	20018.	-3235.4	752.36	-5718.5

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