Design Options and Trade-Offs in
Superconducting Magnetic
Energy Storage with Irreversible Switching

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MASTER

DESIGN OPTIONS AND TRADE-OFFS IN SUPERCONDUCTING
MAGNETIC ENERGY STORAGE WITH IRREVERSIBLE SWITCHING

by

H. L. Laquer, J. D. G. Lindsay, E. M. Little, J. D. Rogers, and D. M. Weldon

ABSTRACT

A program is presently under way at Los Alamos to determine how superconducting magnetic energy storage in conjunction with normal-going superconducting switches can be made to deliver the energies of the order of 200 MJ that will be needed for plasma compression in a pulsed θ -pinch scientific feasibility experiment. After a review of the circuit configurations, the properties of commercially available and of some developmental superconductors relevant to both the energy storage coil and to the switch are discussed. Critical current densities at low fields and stability requirements both with respect to rapidly changing external fields and to self fields are of particular importance in determining optimum operating fields and temperatures. The trade-off between eddy current losses in the stabilizing material and the need for coil protection if a coil normalcy should occur is described. Problems in potting or other forms of mechanical stabilization for both superconducting elements are pointed out. The experimental phenomenon of an only partially normalized superconducting switch is described as are the conditions for attaining fully normal resistance. A number of cryogenic engineering problems are discussed briefly, including the requirements for plastic, non-conducting dewars and for a staged refrigerator to re-cool the switch in the most economical manner. Results of 20 kJ energy transfer experiments into both resistive and inductive loads are given and the design parameters are reported for a 300 kJ experiment now under construction.

Energies of the order of 200 MJ will be needed for plasma compression in the pulsed θ -pinch scientific feasibility experiment proposed by Ribe⁽¹⁾. A program is presently underway at Los Alamos^(2,3) to determine how superconducting magnetic energy storage in conjunction with normal-going superconducting switches can be made to deliver the required energies. Although the irreversible nature and the low (25%) efficiency associated with this mode of energy transfer into inductive loads (in the absence of capacitors) precludes its application to a reactor, a large portion of the pulsed superconductor technology will also be applicable to more efficient reversible energy transfer⁽⁴⁾.

Energy Transfer Circuits

Some possible means of achieving energy transfer from a cryogenic storage inductor, L_S , into a load inductor, L_L , are shown in Fig. 1. For all cases the cryogenic region is enclosed in dashed lines, the transfer element (normal-going superconductor in our case) is X. The "protective" resistor R_p (when present) serves to reduce the energy dissipated in the cryogenic environment during the transfer. Fig. 2 shows somewhat more detailed circuits including the resistance of the cryogenic leads, R_Z and R_Y , and of the load, R_L , the location of the current generator G and the switch S-2 for isolating the generator from the voltage pulse produced during the energy transfer. In Fig. 2a, the transfer switch X also functions as a persistent switch, in parallel with the storage

Fig. 1. Energy Transfer from Cryogenic Inductor into Load Inductor at Room Temperature.

- (a) Direct coupling.
- (b) Direct coupling with resistor R_P to reduce energy deposited in the cryogenic region.
- (c) Transformer coupling.

Fig. 2. Single Unit Energy Transfer Circuits Showing Lead (R_Z), Load (R_L) and Generator (R_G) Resistances.

- (a) Parallel coil switch arrangement.
- (b) Series coil switch arrangement, lead resistance R_Y carries pulse current only.

coil, i.e. the switch is held open (thermally) during charging of the coil, allowed to return to the superconducting state at peak coil current and then made to trap the entire stored flux or current when the generator is turned down. This procedure is an experimental convenience in the present development work where it is desirable to observe long term coil and switch behavior, but it is not a necessary part of the engineered system as shown in Fig. 2b, where the transfer switch carries current in series with the storage coil. The performance and optimization of steady state current leads into liquid helium cooled by boil-off gas has been analyzed by many investigators⁽⁵⁾. Because such leads always add a boil-off or refrigeration cost of at least 1 W/kA/lead, their number should be minimized. Much less work has been done on pulsed current leads shown in the figure as resistances R_Y ; however, it is clear that they will entail much lower refrigeration costs. Dielectric breakdown is bound to be a severe problem in a cryogenic environment with liquid and gaseous helium, accompanied by temperature gradients and with the necessity to provide for differential thermal contraction. For this reason, an arbitrary limit of 40 kV has been accepted for the near term development effort. For the larger systems envisaged (Fig. 3), this then means multiple grounding points connected via switches S-1 just prior to energy transfer. In the parallel system (Fig. 3a) additional 40 kV isolation switches, S-2, would be needed within the cryo-environment. The series system also has the advantages that it can be discharged at any instant, thus making it safer to operate and that the coil inductance automatically filters generator ripple from the switch. For these reasons the series arrangement (Fig. 3b) is preferred in spite of the fact that it does not permit operation in the true persistent current mode.

Properties of Technical Superconductors

The design, cost and performance, both of the storage coil and of the normal-going superconducting switch are primarily determined by the critical current characteristics of superconductors.

Fig. 3. Multi-Unit Energy Transfer Circuits.
(a) Parallel coil-switch arrangement.
(b) Series coil-switch arrangement.

At the present, the only commercially available high field superconductors are the ductile alloy NbTi, usually as a multifilamentary composite, and the brittle intermetallic compound Nb_3Sn , usually in ribbon form. The former can withstand strains of 2%, whereas the latter (and all similar β -W or Al5 materials) will deteriorate at strains between 0.1 and 0.2%. The A-15 materials would offer many advantages, as far as high critical temperatures and high critical current densities are concerned; however, their lack of ductility would essentially dictate a separate low strain structure to support

the ribbon conductors. The engineering problems involved in building such a structure, together with the limited superconducting stability of ribbon materials and the absence of ultrahigh field requirements in the present application, are the basis for choosing the NbTi alloy for the storage coil and probably also for the switch.

Figure 4 shows "short sample" critical current densities at 4 K as a function of magnetic field for commercial multifilament NbTi wires produced by several U.S. manufacturers. Cost of conductor is based on "guaranteed" short sample critical currents, usually reported between 20 and 70 kG (2 and 7 T). For economic reasons, the design objective is then to obtain both reliably and reproducibly at least 90% of these values in an actual structure. In spite of some obvious similarities, one finds that rather different requirements are placed on the conductor in the storage coil and in the switch.

Fig. 4. Typical Short-Sample Critical Current Density Curves as a Function of the Applied Magnetic Field for Various Commercial NbTi Multifilamentary Superconducting Wires.

Storage Coil

The energy, W , stored in any inductor, L , carrying a current, I , is

$$W = (1/2)LI^2 \quad (1)$$

The inductance (in H) of a thin solenoid of radius a , length b (all in cm) and n turns is given by

$$L = 4\pi^2 10^{-9} (a^2 n^2 / b) K \quad (2)$$

where K is a function of the aspect ratio, $2a/b$, and gradually decreases from unity as a long thin solenoid is shortened⁽⁶⁾. On the other hand, for maximum inductance, a short solenoid with maximum a and minimum b is suggested by the remainder of eq. (2). When account is taken of the physical requirements of finite conductor size and limited current densities (in both normal and superconducting materials), maximum inductance and hence stored energy for a given amount of conductor is obtained with the well-known Brooks coil⁽⁶⁾ (Figure 5).

Fig. 5. Brooks Coil Inductor.

Provides maximum inductance for a given length of conductor.

Unfortunately, in this coil the winding is subjected to large field gradients and much of the energy and flux are located on the outside of the coil structure, which would be objectionable in most laboratory and plant environments. A toroid or similar closed structure avoids these problems at a loss in efficiency of conductor utilization. In effect, one can approximate the toroid by a number of straight solenoidal sections. Optimum operating field, B , is determined by the critical current curves which are essentially hyperbolas given by

$$I_c = \frac{\alpha}{B_0 + B} \quad \text{where } \alpha \text{ and } B_0 \text{ are empirical constants.} \quad (3)$$

Ribe has shown⁽¹⁾ that if Eq. (3) holds, a superconducting solenoid of a given length is most economically operated at the lowest practical field which is then set by limitations to the dewar cost and dimensions. Solé⁽⁷⁾ reports, but doesn't derive, an optimum field of 17 kG (1.7 T) for a toroid. At the present, fields of 30 ± 10 kG (3 ± 1 T) appear to be the best choice when trading dewar size and refrigeration costs against quantity of superconductor, although a change in the relative costs of these components could change the optimum operating point. Thus in a recent paper⁽⁸⁾ from the group at the Compagnie Générale de l'Ectricité (C.G.E.) broad, somewhat energy dependent minima in overall systems costs at fields of 40 to 60 kG (4 to 6 T) are reported.

Stabilization of Pulsed Energy Storage Coils

For steady fields, filament diameters within a multifilamentary superconductor are limited to 2 to 8×10^{-3} cm (1 to 3 mil) by the well-known adiabatic and dynamic stability criteria⁽⁹⁾. The former limits the energy that may be associated with the collapse of localized shielding currents within thermally isolated filaments as a function of critical current density, temperature variation of current density, and specific heat of the superconductor. The latter dictates the proximity of a good low resistivity normal conductor to slow down the collapse of the shielding currents sufficiently for the associated heat to be conducted from the superconductor into the matrix. This theory uses critical current density and temperature variation of the current density together with the thermal conductivity of the superconductor and the electrical resistivity of the matrix.

For changing magnetic fields, it was shown by P. F. Smith et al.⁽¹⁰⁾, that there is the additional requirement of decoupling the filaments within the high conductivity matrix by transposition, i.e. twisting and/or braiding. The filaments are decoupled as long as the rate of field change, $\dot{B}$ (in Gauss/sec), is less than a critical value given by

$$\dot{B}_c = \frac{32 J_c \lambda^{1/2} \rho d}{t^2} \frac{w}{w + d} 10^8 \quad (4)$$

where

J_c	critical current density (A/cm^2)
λ	fraction of cross-sectional area of wire occupied by the superconductor
ρ	resistivity of the matrix ($\Omega - cm$)
d	filament diameter (cm)
w	separation between filaments (surface to surface) or width of high resistivity material (cm)
t	transposition distance or 360° twist pitch (cm)

Table I calculates some J_c values according to equation (4) for a number of superconductors used or considered in this work. These include wires with different copper matrix ($\rho_{4K} = 1 \times 10^{-8} \Omega - cm$) to superconductor ratios, wires with cupro-nickel matrix ($\rho_{4K} = 35 \times 10^{-6} \Omega - cm$) and mixed matrix wires (see below). Clearly, there are no difficulties in stabilizing most of these materials during the charging cycle, but there can be problems during the fast discharge.

There are additional theoretical limitations [Wilson⁽¹¹⁾] on maximum filament diameter as well as practical ones on the maximum number of filaments that can be incorporated in a single wire. Superconducting wires with high resistivity matrices have generally been unsuccessful in coils⁽¹²⁾. Eddy current losses in the copper vary as $d^2 f / \rho$ (d = diameter, f = frequency, ρ = resistivity) and can be calculated from formulas given by Weisby⁽¹³⁾. Under pulse or ac conditions, eddy current heating will lower the critical current capacity of the conductor (unless there is sufficient cooling) and may even drive the coil normal. Braids made from insulated multifilament wires reduce eddy current heating problems, but generate new ones in that braids are springy, subject to motion under the influence of the Lorentz forces and hence degrade, i.e. do not work up to short sample critical currents unless potted. However, potting, in turn, reduces heat transfer. McInturff⁽¹⁴⁾ has developed braids immobilized by high resistivity metallic or almost ceramic alloy solders. These may offer some advantages in the present work but are not as yet available commercially.

An alternative approach to high current superconducting wires with minimal eddy current losses is found in mixed matrix superconductors (Fig. 6). Here each filament is surrounded by a copper shell

which in turn is embedded in a high resistivity Cu-Ni matrix. We have found such conductors to be quite stable and reliable.

Fig. 6. Mixed Matrix Superconductor, Supercon 228.

NbTi filaments are surrounded by OFHC copper and decoupled by cupro-nickel matrix. Filaments are twisted at 0.2 twists/cm and the center of the conductor is free of filaments.
Overall dimensions: 0.203 x 0.406 cm;
Critical current: 1 kA at 3 T.

Another possible design which so far has had little application, except by Morpurgo⁽¹⁵⁾, involves hollow or tubular conductors. The main advantage of these would lie in the replacement of liquid helium pool cooling, which is undesirable and uneconomical for large volumes, by a single phase supercritical gas flow system. Tubular conductors have been made by spiral wrapping and soldering wires to a tube⁽¹⁶⁾ and by coextrusion of aluminum⁽¹⁷⁾. Forming a circular braid around a rectangular tube of high resistance alloy and then soldering it in place is another method which needs exploring.

For all storage coil materials, there is a dilemma between enough copper to provide stability during coil charging and cryoconductor behavior during the discharge (if the coil should go partially normal), while also minimizing eddy current heating which will drive the coil normal. Figs. 7

Table I
Critical Field Change Rates for
Various Superconductors

Description	Cu Matrix 500A at 6T	Cu Matrix Braid	Cu Matrix 5kA at 3T	Cu Matrix 10kA at 3T	Mixed Matrix 1kA at 3T	Mixed Matrix 10kA at 3T	Switch Cond. Braid	Switch Cond. Braid
Sample No.	KRYO-155	VSF212	KRYO-A	KRYO-B	SU228	KRYO-C	KRYO-33	VSF230
Size (in.)	0.041 x 0.061	8.2×10^{-3}	0.2 x 0.2	0.2 x 0.4	0.080 x 0.160	0.2 x 0.4	8.0×10^{-3}	8.2×10^{-3}
(cm)	0.104 x 0.155	2.08×10^{-2}	0.508 x 0.508	0.508 x 1.016	0.203 x 0.406	0.508 x 1.016	2.03×10^{-2}	2.08×10^{-2}
Matrix/SC ratio	2.6:1	1:1	6:1	6:1	5:5:1	3:3:1	2.8:1	1:1
Space Factor, λ	0.278	0.5	0.143	0.143	0.091	0.143	0.263	0.5
No. of Filaments	132	400	2700	2700	358	2700	22	360
Fil. Diam., d(cm)	7×10^{-3}	6×10^{-4}	4.8×10^{-3}	6.7×10^{-3}	1×10^{-2}	1.2×10^{-2}	2.6×10^{-3}	6.3×10^{-4}
Fil Spacing, w(cm)	1.6×10^{-3}	1×10^{-4}	5.4×10^{-3}	7.6×10^{-3}	2×10^{-3}	8×10^{-4}	1.2×10^{-3}	2×10^{-4}
No. of twists/in.	2	12.5	1/2.5	1/3.5(1/12)	0.5	1/3.5	5.5	12.5
Transp. dist., t(cm)	1.27	0.203	6.35	8.89 (30.4)	5.08	8.89	0.462	0.203
J_c at 0.5T(A/cm ²)	-	-	-	-	-	-	8.7×10^5	5.8×10^5
J_c at 3T(A/cm ²)	2.2×10^5	1.25×10^5	2.2×10^5	2.2×10^5	1.4×10^5	2×10^5	-	-
Matrix Res, $\rho(\Omega\text{-cm})$	1×10^{-8}	2.8×10^{-8}	2×10^{-8}	2×10^{-8}	3.5×10^{-5}	3.5×10^{-5}	1.5×10^{-5}	3.5×10^{-5}
$\dot{B}_c$ (Gauss/sec)	3.0×10^3	1.64×10^4	334	239 (20.5)	3.05×10^5	3.07×10^4	8.25×10^7	1.69×10^8

and 8 represent plots of these factors for various discharge time constants, obtained from a computer analysis of coil losses for braids made from 0.020 cm (8 mil) diam wires with different amounts of copper.

Fig. 7. Energy Loss during Pulse Discharge of Superconducting Energy Storage Coils.

Braided 1 kA conductor made from insulated 8 mil (0.020 cm) diam wires of different matrix to superconductor ratios (6:1, 3:1, 1:1). External resistance governs time constant and hence discharge rate and relative importance of various loss mechanisms. Joule losses, E_J , hysteresis losses, E_H , and eddy current losses, E_E , are shown separately for the 3:1 conductor.

Fig. 8. Energy Losses during Pulse Discharge as in Fig. 7, but at Half Current.

The calculations⁽¹⁸⁾ assume 42.6 mH coils (divided into 10 segments exposed to different fields) which, at peak current (1000 A), store 21.3 kJ at 40 kG. The analysis includes hysteresis, joule, and eddy current energy losses and is pessimistic especially for the low resistance (low discharge rate or long-time constant) region since adiabatic conditions are assumed. Fig. 7 gives results for the 1000 A ($E_{ST} = 21.3$ kJ) cases; it also shows the separate hysteresis E_H , joule E_J and eddy E_E losses for the 3:1 conductor. Fig. 8 gives similar results for the 500 A ($E_{ST} = 5.3$ kJ) cases. The left-most 6:1 curve indicates in a qualitative way, the response to be expected for the more realistic non-adiabatic cases where joule losses will not be present at all as long as the coil remains superconducting.

Transfer Switch

The main switch in the energy transfer experiment has to break a direct current in an inductive circuit, a practice frowned upon in conventional electrical engineering. There are no real high current, high voltage dc breakers. Available breakers which have severe current limitations include the counter-pulse system⁽¹⁹⁾, which forces a current null to allow breaker contacts to be separated, and the interesting, plasma-decay, crossed-field switch tube under development at Hughes Research Laboratories⁽²⁰⁾.

The switching method under development in the present study is based on the transition of a superconductor from the superconducting to the normal state, and might be more accurately described as a variable resistor or rheostat. Whereas the cost of energy storage devices varies as the peak stored energy, the cost of most switches varies with their peak power handling capacity. For the superconducting switch, it was shown by Hake⁽²¹⁾ [and also by Solé⁽²²⁾] that the volume of superconducting material (and hence the cost of the switch) is given by

$$V_{SC} = A\ell = \frac{E_{\max} I_{\max}}{J_c^2 \rho_N} \quad (5)$$

where A and ℓ are the cross sectional area and length (in cgs units), $E_{\max}$ and $I_{\max}$ the peak voltage and current (in V and A), J_c the critical cur-

rent density (in A/cm^2), and ρ_N the normal state resistivity of the superconductor (in $\Omega\text{-cm}$). If, for purposes of stabilization, a filamentary superconductor is "diluted" with an essentially zero cost non-superconducting matrix to an area ratio $A_M/A_{SC}=a$, then the volume is given by

$$V_{SC} = (a+1) \frac{E_{\text{max}} I_{\text{max}}}{J_c^2 \rho_E} \quad (6)$$

where ρ_E is the effective parallel resistivity of the matrix and the superconductor in the normal state

$$\rho_E = (1+a) \rho_{MSC} / (\rho_M + a \rho_{SC}) \quad (7)$$

Clearly, there is a premium on operating at the highest possible current densities and using the highest resistivity superconductor and matrix material as well as the minimum amount of matrix consistent with stable operation. Materials used so far have had resistivities of up to $5 \times 10^{-5} \Omega\text{-cm}$ and critical current densities of $10^6 \text{ A}/\text{cm}^2$ at self-field, although only $5 \times 10^5 \text{ A}/\text{cm}^2$ has been attained in the superconducting material of actual switches.

Selection of Switching Mode

Superconductivity is destroyed by excess temperature, magnetic field or current density. For proper switching and to avoid local burnout, the normal-going superconducting switch must become resistive uniformly and simultaneously over its entire length. It would be difficult to heat the entire switch material in a few microseconds uniformly with an external heater, except possibly by some radio frequency method or with an infrared laser pulse (in the case of a thin film switch). Neither of these methods has been tried by us.

Magnetic switching can, in principle, be done with steady or with pulsed fields; however, the latter are considerably cheaper. Even so, a sizable amount of energy would be needed to produce a uniform field over the entire switch volume. Solé (23) and the C.G.E. group (8) have reported successful magnetic switching with 5 to 10 kG pulses.

In conjunction with the partial resistance phenomenon discussed below, work was done on pulsed magnetic switching with the hope that it might be immune to the problem. However, this is

not the case and there is no obvious advantage of magnetic switching over current or, more correctly, current density switching.

Current pulse switching of a superconductor is by far the simplest and most uniform way to produce the transition to the normal state. The real problem with any switching mode is to keep the superconductor latched in the open position once the switching condition has relaxed. This is made evident by Figure 9.

Fig. 9. Phase Diagram for Current Carrying Superconductor and Dynamics of Switching.

Switch will only latch in open position when $T > T_c$.

Most circuits will respond to an increase in resistance with a drop in current, so that the switch may partially return to the superconducting state, possibly even before the applied temperature, field or current have decayed. Reliable latching can only be obtained if the switching condition is maintained long enough to deliver enough energy (or to extract enough energy from the storage circuit) to raise the temperature of the switch and of all associated material above the critical temperature T_c .

Figure 10 exemplifies the partial resistance phenomenon and spells out the conditions required to attain proper latching. At insufficient applied

voltages ($V_S < 0.3 I_C R_N$), a superconductor may hover at partial resistance ($R < R_N$) for millisecond times, i.e. until relatively slow longitudinal thermal propagation brings on full normalcy. On the other hand, when the applied voltage is sufficient to drive 30% of the critical current through the fully normal switch, 95% of fully normal resistance will be attained in microseconds. This empirical result still needs refinement, but it is a useful guide in systems planning.

be removed by refrigeration before the system is ready to be charged again, the relative magnitudes of R_{SW} and R_P strongly affect the design and cost of the refrigeration system. One method, suggested by Mawardi⁽²⁵⁾, for preventing excessive energy loss into the low temperature environment is to make resistance R_{SW} much greater than resistance R_P so that most of the energy is dissipated at room temperature. The final temperature of the switch might typically be about 60 K.

Fig. 10. Incomplete Switching or Partial Resistance Phenomenon.

Voltage requirements for complete switching are suggested by shape of curve.

The circuit shown in Figure 11, which resulted from a discussion with R. L. Garwin⁽²⁴⁾, guarantees that all the energy stored in the switching capacitors will indeed be delivered to the superconducting switch. If necessary, it would, of course, be possible to add additional taps on the switch and correspondingly further subdivide the capacitor banks.

Optimization of Switch and Refrigerator Size

Each time the energy storage system is discharged, 50% of the stored energy is dissipated in the parallel resistors R_P and R_{SW} (which of course should be equal to R_N). The resistor R_P is at room temperature, while R_{SW} is at cryogenic temperatures. Since all of the energy lost in R_{SW} must

Fig. 11. Double Capacitor Circuit.

Guarantees delivery of entire capacitor energy into center tapped switch.

An alternate solution proposed by Garwin⁽²⁴⁾ is to reduce the resistance of the switch, eliminate or at least reduce the size of R_P , and allow the temperature excursion of the switch to go to room temperature or higher. While an order of magnitude more energy would be dissipated in the switch compared to the first method, recooling the switch might be easier because of the higher thermodynamic

efficiency of refrigerators at higher temperatures. Also, the cost of the material in the switch would be substantially reduced. Recooling of the switch would be done by a series of small refrigerators, each with a progressively lower exit temperature until the proper switch operating temperature is reached.

A preliminary cost analysis⁽²⁶⁾ of the two systems for 1 GJ of stored energy showed that as long as there is no extra material in thermal contact with the switch, the low resistance switch cooled by staged refrigerators has a decided advantage over the high resistance switch cooled with one stage. However, a certain amount of material in thermal contact with the switch is inevitable, (e.g. switch support form, plastic potting, helium gas for cooling), and as this mass increases the advantage of the low resistance switch rapidly disappears. The net effect is that a fixed amount of energy has to be removed from a larger mass at a lower temperature and at a consequently lower refrigeration efficiency. A very detailed knowledge of the switch design is needed to make a choice between the two methods. Generally speaking however, if the amount of plastic or structural material in intimate thermal contact with the switch reaches three to five times the mass of the switch, it would seem that the cost advantage of the second method would be marginal.

Switch Materials and Configurations

The normal-going superconducting switch has to be able to carry supercurrents stably as near to the short sample critical current as possible for economy in usage of superconducting material and, according to equation (6), should contain as little normally conducting material as possible (and certainly no low resistivity stabilizer such as high purity copper). It should also be assembled in a non-inductive fashion and with each half shown in Figure 11 separately non-inductive for quick switching and minimum capacitor size and energy. Coaxial film geometries were originally suggested by Mawardi⁽²⁵⁾ but still present unsolved manufacturing and stabilization problems. All the switches built so far and under design are based on braids of wires of multifilamentary NbTi in a high resistivity CuNi alloy matrix.

As mentioned earlier, such a material can be made to meet the criteria for adiabatic stability, but it cannot be dynamically stable or cryostable and it will be sensitive to motion, i.e. it has to be immobilized by some bonding or soldering process, especially since braids of stiff wires are naturally springy. Some success has been had in potting with a mixture of paraffin and beeswax and with a filled epoxy (Stycast 2850 FT)⁽²⁷⁾. However, these methods are not entirely satisfactory and metallic bonding or tubular conductors will have to be developed as discussed above as alternatives in the design of storage coil conductors.

The mechanical arrangement of the switch conductor has been done as spiralled hairpins which fill space rather efficiently but are somewhat hard to insulate and immobilize, and with the Ayrton-Perry counter spiraling tubular geometry (Figure 12), which doesn't fill space efficiently but is more easily insulated.

Fig. 12. Counter Spiraling Ayrton-Perry Switch during Assembly.

The two parallel 13-wire braids cross over each other twice for each 360° turn.

Energy Transfer Experiments

Energy transfer experiments have been performed with 10 and 20 kJ storage coils at currents up to 1100 A, voltages up to 2.2 kV, and with 2 to 5 ohm

superconducting switches. Resistive loads were used in most of the work, except for a few experiments with a current step-up transformer internal to the coil and feeding an inductive load. A major part of the effort has been on developing the instrumentation needed to ascertain proper performance of all components and especially of the superconducting switch.

Fig. 13. Overall View of 20 kJ Energy Transfer Experiment.

Single 12-in. (30 cm) dewar accommodates coil and switch. Small brass can (in front) connected by coaxial cable houses the electrolytic load resistor.

Figure 13 is an overall view of the experiment housed in a 30 cm diam by 122 cm deep dewar made of fiberglass reinforced plastic and aluminum. Figure 14 gives a more detailed view of the top of the

apparatus showing the counterflow current leads, the triggering capacitor banks, one form of manganin grid load resistor (the other load resistor is an electrolytic tank, seen in front of the dewar in Fig. 13), and some of the instrumentation and instrumentation leads.

Fig. 14. Close-up View of High Current Leads and Instrumentation Used in 20 kJ Experiment.

Figure 15 gives a close-up view of the 10 kJ storage coil with the Ayrton-Perry switch mounted below it. The switch is an early beeswax and paraffin potted version which allows a view of the winding geometry. Recent versions are potted in epoxy.

Figure 16 is a photograph of the high purity single turn aluminum transformer and the four turn load inductance. When in use, the transformer is mounted inside the storage coil and braced appropriately.

Voltages are measured in the usual manner with precision voltage dividers and calibrated oscilloscopes. Considerable care is needed in establishing a well-defined ground point at room temperature and referencing all measurements to it. Currents which are changing rapidly are measured with Rogowski loops and with Pearson⁽²⁸⁾ transformers. For currents which vary on a millisecond timescale, low inductance coaxial resistors ("Current Viewing Resistors," or CVR's⁽²⁹⁾) have been found most satisfactory. The main reason for

the high accuracy required in the current and voltage instrumentation is that the current and hence resistance of the normal-going superconducting switch can only be obtained from differences of relatively large numbers. Semi-conductor Hall effect probes⁽³⁰⁾ and pick-up coils are used to measure magnetic fields and field changes.

Fig. 15. 10 kJ - 18.7 mH Storage Coil with 2.2 ohm Switch.

Coil is wound from insulated superconductor braided over fiberglass rope core. Switch mounted below coil is early version potted in mixture of beeswax and paraffin.

Figure 17 is a reproduction of the oscilloscope traces of current and voltage decays in the load resistor R_p of Fig. 11. The decay time constant obtained from these curves is a measure of the parallel resistance of R_p and R_{SW} plus any series resistance that might develop from partial normalcies in the storage coil. The linearity of different least square fits of these decays (on a semilogarithmic plot, Figure 18) becomes a measure of the constancy of the various resistances as a function of time.

Fig. 16. Internal Aluminum Transformer and Load Inductance.

Fig. 17. Current and Voltage Decays in Load Resistor during Energy Transfer.

Upper trace (Ch. 1): Current at 50A/div.
Lower trace (Ch. 2): Voltage at 200V/div.

Figure 19 gives the peak voltages reached during various transfer experiments as a function of the stored current, I_{ST} , and for different values of the external resistor R_p in parallel with R_{SW} . The maximum voltage attained so far has been (in agreement with Ohm's law) 2.2 kV at 1000 A stored current with a 2.2 ohm switch and no R_p (i.e. $R_p = \infty$).

Fig. 18. Analysis of Current and Voltage Decays from Fig. 17.

Dashed line: linear least squares fit.
Solid Lines: second order least squares fits.

The question of times and currents required to drive this 2.2 ohm 26 wire braided switch normal is partly answered by Fig. 20, which is a plot of the peak pulse current from each capacitor bank into each half of the switch (cf Fig. 11) for many of the experiments of Fig. 19. Clearly, each half switches into the normal state when the algebraic sum of pulse current plus stored current reaches 2050 ± 100 A. The actual transition, as indicated by the limiting of the pulse current, takes place in less than a microsecond and the two halves of the switch reach switching currents simultaneously to within 2 or 3 microseconds. This simultaneity can easily be improved by reducing the presently large inductance of the switching circuit.

Fig. 19. Peak Voltages during Energy Transfer from 18.7 mH Coil with 2.2 ohm Switch.

Voltages are plotted against current stored in coil prior to energy transfer with the external resistance, R_E , as a parameter. R_E is the sum of R_P , the measuring CVR and the lead resistance. The solid circles are for energy transfer into an inductive load.

Figure 21 gives the time history of secondary currents and voltages during one of the transformer experiments.

300 kJ Energy Transfer Experiment

A 300 kJ energy transfer experiment has been designed and is presently under construction. Fig. 22 is an artist's sketch of the various components to be housed in separate dewars with an external transformer and load coil to be located at room temperature. Table II lists the design parameters of the experiment. Fig. 23 gives a calculated plot of the primary, I_1 , and secondary currents, I_2 , to be produced with a load coil, and Fig. 24 gives a plot of the same currents when the

Fig. 20. Peak Currents Delivered from Each of Two Capacitor Banks into Separate Halves of Center-Tapped Switch.

Bank voltage: 3 kV (cf Fig. 11). Different symbols are for different values of the external load resistance.

load coil is shorted out. Skin effect resistance at earlier times is included in the calculations of I_2 and reduces the peaks by about 20% from what they would be otherwise. Finally, Fig. 25 indicates the location of various instrumentation elements, voltage taps and current and field sensors together with the lead resistances which can affect the measured voltages.

Fig. 21. Energy Transfer into Transformer Coupled Inductive Load.

Voltage at load inductor: E_2 .

Current through load inductor: I_2

Long Range Prospects

There is little question that superconductive magnetic energy storage in conjunction with normal-going superconducting switches is capable of delivering millisecond power pulses into inductive loads and even faster pulses into resistive loads. Efficiencies in excess of 90% can be attained with resistive loads by proper sizing of the switch resistance relative to the load resistance. However, the limited (25%) efficiency encountered with inductive loads makes the method impractical when overall energy balance is important as in a controlled thermonuclear reactor. The use of transfer capacitors or of rotating machinery⁽⁴⁾ would, of course, markedly increase overall efficiency. Further analysis is needed to establish cost and improvements possible in a hybrid system containing both inductive storage and capacitors or rotating machinery.

Table II
300 kJ Experiment

Fig. 22. 300 kJ Energy Transfer Experiment.

Switch dewar i.d.: 17 in. (43 cm).
Fiberglass-epoxy storage coil dewar
i.d.: 24 in. (61 cm).

Single turn transformer secondary is located on the outside of the storage coil dewar and feeds multi-turn load coil of matched inductance.

Energy losses in the superconducting storage coil during the fast discharge also need further study and in particular correlation of the theoretical analysis with experimental data. These losses are not very important at low pulse repetition rates, but do become limiting at high repetition rates when overall energy economy and maintenance of the superconducting state are required. In the latter case, operation of the storage coil at temperatures above 4 K offers the possibility of reducing both the capital and power costs of the refrigeration equipment.

Storage Coil (Single Layer, Edgewound)

Energy Stored	300 kJ
Inductance	6mH
Current	10 kA
Number of Turns	133
Inner Diameter	57 cm
Length	70 cm
Conductor Dimensions	0.51 x 1.02 cm
Central Field at 10 kA	1.8 T
Max. Field at Conductor	2.0 T
Critical Current of Cond. at 2 T	13 kA

Switches

Normal State Resistance	2 to 4 Ω
Peak Voltage Generated	20 to 40 kV

Transformer Secondary Winding (Room Temperature)

Inner Diameter	76.8 cm
Length	76 cm
Thickness	1.27 cm
Number of Turns	1
DC Resistance	6 $\mu\Omega$
Coupling Constant	0.74
Peak Current	280 kA
Peak Voltage	~140 V

Load Coil (Room Temperature)

Mean Diameter	19.7 cm
Length	76 cm
Number of Turns	3
DC Resistance	11 $\mu\Omega$
Peak Field	1.4 T
Energy at Peak Field	21 kJ

The superconducting switch itself represents the area in which the most extensive improvements should be possible. Stabilization of a large switch at better than 90% of the inherent short sample critical current remains as yet an unattained goal. Similarly, the operation of switches at elevated temperatures and with gas cooling remains to be explored.

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Fig. 23. Primary and Secondary Currents Expected in 300 kJ Transfer Experiment with 4 ohm switch.

Current in storage coil: I_1
Current in transformer secondary and load coil: I_2

Fig. 24. Primary and Secondary Currents with Shorted Secondary (No Load Coil).

Fig. 25. Instrumentation Layout for 300 kJ Energy Transfer Experiment.

- ① Voltage tap near ground potential.
- ⑤ Voltage tap at elevated potential.
- CVR Current viewing resistor.
- Rog Rogowski loop.
- B Pick-up coil for field change.
- HP Hall effect field probe.
- G Spark gap or trigatron.
- Flow He gas flow in high current leads.
- Level Liquid helium level in dewar.
- TX-1 Current measuring transformer (Pearson).
- TX-2 Pulse transformer to trigger gap G-2.
- PS Power supply.

References

1. F. L. Ribe, Bull. Am. Phys. Sec. II, 16, 1290 (1971), also Los Alamos Scientific Laboratory Report LA-4828-MS, 1971.
2. H. L. Laquer, F. L. Ribe and D. M. Weldon 1971 Intersociety Energy Conversion Conference, Proceedings P38, 1089 (1971).
3. H. L. Laquer, J. D. G. Lindsay, E. M. Little and D. M. Weldon, 1972 Applied Superconducting Conference, IEEE Pub. No. 72CH0682-5-TABS, p. 98 (1972).
4. K. I. Thomassen, 1972 Texas Symposium on the Technology of Controlled Thermonuclear Fusion Experiments and the Engineering Aspects of Fusion Reactors, Proceedings. See also Los Alamos Scientific Laboratory Report LA-5087-MS (1972).
5. (a) K. R. Efferson, Rev. Sci. Inst. 38, 1776 (1967).
(b) J. M. Lock, Cryogenics 9, 438 (1969).
(c) V. S. Okolotin and V. i. Bol'shakov, Cryogenics 12, 227 (1972).
6. F. W. Grover, Inductance Calculations, Dover Publications, New York, 1962.
7. J. Solé, Saclay Report CEA-R 3243 (1967).
8. J. P. Krebs, E. Santamaria and J. Maldy, 4th International Cryogenic Engineering Conference, Proceedings, p. 172 (1972).
9. (a) S. L. Wipf, Phys. Rev. 161, 404 (1967).
(b) H. R. Hart Proceedings of the 1968 Brookhaven Summer Study on Superconducting Devices, Report BNL 50155(C-55) p. 571 (1969).
10. M. N. Wilson, C. R. Walters, J. D. Lewin and P. F. Smith, Jour. Phys. D, 3, 1518 (1970).
11. M. N. Wilson, 1972 Applied Superconductivity Conference, IEEE Pub. No. 72CH0682-5-TABS, p. 385 (1972).
12. P. F. Smith, M. N. Wilson and A. R. Spurway, Jour. Phys. D, 3, 1561 (1970).
13. V. G. Welsby, The Theory and Design of Inductance Coils, Mac Donald, London, 1960.
14. A. D. McInturff, 1972 Applied Superconductivity Conference, IEEE Pub. No. 72CH0682-5-TABS, p. 395 (1972).
15. M. Morpurgo, CERN Report 69-25 (1969).
16. N. Schaetti, Brown Boveri Review 2/3, p. 3 (1972).
17. Compagnie Générale de l'Electricité, Marcoussis, France.
18. D. M. Weldon, Los Alamos Scientific Laboratory Report LA-5292-MS (1973).
19. A. N. Greenwood and T. H. Lee, IEEE Transactions on Power Apparatus and Systems PAS-91, 1570 (1972).
20. H. Gallagher, G. Hofmann and M. Lutz, IEEE Transactions on Power Apparatus and Systems PAS-92, 702 (1973).
21. R. R. Hake, Los Alamos Scientific Laboratory Report LA-4617-MS (UC-20, TID-4500) (1971).
22. J. Solé, Limeil Report CEA-R 3515 (1968).
23. J. Solé, Entropie 39, 21 (1971).
24. R. L. Garwin, Private Communication (1972).
25. O. K. Mawardi, U. S. Patent 3,384,762.
26. D. M. Weldon, J. D. G. Lindsay and H. L. Laquer, Los Alamos Scientific Laboratory Report LA-5218-MS (1973).
27. Trademark Emerson - Cummings Inc., Canton, Massachusetts.
28. Pearson Electronics, Inc., Palo Alto, California.
29. T & M Research Products, Inc., Albuquerque, New Mexico.
30. Siemens Types SBV-552, RHY-17 and RHY-18, distributed by Instrument Systems Corp., Huntington, New York.