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Considerations of Coil Protection and Electrical Connection Schemes in Large Superconducting Toroidal Magnet System

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Abstract

A preliminary comparison of several different coil protection and electrical connection schemes for large superconducting toroidal magnet systems (STMS) is carried out. Our tentative recommendation is to rely on external dump resistors for coil protection and to connect the coils in the toroidal magnet in several parallel loops (e.g., every fourth coil is connected into a single series loop). For the fault condition when a single coil quenches, the quenched coil should be isolated from its loop by switching devices. The magnet, as a whole, should probably be discharged if more than a few coils have quenched.

I. THE PROTECTION PROBLEM

Typical Parameters

Table I compares some key parameters in several designs[1-3] of the superconducting toroidal magnet systems for fusion power reactors. Column 1 of Table I is a design we shall use in Section III below to illustrate the differences between various electrical connection schemes. (We shall refer to this design as "our design" from now on.)

The high magnetic field and the large size of magnet common to all our designs are believed to be required in order to confine the plasma and to sustain fusion. Consequently, a substantial amount of magnetic energy (34-280 GJ) is stored in these toroidal field coils. Let R denote the major radius and N the number of coils in the torus, then

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for a fixed central field and aspect ratio of the torus, the total energy stored scales like R^3 and the energy available for discharge when one coil quenches scales like R^3/N^2, provided that N is not too small.[4] For our design, the energy available for discharge when one coil quenches is 645 MJ.

Protection Problems for a Single Coil

A superconductor may revert to the normal state as a result of heat input which can originate from a flux jump, wire motion, friction, cracking of impregnating compound, etc. This phenomenon is known as the quenching of superconductivity. During a quench of a magnet, several bad things could happen if the magnetic energy stored in the quenched coil is not quickly removed. First, if the Joule heating associated with quenching remains localized, this could lead to a local burnup. Secondly, large temperature gradients and thermal strains could result from a quench, which may lead to plastic deformation and failure of the magnet. If the coil warms up quickly from 4K to 100K, its thermal strain could be as large as $\sim 5 \times 10^{-4}$. Considering the fact that there will be mchanical strain due to electromagnetic forces and tension applied during winding, only a small fraction of the yield strain of copper ($\sim 3 \times 10^{-3}$) may be allowed during a quench. Thus we do not believe that the magnet should be allowed to warm up quickly from 4K to above 100K during a quench.

The amount of time it takes to form a hot spot in the magnet during quench will depend on the current density and magnetic field as well as the heat transfer characteristics of the magnet. This time scale, τ, will also be the main factor in deciding whether the coil protection mechanism can be manually operated or needs to be automatic; for example, if a magnet has a relative low maximum field B_M, and low current density in the conductor, j (say, B_M = 1.8 tesla, j = 1.7 kA/cm^2), then it takes four minutes to reach 100K and 7.4 minutes to reach 300K, assuming adiabatic heating at constant current level. In contrast, for the Eccentric Coil Test (ECT) background magnet currently under study at ORNL (B_M = 8 tesla, j = 4.2 kA/cm^2), it takes only 24 sec to reach 100K and 51 sec to reach 300K.

Thus, if we wish to dissipate the magnet energy of a quenched coil in some harmless manner within a period of τ, the voltage associated with this conversion process will scale like $R^3/N^2\tau I$, where I is the operating current of the coil at the onset of the quench. If I is small, the charging time will be long, and the number of turns in the winding will be large and hence the fabrication cost will be relatively high. If I is large, then the power supplies and circuit breaker (if used for protection) may be expensive, or less safe to operate. A value of 5-10 kA for I has been suggested in the various designs. If N is large, the access space for diagnostics is limited. If N is small, the ripple in the magnetic field will be larger. Hence, N, τ, I tend to be fixed by factors other than size, and the electrical protection becomes a more serious problem for coils of larger size.

For coils in our design, if we want to discharge the toroidal magnet in series by an external dump resistor during a time interval of 100 seconds, the terminal voltage difference will be 68 kV. To discharge just a single coil in 100 seconds requires a terminal voltage of 1.3 kV. To discharge the toroidal magnet by simultaneously discharging each coil by its own external dump resistor leads to a terminal voltage difference (and a maximum voltage difference in the toroid) of 2.8 kV. Hence, segmentation is one way to limit the terminal voltage in a large coil.

To summarize, in the protection of a large superconducting coil, there are twin conflicting problems of temperature excursion vs. voltage excursion. If magnetic energy ($E \sim P\tau \sim VI\tau$) in coil is extracted too slowly, internal overheating may result. If energy is extracted too quickly, high voltage may result. One way to handle the latter problem is to segment the coil into independent sections during quench by switching devices. ($E \sim (V/n)(nI)\tau$, n is number of sections.)

Protection Problems for Multiple Coil Systems

If the magnet is composed of more than one coil, one must decide what to do with the rest of the coils when one coil quenches. Should one discharge all the coils whenever one coil quenches? Or should one try to isolate the quenched coil and preserve the rest in the superconducting state? This will largely depend on how frequently quenching occurs. If it is very rare, probably total system discharge is the simplest solution. If quenching is frequent, the second strategy may be needed.

The former strategy implies longer down time of the magnet system. (For a given power supply, the recharging time scales like m or m^2, where m is the number of the quenched coils, depending on whether the quenched coils are far apart or close to each other.) Furthermore, if there are some configurations where the power reactor could still produce net gain in power even with missing toroidal field coils, then the economics of the power reactor would favor continuous operation and the number of coils to be discharged during a fault condition should be kept to a minimum.

On the other hand, if all the coils are not discharged during a quench, the consequences of inductive coupling—e.g., inductive voltage, changing magnetic forces and stress in the structures, induced current increment—must be faced. As we shall see below, under certain conditions, the current in some coils may increase by as much as 30% over its original value. Furthermore, the mechanical design problem is complicated. The mechanical loading during transient fault condition needs to be examined to determine if one shape of coil , which has a lower bending moment during normal operation, is still superior to other shapes during fault condition.

II. PROTECTION SCHEMES FOR A SINGLE COIL

Many different schemes have been proposed for the protection of a single superconducting coil.[5,6] We may classify them into two broad classes: passive schemes and active schemes. In active schemes, one must be able to detect a quench condition before any protection action can be initiated. On the other hand, in the passive schemes, the magnet is protected by its built-in material or structure properties.

Passive Schemes

Inductive coupling offers a reliable mechanism to transfer energy from the primary circuits (the toroidal field coils) to the secondary inductor coils, whenever there is a change in the current of the primary. Furthermore, there is no terminal voltage across the primary in this scheme, hence the chance of an electrical breakdown is significantly reduced.

On the other hand, the energy extraction efficiency η of this scheme is not likely to be high. Here η represents the maximum percentage of energy in the quenched coil that can be transferred to the protection components (in this case, the secondary circuit). For two coupled LR circuits, η is $k^2/(1+\gamma)$.[7] Here k is the coupling coefficient $M/\sqrt{L_1 L_2}$ and γ is the ratio of the primary and secondary circuit time constants. ($\gamma = \tau_1/\tau_2 = (L_1 R_2)/(L_2 R_1)$.) $L_1(L_2)$, $R_1(R_2)$ are respectively the self-inductance, resistance of the primary (secondary) circuit, and M is the mutual inductance. Thus, efficient energy transfer requires good coupling ($k \sim 1$) and small γ ($L_1 \ll L_2$. $R_2 \ll R_1$), or a bulky secondary coil if it is resistive.[5] (Superconducting secondary coil would be too prohibitively expensive an option.) Small γ, however, also implies a slow energy transfer process, and this could lead to overheating in the primary coil.

Because of the space limitation in toroidal magnet systems, we probably can at best hope for room to accommodate a secondary coil with values $L_1 \sim L_2$ and $R_1 \sim R_2$. (Note that R_1 is already made of OFHC copper or high purity Al at liquid helium temperature, although one may arrange to have R_2 exposed to a lower magnetic field.) This then leads to at best a 50% energy extraction efficiency, and is probably not good enough for protection if used alone. On the other hand, if $R_2 \gg R_1$, not only the energy extraction efficiency goes down, but also the voltage problem in the secondary coil becomes more serious. Furthermore, since the secondary has to be kept cold in order to get $k \sim 1$, the eddy current heating in the secondary and the resulting loss of helium may be severe during the charging up of the primary. If switching devices are introduced into the secondary circuit in order to avoid this problem, the scheme is no longer passive. The above comments apply equally well when there is more than one secondary coil. As far as the primary is concerned, the effect of several secondary coils may be approximated by a single secondary coil with some effective resistance and inductance value.

Another passive protection scheme is to have one or more resistors permanently connected in parallel to a coil or a section of a coil. This scheme suffers the same drawback as the inductive coupling scheme in that it takes a long time to transfer energy. The percentage of current diverted to the resistor will be quite small until the internal resistance of the coil is comparable to the external resistor. So the energy extraction coefficient is also low in such a case. Further, because of the permanent attachment of current leads, the heat leak due to these leads during normal operation of the coil may be quite significant. Even charging is difficult to ensure in such a system[5] and the use of switching devices is suggested to improve the performance.[8]

A very attractive self-protection scheme is to use an anodized Al disk as an interpancake insulator.[9] Not only does Al have a more compatible thermal contraction with the conductor than epoxy, but more important for protection, it also provides better transverse thermal conduction and larger enthalpy than can be provided by epoxy sheets. Another possibility is to use an epoxy resin with a filler of high thermal conductivity. However, the benefit of the filler may be neutralized by contact resistance between the filler and the matrix at low temperature.[10] The main idea here is to utilize the good thermal conductivity of an interpancake insulator to provide rapid propagation of a normal zone in both axial and radial directions of the coil. So, whenever there is a quench, the whole coil will become normal in a time shorter than the characteristic time for the formation of a local hot spot. Then the total enthalpy of the coil (which is very large for copper stabilized conductor) will be available to deposit the magnetic energy stored, and the asymptotic temperature rise of the coil can easily be limited to below 100K even under adiabatic heating conditions (i.e., no heat transfer into helium). The main disadvantage of this scheme is that, first, development work is required to try out various materials, bonding and fabrication schemes. Secondly, as common with other "self-protection" schemes (i.e., deposition of magnetic energy internally as heat), a longer down time for coils results (time required to cool down the coil again after warm up), and possible loss of a large amount of liquid helium. (Being a passive scheme, there is no provision for action to extract and preserve the liquid helium during quench and the thermal cycling of the coil.)

Active Schemes

Self protection may also be feasible by active means. For example, at the onset of a quench, one may try to expel the liquid helium rapidly and/or induce uniform quenching by implanted heating elements. The same comments above concerning cool down time and thermal cycling of the magnet still applies. As in all other active schemes, the question of the reliability of the detection sensors and the reliability of the protection circuitry needs to be assured.

The most common protection scheme in use is by providing a standby external resistor, which will be switched into the coil circuit during quench. An external resistance, large compared with the resistance of the coil when it is in the normal conducting state will assure a nearly 100% energy extraction efficiency. However, as we have mentioned before, the terminal voltage in this scheme is likely to be quite high for a large coil, and the current leads cause a lot of loss of coolant during normal operation. As we shall discuss in more detail below, the terminal voltage can be reduced by segmentation. Suppose P represents the power we need to extract from the magnet during a quench, then $P \simeq VI$, where I is the operating current and V is the terminal voltage. If the circuit is split into n parallel loops by switching devices during quench, then $P = V'I'$, with $I' = nI$. Hence, terminal voltage across each loop will be reduced n-fold. Although voltage reduction by segmentation is discussed here in the context of discharging a superconducting magnet into a resistive load, the same principle can be adopted for energy storage and transfer devices, such as the ohmic heating coil in a Tokamak device.

A related scheme of energy removal is to feed the electricity back into the utility grid. Assuming a rate of 1 ¢/KW-hr, the stored energy of 40 GJ in our design costs only $111. Even if the rate is ten times higher, the saving in the electricity cost is still quite small. More likely, a higher rate will be charged if electricity is allowed to feed back to the grid, and the initial cost of filter and other equipment necessary to eliminate any transient disturbance on the grid will more than offset any saving in electricity cost.

Another active protection scheme is to transfer the coil energy into capacitor banks. In contrast with the external resistor scheme, the initial terminal voltage will be small in this case. A diode or rectifier is needed to prevent the back swing of oscillation in the LC circuit, which would feed energy back into the quenched coil again. Compared with an inductor ($\sim$ 1 MJ/m^3) the capacitor stores energy at a much lower energy density ($\sim$ 0.1 J/m^3).[11] On the other hand, large energy can be deposited in a resistor (ΔT = 200K, iron, ~600 MJ/m^3) which can be cooled down quickly again by forced flow cooling or natural convection and radiation. Hence, the capacitor scheme is likely to be bulky and more expansive than the resistor scheme. Furthermore, for the same energy extraction efficiency, from Dowley's work,[6] one can show that the capacitor bank scheme will suffer a higher (~20%) maximum terminal voltage as compared with the external resistive scheme.

An obvious extension of the above protection schemes is to use one or more LCR circuits to deposit the coil energy. Such a scheme is more complex to analyze, less reliable because of the increased number of components, and offers no intrinsic advantage over the simpler scheme of external dump resistors. Spark gap and fuse can only dispose of a very small amount of coil energy. The use of SCR thyrites may also be limited by reliability consideration.

III. PROTECTION SCHEMES FOR MULTIPLE COILS (ELECTRICAL CONNECTION SCHEMES)

We shall use our design (column 1, Table I) to illustrate the protection problems in a multiple coil toroidal magnet. For the sake of clarity, the coils will be labelled consecutively in increasing order in the clockwise direction (Fig. 1). The electrical connection between coils can be divided into two broad classes, fixed or switchable. Fixed connection means we cannot rearrange the connection between coils in any way, while switchable means we can use switching devices to reconnect the coils if necessary.

If the total magnet is to be discharged whenever one coil quenches, then there is no big difference between fixed or switchable electrical connection, although from the viewpoint of limiting the terminal voltage, one would like to discharge each coil (or section of a coil) through its own dump resistor, which is electrically isolated from the other coils (or sections). Because power supplies are likely to be limited, switchable electrical connection is preferred.

However, if we like to preserve all other coils in the superconducting state whenever one coil quenches, then fixed connection is not acceptable as we shall explain below.

Fixed Connections

Fixed electrical connections—whether it is for each coil to form a closed loop (parallel connection), or all coils to be connected in series, or some other in-between scheme of several parallel loops with one or more coils in each loop—are all very inflexible.

As mentioned before, the (fixed) series connection leads to an unacceptably high voltage during total magnet discharge. The parallel connection with each coil forms a closed loop by itself and leads to a large increment of current (~ 30%) in coils next to the quenched one (Table II). This is due to the fact that the mutual inductance between two coils, hence the inductive voltage which drives the current in the unquenched coils, decreases rapidly as the spacing between them increases.

If we connect, say, every third coil in a fixed series connection, a single coil quench will lead to the discharging of seven other coils in a twenty-four coil magnet. Furthermore, there will also be a substantial current increment (~ +20%) in the remaining current loops.

Hence, all fixed electrical connection schemes suffer either from high terminal voltage or high induced current increment or both during quench. The latter in turn endangers the structural integrity of the magnet system.

Switchable Connection

We shall subdivide the discussion of switchable electrical connection schemes according to the number of coils we allow to discharge, namely: 1) total magnet discharge, 2) quench of a single coil, and 3) multiple quenches.

1) Total Magnet Discharge. As indicated before, one needs to guard against excessively high terminal voltage during a total magnet discharge. One way to accomplish this is by segmenting the magnet into independent loops and/or the coil into independent sections. A segmentation scheme using persistent switches[12] has been proposed and tested on a small scale model. Its effectiveness in reducing the terminal voltage across a quenched coil has been demonstrated. Persistent switches are used both for providing a current by-path, or to open a circuit loop. For high operating current, the latter function can be served with less cost by a contactor or circuit breaker. Figure 2 compared the voltage profile in the ECT coil we mentioned above, with (three identical sections) and without segmentation. The current in both cases is assumed to decay in identical fashion. We note that, by segmentation, the maximum voltage difference inside the coil is reduced by a factor of three. Also, because of better inductive coupling with its neighboring sections, the middle section develops a slightly higher terminal voltage. Alternatively, if identical resistors are used for all three sections, then the middle section will discharge more slowly, hence mechanical reinforcement as well as electrical insulation between the sections must be provided. The voltage difference at the interface between two sections changes drastically as a result of the switching. Thus, segmentation tends to

decrease terminal voltage at the expense of uneven current level in each section. We shall see this conflict in a more pronounced way in the next subsection. Another point is that the segmentation scheme does not reduce the turn to turn voltage difference. However, a better design in the dump resistor, e.g., the one suggested by Luton[13], could be used to reduce the turn to turn voltage difference during quench. Segmentation requires more current leads. However, there is likely plenty of helium vapor to cool them in fusion magnets because of the eddy current heating due to pulsed coils.

2) Quench of a Single Coil. If a single coil quenches, one can isolate and preserve the other coils in the superconducting state by using switches.[12] The terminal voltage across the single coil can be reduced to a manageable level by segmentation. We must now look at the twin (conflicting) problems of inductive voltage and the induced current increment in the unquenched coils.

As mentioned above, if each unquenched coil is switched into an independent loop (parallel connection), the induced current increment in some of them may be excessively large (∿ 30%). This problem is avoided if all unquenched coils are switched into series connection. The induced current increment in our design for this case is a more manageable 3% (Table II, Fig. 3).

However, while series connection is favored over parallel connection because of the induced current increment value, the opposite is the case from the angle of the inductive voltage. Figure 4 gives the voltage profile in the toroidal magnet when one coil quenches. We note that, for the case of series connection (curve with circle), maximum voltage difference in the torus can be as high as 80% of the terminal voltage of the quenched coil. Furthermore, this voltage is not reduced by the segmentation of the quenched coil as it depends only on the mutual inductance and the discharge rate of the quenched coil. This means that insulation against high voltage breakdown from magnet to ground must be provided for all coils and all turns of the toroidal magnet, since we have no control as to which coil will quench. The total induced voltage across a small number of the unquenched coils is initially dominated by the induced voltage produced by the quenched coil, so it has a negative sign. By symmetry, the voltage difference across half of the unquenched coils is zero. Alternatively, one may say that near the quenched coil, the axial magnetic field is decreasing while further away from the quenched coil, it is increasing.

From the above discussion, it seems desirable to have a compromise so that neither the induced current increment nor the inductive voltage will become excessive. One such compromising scheme is to connect the coils in the toroidal magnet in several similar loops (e.g., every thrid or fourth coil is connected into a single loop) during charging and normal operation. In the case of the quenching of a single coil, the quenched coil will be isolated from the loop where it previously belongs by switching devices. For example, in our design, if we assume three parallel loops (i.e., coil No. 1, 4, 7, 10, 13, 16, 19, 22 are in series before quenching [Fig. 1]), then if coil No. 1 quenches, the asymptotic current increment in this loop after switching will be -2%, while the currents in the other two loops increases by about 5% (Fig. 3). On the other hand, the maximum voltage difference in the unquenched loops (Fig. 4) is now reduced to about 35% of the terminal voltage of the quenched coil.

Other more complex/flexible switching schemes are possible, but they do not seem to offer much advantage over the compromise scheme described above, and their reliability is likely to suffer because of the increased complexity in switching pattern.

Our consideration above on inductive coupling so far ignored the presence of other conductors besides the toroidal field coils. The mutual inductance between toroidal field coils and ohmic heating coils or vertical field coils is quite small as their currents are nearly perpendicular to each other. The cryogenic dewars, structure supports and iron core represent single-turn secondary circuits with very short (less than a second) characteristic circuit time constant, and the voltage induced in these circuits during the quenching of toroidal field coils is likely to be quite small (a few volts). The eddy currents induced in these secondary circuits will be diffused and saturated in a time scale much shorter than the duration of quench, thus the inductive voltage in the toroidal field coils due to eddy currents is negligible except during the very short initial buildup phase of the eddy currents. During this phase, the presence of other conductors tends to slow down the discharge of the quenched toroidal field coil. Since only a very small fraction of the available energy for discharge can be dissipated in these conductors, the maximum induced voltage in the toroidal field coils is essentially unaltered. If high purity Al pulsed field shield is placed in close proximity of the toroidal field coil, there may be excessive loss of liquid helium as a result of the eddy current heating in the Al shield, during the charging of the toroidal field coils. Thus it would be desirable to have a cut in the Al shield along the axial direction of the toroidal magnet. Its effectiveness as a shield is not affected by the cut as currents in the pulsed field coils tend to flow along the axial direction of the toroidal magnet too.

3) Multiple Quenches. How many quenched coils could the magnet take without total system discharge depends to a large extent on how much electrical insulation and/or structure support (especially for axial loading) can one provide.[14] The coil shape which minimizes the bending moment during normal operation would be less attractive if its bending moment during quench turns out to be excessive. It is very doubtful that the plasma could still be stabilized if more than a quarter of the coils in the magnet are out of operation. Let us look at some examples in order to get a rough idea on the order of magnitude of things. For our design, assuming a switchable series connection, let us consider the case where six coils are out of operation. Depending on whether the quenched coils are localized (say, coil No. 1 through No. 6) or evenly distributed in the magnet (say, coils No. 1, 5, 9, 13, 17, 21), the induced current increment (Fig. 5) and the initial voltage profile (Fig. 6) in the unquenched coils are quite different. Multiple quenches with evenly distributed quenched coils tend to lead to higher percentage of current increment (22%) but smaller maximum voltage differences (11% of the initial terminal voltage across a single quenched coil). On the other hand, multiple quenches with localized quenched coils tend to lead to a smaller current increment (8%), but a higher maximum

voltage difference in the unquenched coils (90% of the initial voltage across a single quenched coil). At first sight, it may be surprising that the induced voltage due to six quenched coils is not much bigger than the induced voltage due to a single quenched coil (Fig. 4). This is because we assume that the external dump resistor for each coil has the same resistance for both cases. Thus, because of the mutual inductance between quenched coils, the current in the quenched coils tends to discharge more slowly in the case of multiple quenches than in the case of a single quenched coil. Alternatively, a dump resistor sized to discharge a single coil sufficiently rapidly to avoid internal heating may not be able to do that when two such coils discharge simultaneously. To get a conservative estimate on the dump resistance required, one should consider the worst case in discharging rate, namely, the case of total system discharge.

From the above discussion, it seems that either the voltage or the mechanical loading would be too severe if more than a quarter of the coils in the magnet are quenched. The two distributions we looked at do not necessarily represent the worst case; and it is unlikely that more complex electrical connection schemes would improve the situation very much. Thus, while the actual electrical connection scheme for multiple quenches needs to be worked out after the design (number of coils, operating current, etc.) is more definite, it is likely to be too expensive in terms of available space, materials and fabrication cost in structure and insulation to preserve the magnet in superconducting state after a few (two or three) coils have quenched.

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TABLE I

COMPARISON OF TOROIDAL FIELD COIL PARAMETERS IN

VARIOUS POWER REACTOR DESIGNS

	This Work	UWMAK-I[1]	ORNL(1971)[2]	Princeton[3]
Number of Coils	24	12	48	48
Conductor	NbTi-CU	NbTi-Cu	NbTi-Cu	Nb_3Sn
Stabilization	Cryostatic	Cryostatic	Cryostatic	Dynamic
Major Radius (m)	10	13	10.5	10.5
Central Field	4	3.82	3.7	6
Max Field in Winding	8	8.66	8	16
Coil Shape	Circular	D	Circular	D
Inner Diameter (m)	10	12.2, 20	11.2	12, 19
Operating Current (A)	5,000	10,212	5,000	10,000
Average Current Density in Winding 10^7 x (A/m^2)	1.7	1.318	1.55	2.1*
Energy Stored in Torus (x 10^{10} J)	3.367	28	4	25

*This is the average current density in conductor.

TABLE II

CURRENT INCREMENT RESULTS FOR AN EPR COIL SET

System Parameters

Number of Coils in the Toroidal Array	24
Torus Major Radius	10 m
Coil Inner Radius	5 m
Coil Outer Radius	5.576 m
Coil Axial Length	0.85 m
Operating Current	5000 A
Turns Per Coil	1667

Inductance (in henries)*

L_1 = 53.351	L_8 = 0.7563
L_2 = 17.951	L_9 = 0.5619
L_3 = 8.3602	L_{10} = 0.4424
L_4 = 4.4663	L_{11} = 0.3707
L_5 = 2.5992	L_{12} = 0.3323
L_6 = 1.6219	L_{13} = 0.3202
L_7 = 1.0763	$L_{(Total)}$ = 3138

L_1 is the self-inductance of a single coil, L_i is the mutual inductance between two coils with (i-2) coils between them.

Asymptotic Value of Current if Each Coil Forms a Closed Persistent-Current Loop

Y_1 = 1.276	Y_7 = 1.001
Y_2 = 1.033	Y_8 = 1.001
Y_3 = 1.012	Y_9 = 1.001
Y_4 = 1.005	Y_{10} = 1.001
Y_5 = 1.003	Y_{11} = 1.001
Y_6 = 1.002	Y_{12} = 1.001

Define the ratio $Y_i = I_i\ (t \to \infty)/I_0$, where I_0 is the initial current in each coil and $I_i\ (t \to \infty)$ is the current in the i^{th} neighbor of the discharged coil after the discharge is complete.

Asymptotic Value of Current if All Coils Except the Quenched One Are Connected in Series (N = 24)

$$Y = 1 + \frac{L_{Total} - NL_1}{(N - 2)L_{Total} - (N + 2)L_1} = 1.027$$

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*Calculated from a computer program written by P. L. Walstrom.

FIGURE CAPTIONS

1. Labelling of coils in a 24 coil magnet system.
2. Voltage profile in a single coil. Curve with 0 represents voltage profile without segmentation; curve with Δ represents voltage profile with three equal sections.
3. Current increment in coils for switchable connection with quenching of a single coil (No. 1). Curve with 0$^{(\Delta)}$ represents switching into parallel (series) connection for the remaining coils during quench. Curve with + represents the case of three parallel loops (connect every thrid coil in series).
4. Voltage profile in torus for switchable connection with the quenching of a single coil (No. 1). Curve with 0 represents switching into series connection for the remaining coils. The other three curves represent the voltage profile in the three parallel loops for the case of connecting every third coil in torus in series.
5. Current increment in coils with multiple quenches. Curve with 0 represents switching into series for a single coil quench. Curve with Δ represents switching into series for the quenching of six localized coils (No. 1 through No. 6). Curve with + represents switching into series of the remaining coils for the quenching of six evenly distributed coils.
6. Voltage profile in torus with multiple quenches. Curve with 0 represents switching into series connection for the remaining coils for the quenching of six localized coils (No. 1 through No. 6). Curve with Δ represents switching into series of the remaining coils for the quenching of six evenly distributed coils.

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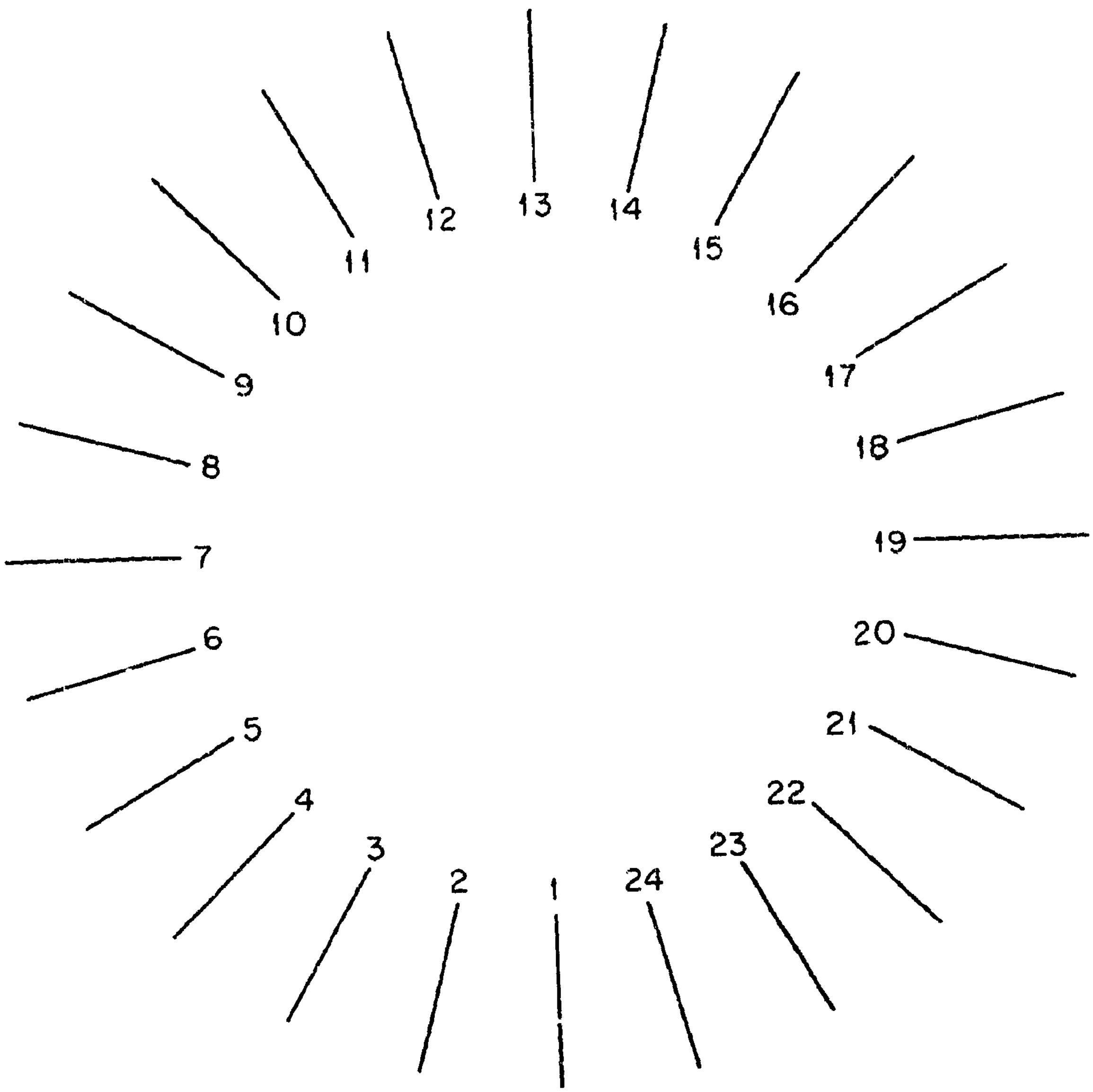
11. Exotic battery (LiS) may offer high energy density, See H. L. Laquer, "Superconducting Magnetic Energy Storage," Cryogenics (1975).

12. H. T. Yeh, J. N. Luton, J. E. Simpkins, "Current Averaging and Coil Segmentation in the Protection of Large Toroidal Superconducting Magnet Systems," paper presented at the 1975 Cryogenic Engineering Conference, Kingston, Canada.

13. J. N. Luton, U. S. Patent 3,7,11,744 (Jan. 16, 1973).

14. Mechanical reinforcement during fault condition is discussed in W. C. Young, I. N. Sviatoslavsky, "Construction Techniques and Stress Analysis of Toroidal Field Magnets for Tokamak Fusion Reactors," paper presented at the 1975 Cryogenic Engineering Conference, Kingston, Canada.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13
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1
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Figure 1

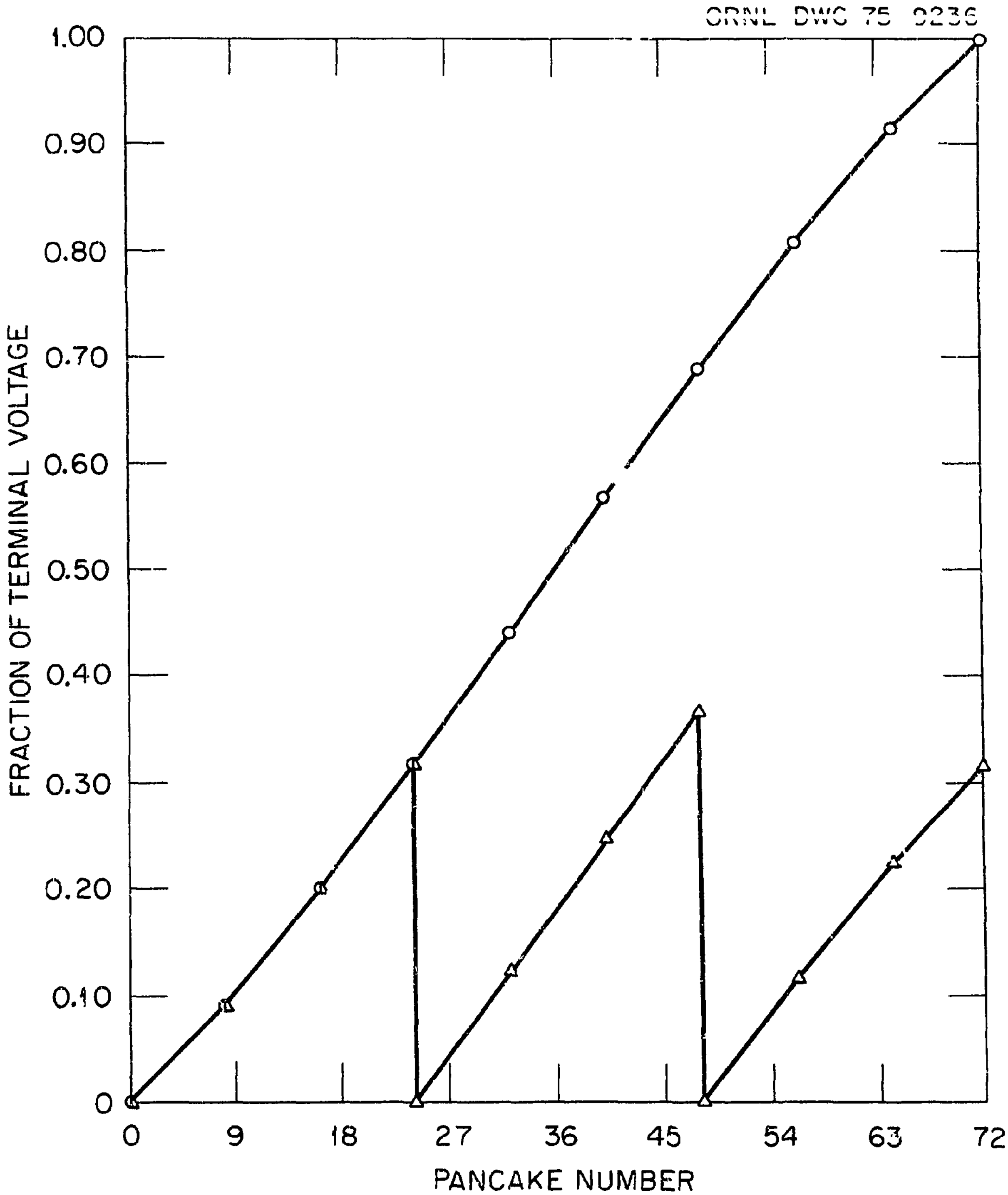

ORNL DWG 75 9236
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0
FRACTION OF TERMINAL VOLTAGE
0
9
18
27
36
45
54
63
72
PANCAKE NUMBER

Figure 2

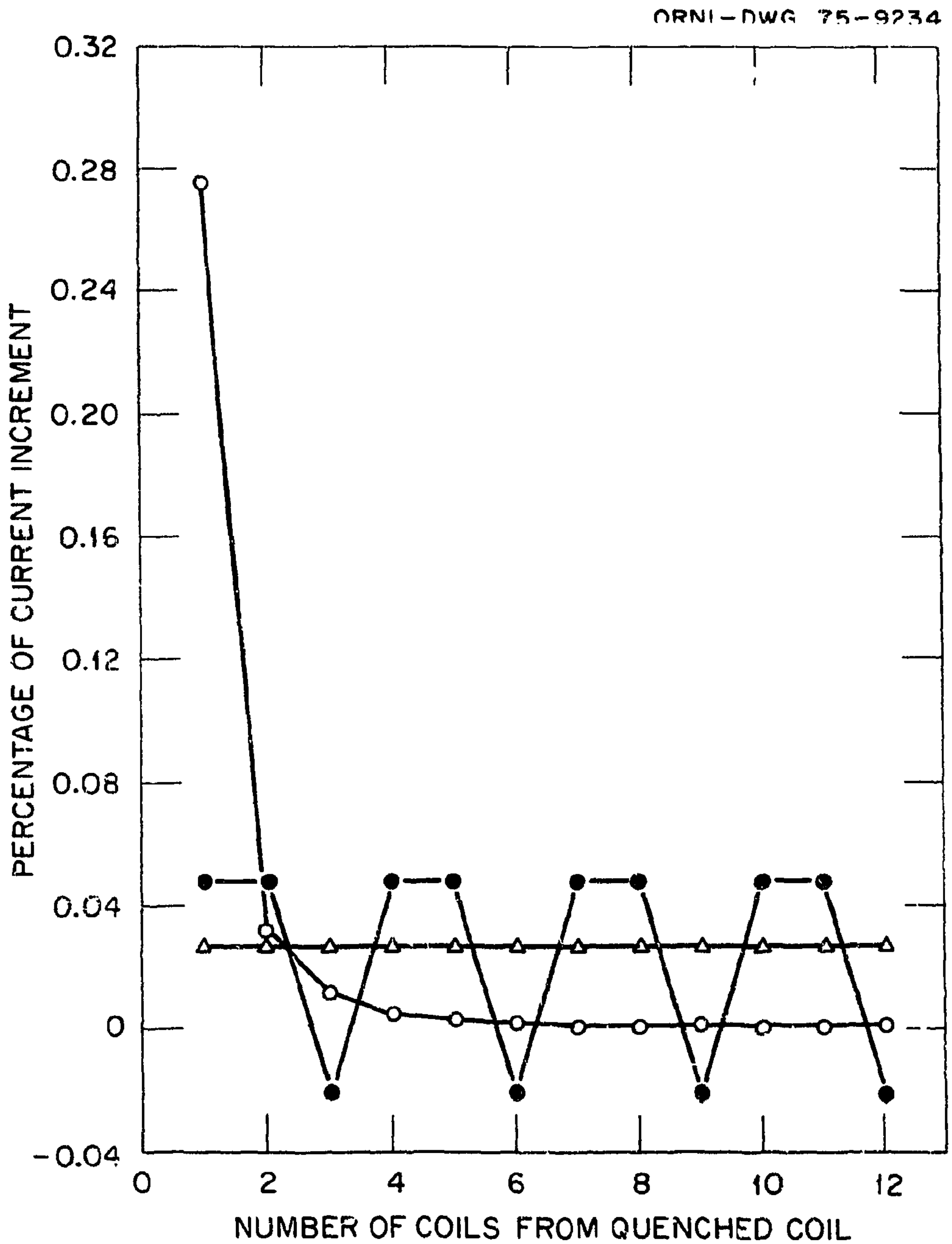

ORNL-DWG 75-9234
0.32
0.28
0.24
0.20
0.16
0.12
0.08
0.04
0
-0.04
PERCENTAGE OF CURRENT INCREMENT
0
2
4
6
8
10
12
NUMBER OF COILS FROM QUENCHED COIL

Figure 3

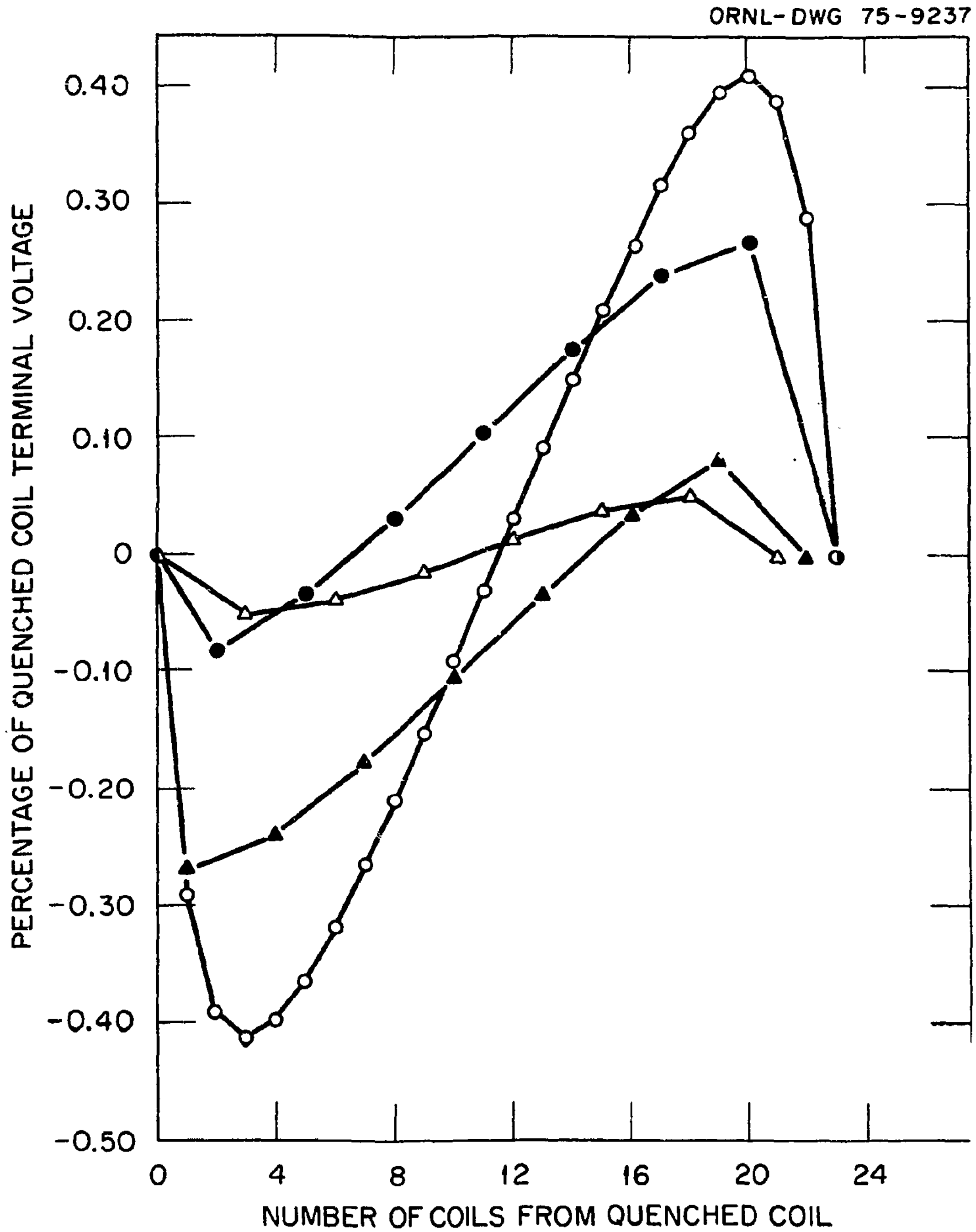

ORNL-DWG 75-9237
PERCENTAGE OF QUENCHED COIL TERMINAL VOLTAGE
0.40
0.30
0.20
0.10
0
-0.10
-0.20
-0.30
-0.40
-0.50
0
4
8
12
16
20
24
NUMBER OF COILS FROM QUENCHED COIL

Figure 4

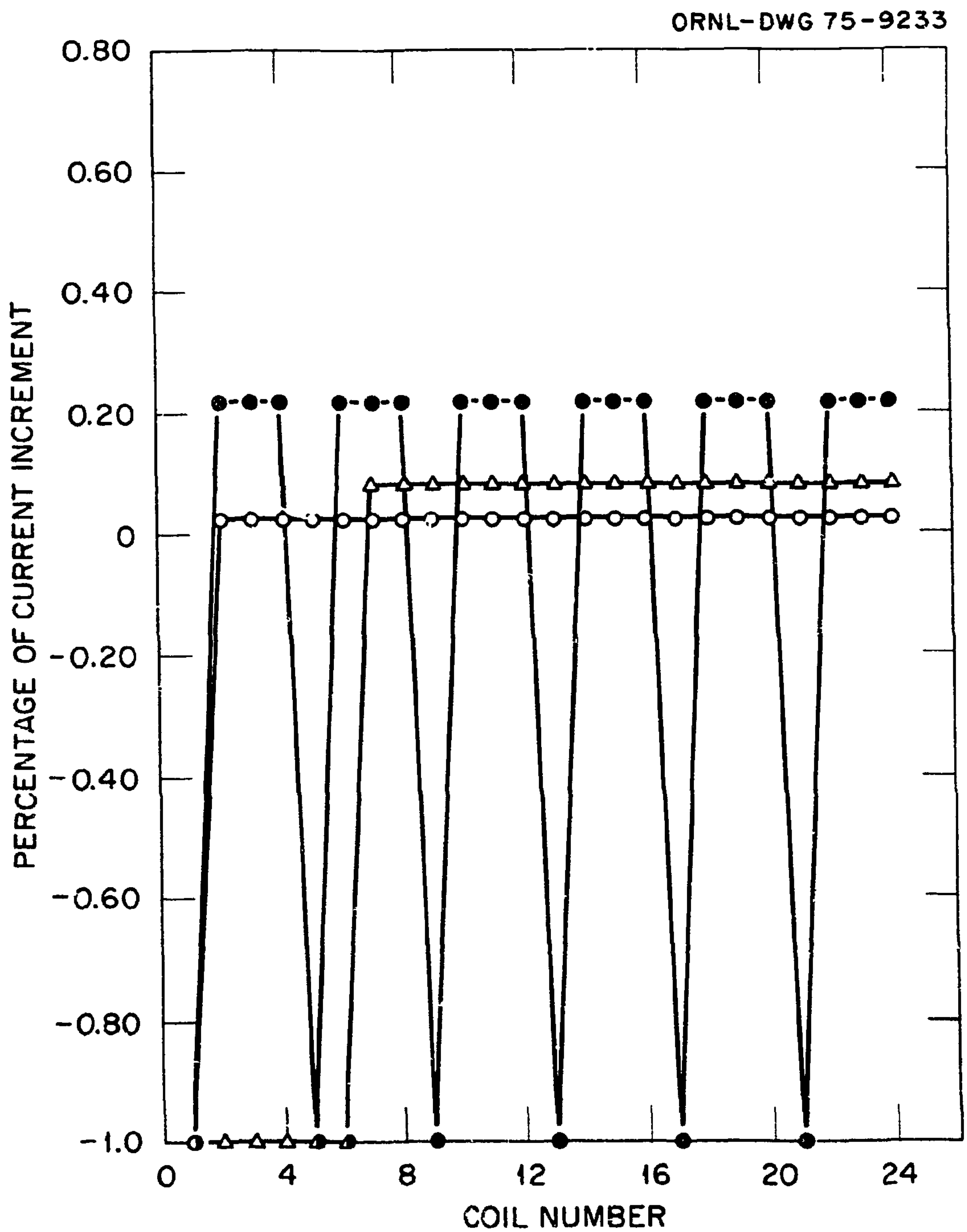
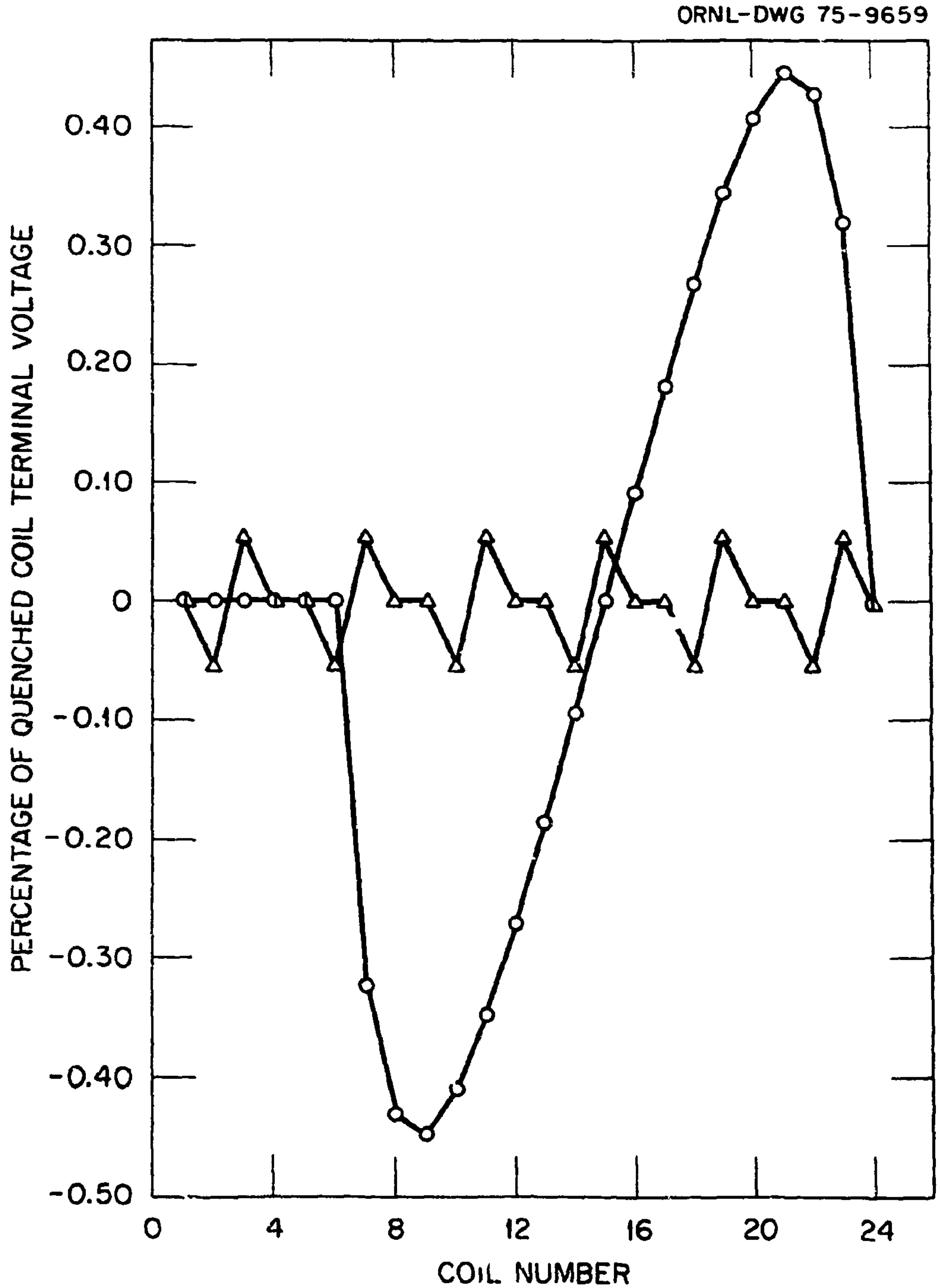

ORNL-DWG 75-9233
PERCENTAGE OF CURRENT INCREMENT
0.80
0.60
0.40
0.20
0
-0.20
-0.40
-0.60
-0.80
-1.0
0
4
8
12
16
20
24
COIL NUMBER

Figure 5


ORNL-DWG 75-9659
PERCENTAGE OF QUENCHED COIL TERMINAL VOLTAGE
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0.20
0.10
0
-0.10
-0.20
-0.30
-0.40
-0.50
0
4
8
12
16
20
24
COIL NUMBER

Figure 6