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TITLE: COIL PROTECTION FOR A UTILITY SCALE SUPERCONDUCTING
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COIL PROTECTION FOR A UTILITY SCALE
SUPERCONDUCTING MAGNETIC ENERGY STORAGE PLANT

Mexico City, July 20-25, 1986

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Abstract - Superconducting Magnetic Energy Storage (SMES) is proposed for electric utility load leveling. Attractive costs, high diurnal energy efficiency ($\approx 92\%$), and rapid response are advantages relative to other energy storage technologies. Recent industry-led efforts have produced a conceptual design for a 5000 MWh/1000 MW energy storage plant which is technically feasible at commercially attractive estimated costs. The SMES plant design includes a protection system which prevents damage to the magnetic coil if events require a rapid discharge of stored energy. This paper describes the design and operation of the coil protection system, which is primarily passive and uses the thermal capacity of the coil itself to absorb the stored electromagnetic energy.

INTRODUCTION

The operation of a SMES plant for utility load leveling, as has been described previously [1], involves charging a superconducting coil from the utility system during off-peak hours to store energy in the form of an electromagnetic field. The AC grid is connected to the DC magnetic coil through a power conversion system (PCS) that includes an inverter/rectifier. Once charged, the superconducting coil conducts current with virtually no energy loss. During hours of peak load, the stored energy is discharged through the PCS back to the grid as line quality AC power. The coil is maintained at a superconducting temperature by immersion in a bath of

liquid helium. A schematic diagram indicating the principles of operation of a SMES plant is shown in Fig. 1.

Industrial leadership in the development of SMES technology began in 1981. Efforts since that time [2,3,4] have resulted in a conceptual design for a 5000 MWh/1000 MW SMES plant, which consists of a 556 turn, four radial layer, superconducting solenoidal coil plus all necessary support systems. The 19 m high, 1 m wide, 1000 m diameter coil is constructed in an open trench. Figure 2 is a cut-away view showing the coil and related components. The coil employs a 200 kA conductor made of copper/niobium-titanium superconductor stabilized by high purity aluminum. The conductor is positioned in an alloy aluminum structure (conductor support assembly) which supports the conductor against magnetic loads. The coil operates in a superfluid helium bath at a nominal temperature of 1.8 K and a nominal pressure of one atmosphere.

Each of the 556 coil turns consists of a conductor in a conductor support assembly, as shown in Figs. 3 and 4. The coil turns are electrically isolated from one another by vertical and horizontal insulator sheets. The conductor consists of numerous 1-mm superconductor strands imbedded in the surface of a rectangular, high-purity aluminum stabilizer.

COIL PROTECTION

A SMES plant must be equipped with a reliable protection system that can dissipate the stored energy to insure that damage will not occur in the unlikely event of an imminent or actual loss of superconductivity. The only events which could lead to a loss of superconductivity in a coil that is well designed for cryogenic stability are falling liquid helium level resulting from a helium vessel breach, or large thermal loads caused by a rapid loss of vacuum. If either of these events were to occur, there would be no time for discharge of the coil to the utility system, so that the coil energy must be dissipated by other means. Dissipation of energy via an external resistor is not possible because it would result in unacceptably high voltages across the coil. Therefore, the stored energy must be dissipated resistively as heat within the coil itself. To avoid damage from high voltages and/or high temperatures, this internal dissipation must be nearly uniform. This process, called a coil protective energy dump, places a number of requirements and constraints on the plant and coil design. These include the ability to rapidly remove the liquid helium coolant from the coil, good current and heat transfer from the conductor to the conductor support assembly, and adequate thermal capacity of the structure.

A system that can rapidly and reliably dump the coil's inventory of liquid helium coolant has been described previously [5]. It contains only a few active components (valves) to initiate the energy dump

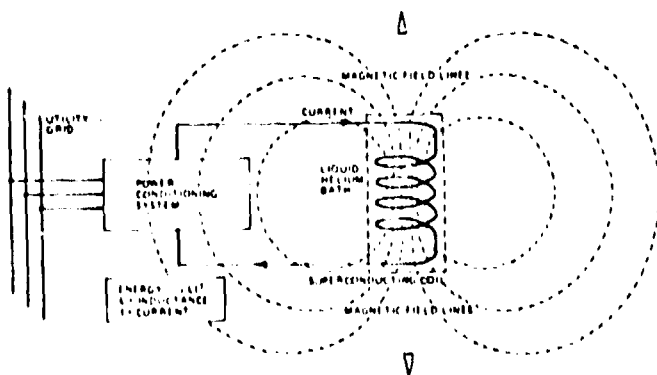


Fig. 1 Schematic diagram of SMES operating principles

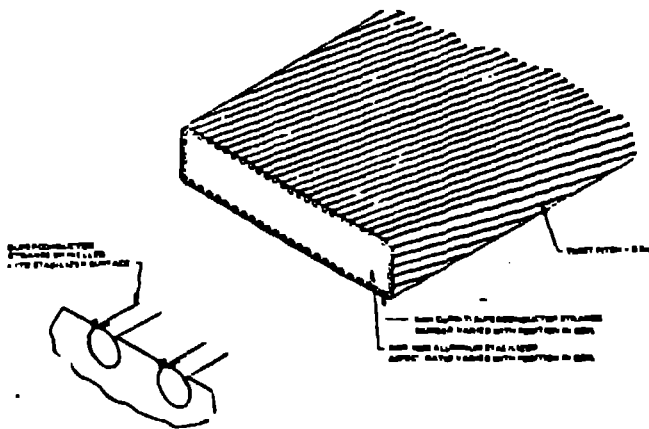


Fig. 4 200 kA conductor configuration concept

sequence and these are accessible for maintenance while the coil is operating. After the helium dump system has been activated, the coil protective energy dump process is fully passive.

The helium dump process requires about 20 s and leaves the conductor in a resistive state. (When no longer superconducting, the conductor is termed "normal".) The design of the conductor and conductor support assembly assures good electrical contact between these components, so that once the superconductor is normal, the coil current is shared between the conductor and the conductor support assembly in inverse proportion to their resistances at their respective temperatures. The stored energy is resistively converted to heat, which is absorbed by the conductor, the conductor support assembly, and an inexpensive heat absorbing material that is contained in the enclosed voids of the conductor support assembly.

During an energy dump, the temperatures of the conductor and the conductor support assembly rise closely together, primarily because of good electrical and thermal contact. The coil warms to a safe temperature, near ambient, because adequate thermal capacity is provided by the coil materials. The thermal capacity of the aluminum components of the conductor support assembly, which are sized for structural functions, is supplemented by heat absorbing material, such as tar, which provides about half of the total required thermal capacity. Additional solid aluminum for this purpose would be prohibitively expensive. The resulting coil consists of approximately 75,000 tons of aluminum plus 35,000 tons of tar. Aluminum fins, 2 percent by volume of the heat absorbing material, serve as heat paths into the tar. Tar block time constants for several structure-to-tar block helium gap sizes and aluminum fin volume fractions were estimated analytically. These are shown in Fig. 5.

COIL PROTECTIVE ENERGY DUMP MODEL

The coil behavior described in the following text and figures was analyzed using the computer code CPED (Coil Protective Energy Dump) developed specifically for this purpose. Quantities calculated by the CPED code are:

- Stored energy:

$$E = LI^2/2$$

where E is the coil magnetic energy, L is the coil inductance, and I is the total current in each coil turn.

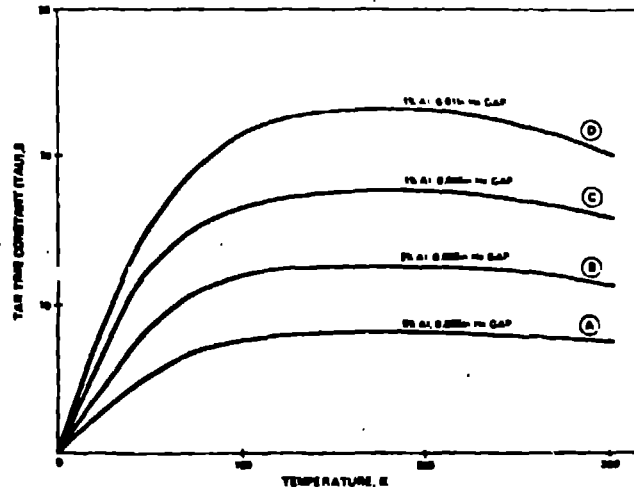


Fig. 5 Estimated tar block time constant vs. mean temperature for various configurations

- Current sharing between structure (s) and conductor (c):

$$(IR)_s = (IR)_c$$

where I is current, and R is resistance.

- Joule heating per time step, dt:

$$dE = [(I^2R)_s + (I^2R)_c] dt$$

where dt is the time step.

- Heat transfer per time step from conductor to structures:

$$dQ_{cs} = h A (T_c - T_s) dt.$$

where h is the thermal contact conductance between the conductor and conductor support assembly and A is the contact area per unit circumference.

- Heat transfer per time step from structure to heat absorbing material (tar, T):

$$dQ_{sT} = C_T [T_T(t+dt) - T_T(t)] dt$$

where C_T is thermal capacity of the tar and the mean tar temperature, T_T , lags the structure temperature as determined by the time constant, tau, which is defined by:

$$T_T(t+dt) = T_T(t) + [T_S(t) - T_T(t)] [1 - \exp(-dt/\tau)].$$

Variable time steps are calculated to assure stable solutions.

The above equations model the local average conductor, structure, and heat absorbing material temperatures. The CPED code also accommodates circumferential or axial thermal conduction and allows for circumferential or axial variations in material area cross sections and initial temperatures.

The CPED code was used to investigate the effects of numerous parameters on temperatures and voltages occurring during a protective energy dump.

THERMAL EFFECTS

Calculated results for energy decay, temperatures, and fraction of total current in the structure are shown in Fig. 6. Assumptions for this "base" case are that the entire coil is driven uniformly normal at 2.95 K, that the thermal contact conductance, h , between the conductor and structure equals $1.0 \text{ W/cm}^2\text{-K}$, and that the heat absorbing material time constant follows curve B in Fig. 5. RRR refers to the electrical resistivity of the conductor stabilizer, which is discussed later in this section. Thermal and electrical property data for aluminum are taken from Ref. 6 and the estimated specific heat of the tar blocks is given in Table 1. The time required for half of the coil energy to be converted to heat is about 2.2 minutes. The temperatures of the conductor, structure, and tar increase at nearly equal rates and reach 296 K when all of the coil's electromagnetic energy has been dissipated. By the time half of the coil energy has been dissipated, the conductor support assembly is carrying over 83 percent of the total current remaining. This current shift from the conductor to the conductor support assembly occurs because the relative resistances of these two components shifts with increasing temperature.

Effect of Thermal Contact Conductance. The thermal contact conductance, h , represents how well the conductor is thermally coupled to the conductor support assembly. A value of $h = \infty$ implies perfect thermal coupling, i.e., the two components are at the same temperature at all times. A value of $h = 0$ implies that the conductor and structure are thermally isolated, i.e., there is no heat transfer between them. The case of thermal isolation leads to high conductor temperatures which would probably cause damage. Fig. 7 shows the conductor and structure temperature vs. time for various values of h . The value of $h = 1.0 \text{ W/cm}^2\text{-K}$ used for the "base" case is a conservative value, estimated from published data for thermal contact conductance. The conclusion to be drawn is that no severe temperature gradients occur between the conductor and structure for any reasonable values of h .

Effect of Tar Time Constant. The effect of tar time constant on the temperatures of the conductor, conductor support assembly, and tar during a protective energy dump is shown in Fig. 8, using the time constant vs. temperature curves plotted in Fig. 5. The

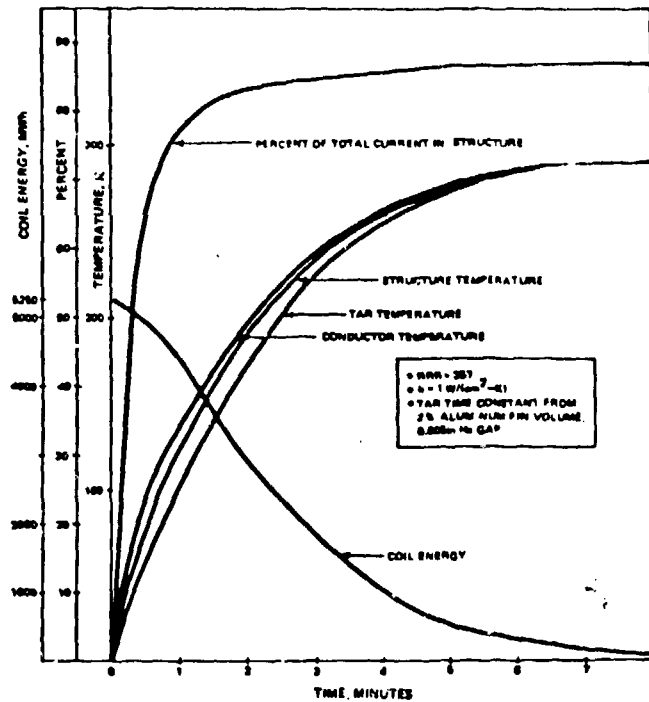


Fig. 6 Coil temperatures, energy and current during a coil protective energy dump

Table 1. Estimated specific heat of tar, which is proposed as heat absorbing material.

Temperature, K	Specific Heat (J/g)
1.8	0.0170
4	0.0195
10	0.024
20	0.10
50	0.35
100	0.70
200	1.18
300	1.52

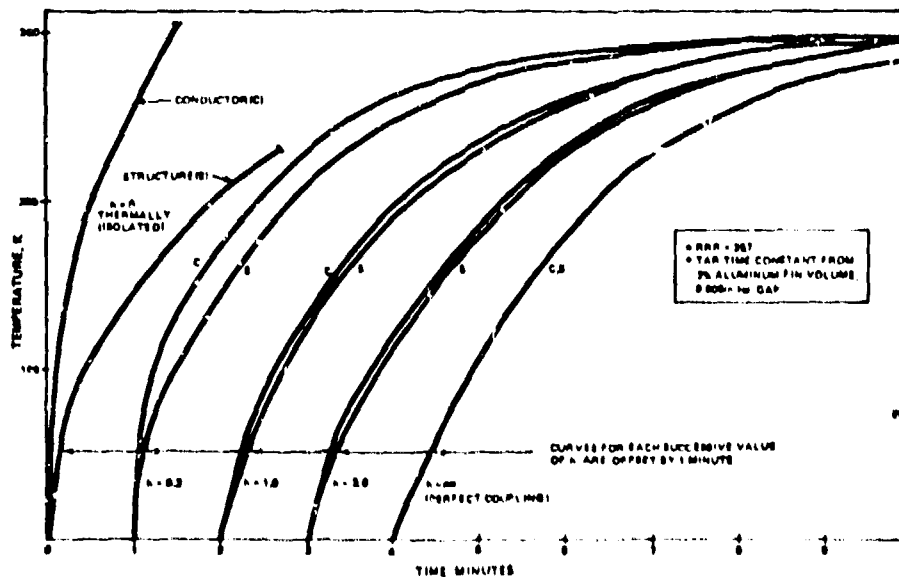


Fig. 7 Coil temperatures vs. time for various thermal contact conductances during an energy dump

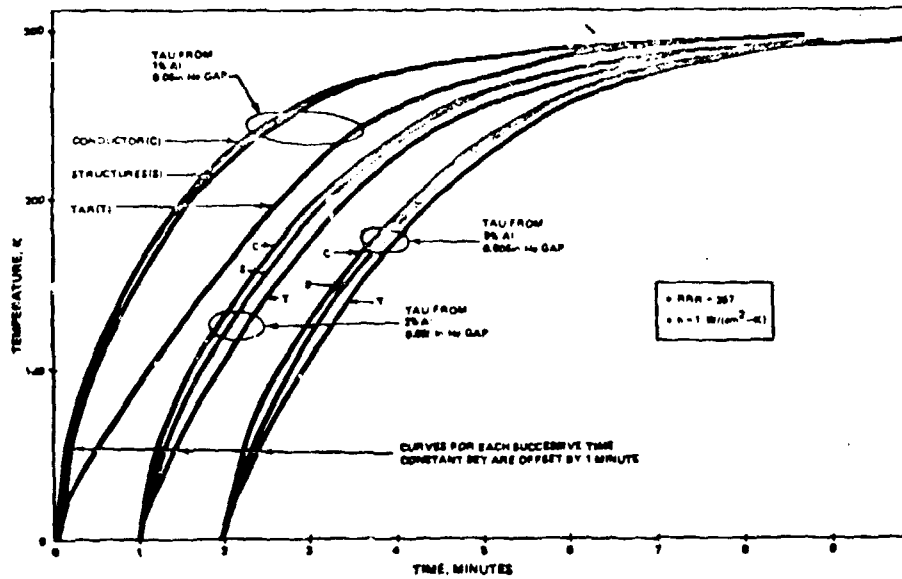


Fig. 8 Coil temperatures vs. time for various tar thermal time constants during an energy dump

results indicate that the conductor and structure temperatures are fairly insensitive to time constant over the range which is expected.

Effect of Circumferential Non-uniformities. The CPED code accommodates initial temperature nonuniformities over a selected circumferential segment of the coil. The results shown in Fig. 9 indicate that initial temperature hot-spots do not grow during an energy dump. Rather, hot spots shrink because heat capacity increases with temperature faster than electrical resistance. Circumferential thermal conduction has only a minor smoothing effect. The fact that hot spots shrink rather than grow in magnitude is very significant because unstable growth would lead to coil damage.

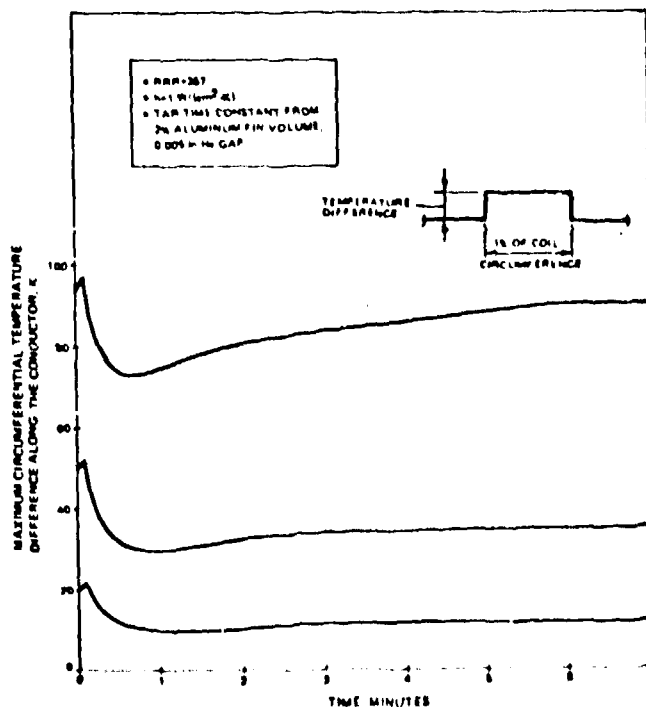


Fig. 9 Maximum circumferential temperature difference for various non-uniform initial temperatures

Non-uniformities in cross sectional areas, which might be expected as a result of manufacturing tolerances, also do not lead to major hot spots. A local reduction of 5 percent in the cross section of the structure causes the local conductor temperature to exceed the average conductor temperature by a maximum of only 20 K. Variations in conductor and tar area cross sections have a smaller effect. These results are shown in Fig. 10.

Effect of Stabilizer Resistivity. The electrical resistivity at cryogenic temperatures of high purity aluminum, such as that used as the conductor stabilizer, is a strong function of both temperature and purity. Conductors used at cryogenic temperatures

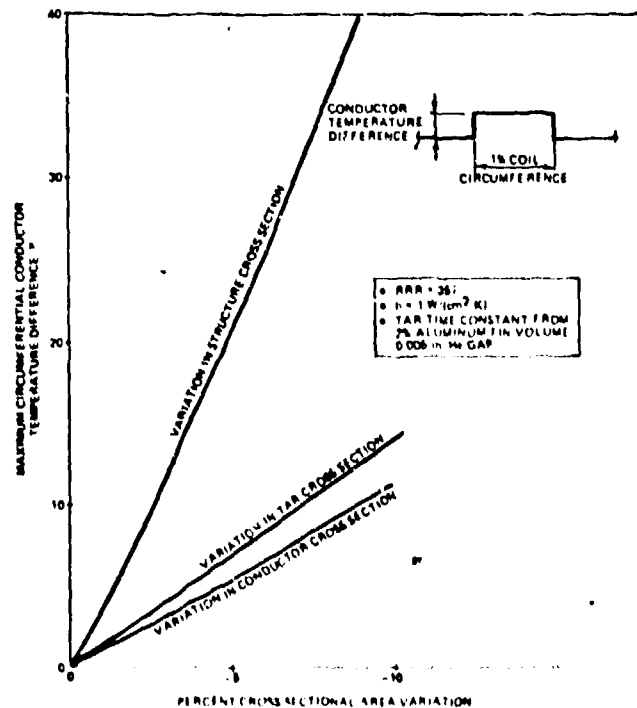


Fig. 10 Maximum circumferential temperature difference for cross sectional area variations

often are characterized by the ratio of resistivity at 273 K to that near 0 K. This ratio is called the residual resistivity ratio (RRR). The conductor stabilizer currently proposed for SMES is RRR 1000 aluminum. A range of effective RRR is expected for an operating SMES conductor because the resistivity also is affected by magnetic field and local strain. However, the conductor temperature behavior during an energy dump is not noticeably dependent on RRR over its expected range. This is because the resistivity of high purity aluminum is nearly independent of RRR once the temperature exceeds 40 K. Therefore, a conservative value of RRR 300 was used in this analysis.

COIL VOLTAGE

For those calculations described so far, for which the area cross sections and initial temperature were uniform over the coil height, there was no voltage gradient in the coil. However, because the liquid helium coolant removal occurs over a finite period of time, in reality there will be an axial temperature gradient in the coil. The axial voltage caused by the thermal gradient must be limited to a safe range. Fig. 11 shows schematically the inductive, resistive, and total voltage in one radial layer of the coil at a time when the liquid helium is draining from the helium vessel. The exposed normal turns of the coil generate a resistive voltage. As energy is resistively dissipated, an inductive voltage of the opposite sign results. The algebraic sum of these two components is the voltage which the insulation between the coil and the helium vessel must withstand. A voltage differential persists as long as there is an axial temperature gradient. The magnitude and axial location of the point of maximum voltage depends on the temperature profile and coil current at any given time. A consequence of the coil winding pattern (parallel helix) is that the peak coil voltage that would otherwise occur during an energy dump is reduced by a factor equal to the number of radial layers, in this case by 4.

Effect of Helium Dump Time and Initial Temperature. Fig. 12 shows peak coil voltage as a function of helium dump time and initial, or "kick-off" temperature of newly uncovered conductor turns. The kickoff temperature is assumed equal to that of the helium gas which displaces the liquid, and the conductors are assumed to jump instantly to the kickoff temperature as they are exposed. Above about 40 K, the conductor kick-off temperature has a stronger effect on peak coil voltage than helium dump time.

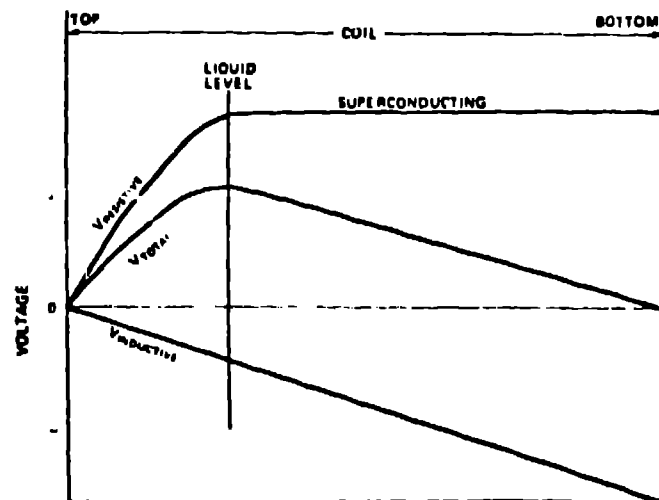


Fig. 11 Coil voltage behavior during an energy dump

Below about 30 K, the kick-off temperature of newly exposed conductor turns has little effect. For the SMES plant design reported here, 28 K helium gas is used to initiate the energy dump.

Coil voltage is a weak function of helium dump time, as shown in Fig 12. While a maximum coil voltage of 20 kV is thought to be acceptable, the helium dump system is designed for a dump time of 20 s, resulting in a maximum coil voltage of only 10 kV. This is just slightly above the peak coil voltage of 9.4 kV which occurs during normal charge/discharge operation of the coil.

Figure 13 shows the temperature difference between the top and bottom turns of the coil as a function of helium dump time, based on a conductor kick-off temperature, T_c , of 28 K. For a 20 s helium dump, the maximum temperature difference is 80 K, which is not enough to damage the coil. (The curves in Figs. 11 and 12 were calculated for the condition that the conductor support structure and tar were kicked off at temperatures of $0.9 T_c$ and $0.5 T_c$, respectively.)

Effect of Thermal Contact Conductance and Tar Time Constant. The effects of thermal contact conductance between the conductor and the conductor support assembly, and of the tar time constant on maximum voltage are shown in Figs. 14 and 15. Both show that better heat transfer results in lower voltage, although the results are rather insensitive to either parameter.

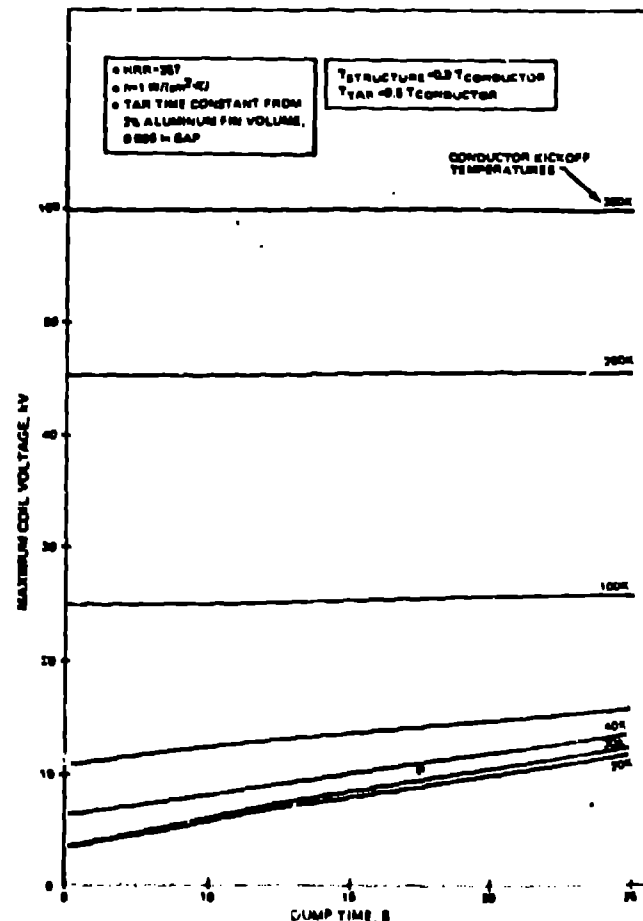


Fig. 12 Maximum coil voltage vs. helium dump time and kick-off temperature of exposed coil turns

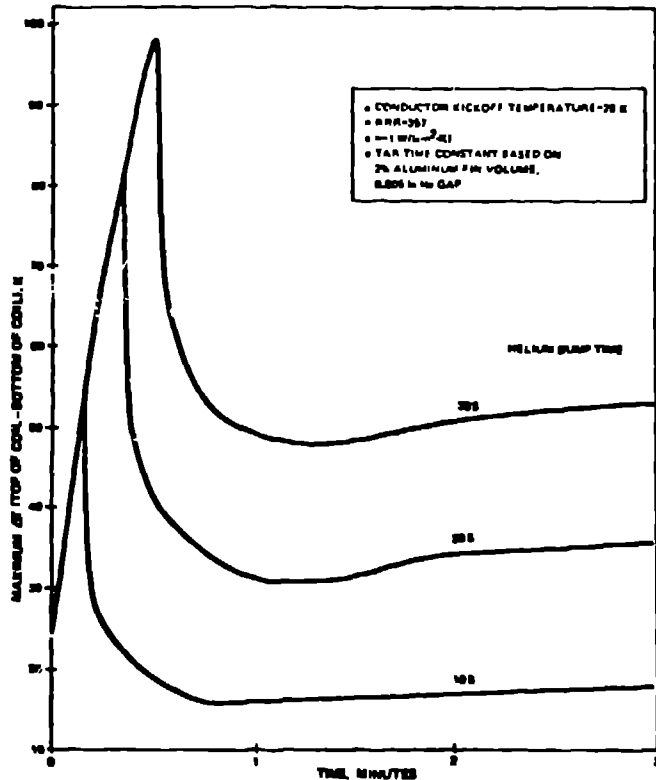


Fig. 13 Maximum axial temperature vs. time for various helium dump times

CONCLUSIONS

The conceptual design of the coil protection system and analysis of the helium and energy dump processes leads to the following conclusions, which are important to the advancement of SMES.

- The dissipation of energy in the coil during a protective energy dump proceeds nearly uniformly. The maximum temperature following an energy dump is low enough that no damage to the coil results. Initial temperature differences in the coil do not grow, but rather shrink. For a modest rate of liquid helium removal, excessive coil voltages do not occur.

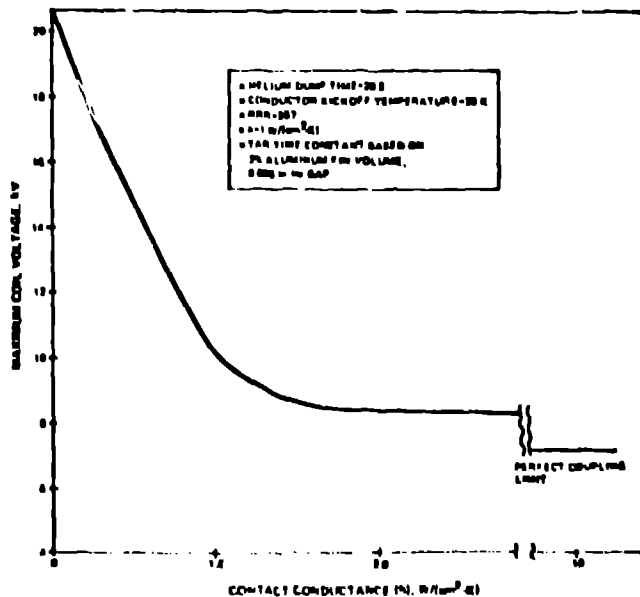


Fig. 14 Maximum voltage vs. thermal contact conductance

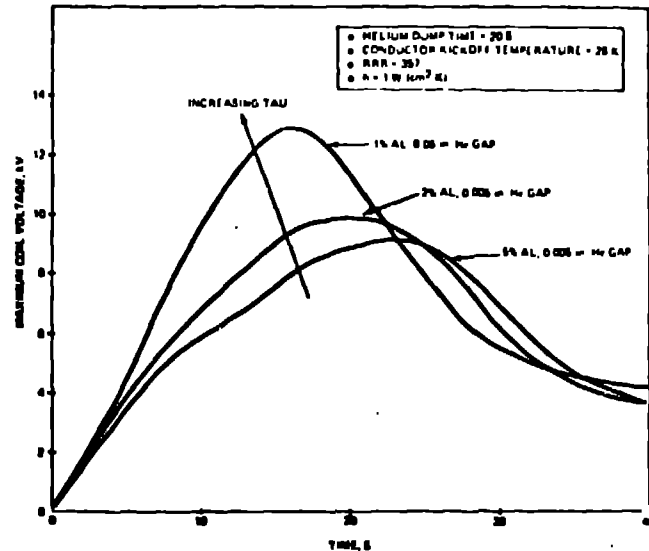


Fig. 15 Voltage vs. time for various tau time constants

- The development of a mostly passive system for an emergency energy discharge which is reliable and results in no damage to the coil resolves a major concern regarding the technical viability of SMES for electric utility load leveling.

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