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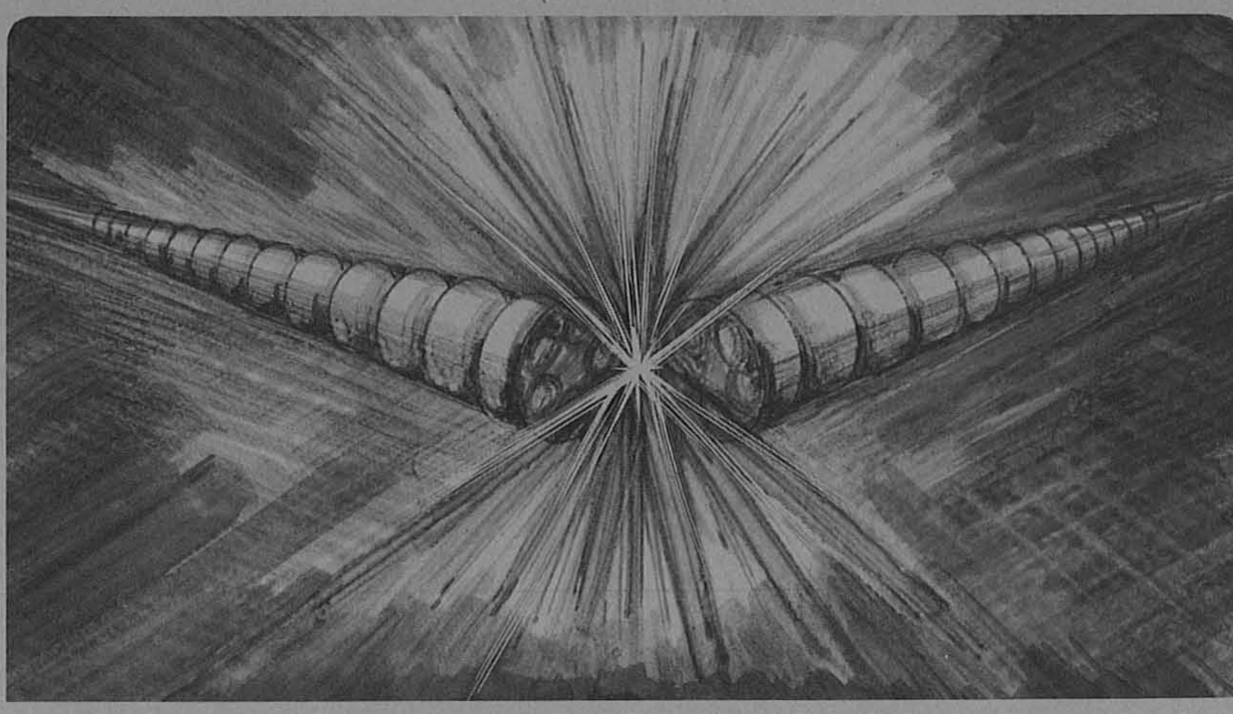

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SUPERCONDUCTING MAGNETIC ENERGY STORAGE*

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ABSTRACT

Recent programmatic developments in Superconducting Magnetic Energy Storage (SMES) have prompted renewed and widespread interest in this field. In mid 1987 the Defense Nuclear Agency, acting for the Strategic Defense Initiative Office issued a request for proposals for the design and construction of SMES Engineering Test Model (ETM). Two teams, one led by Bechtel and the other by Ebasco, are now engaged in the first phase of the development of a 10 to 20 MWhr ETM. This report presents the rationale for energy storage on utility systems, describes the general technology of SMES, and explains the chronological development of the technology. The present ETM program is outlined; details of the two projects for ETM development are described in other papers in these proceedings. The impact of high Tc materials on SMES is discussed.

INTRODUCTION/THE NEED FOR ENERGY STORAGE

Variations in electric power demand are experienced by all electric utilities. Most variations are periodic, but the cycle times range from a few seconds to a year. The annual variation is typically accommodated by scheduling power equipment outage and major maintenance for seasons of low demand. The time of year for the peak season depends somewhat on geographical location, and there is some long range power transmission, for example north to south in the U.S. and other countries, to reduce peak power generation requirements. The daily or diurnal cycles are perhaps the most serious because of the sheer magnitude and rate of power variation that may occur in a 24 hour period[1], as shown in Fig. 1. The variation may be from 50% of peak load at 7 am to 90% at 9 am. On a utility system with a 2000 MW peak, this variation is 800 MW. This is significant as it is the equivalent of turning on a full sized nuclear power plant in a period of 2 hours.

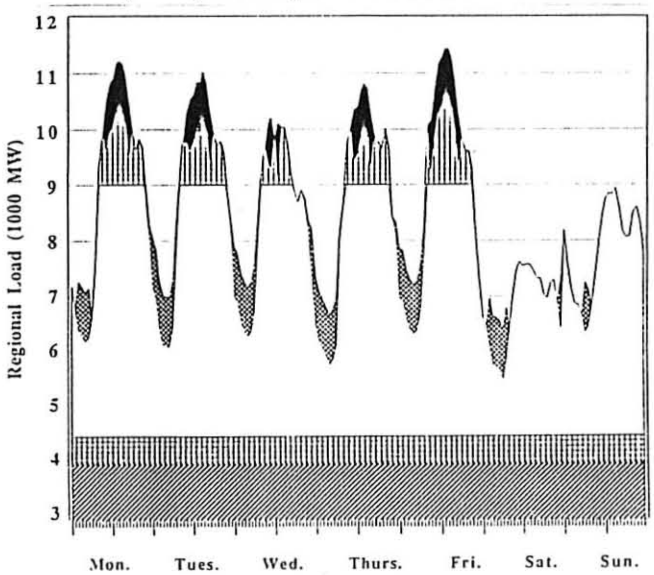

Fig. 1 A weekly load cycle that might be experienced for a region of the United States. The uppermost curve is the actual power delivered. The shaded areas near the delivered power curve show the charge and discharge of an energy storage plant.

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The base load, the power required for the full 24 hours, is only about half the power required at the peak (see Fig. 1). Large coal fired and nuclear power plants, which are most efficient (in terms of converting heat into electricity), are normally designed for and, where possible, programmed to meet the base load needs by operating at full capacity for months without significant power variation. Though power levels can be changed on these expensive units, their life expectancy is decreased considerably when forced to cycle by significant fractions of their maximum capacity.

Since this base generation cannot be cycled, the other half of the power generating capacity of most systems must be capable of cycling 100% on a daily basis. Old and intermediate sized coal fired power plants, hydro electric plants and gas turbines, are less effected by changing power levels and historically have been used to meet the daily and weekly power variations. The price paid for using these units is efficiency. Roughly 1/3 of the thermal energy of a coal fired or nuclear plant is converted into electricity. For a gas turbine the conversion efficiency may be only 25% and expensive fuels are needed.

Though some fraction of the capacity to meet the peak demands must be in form of primary power sources, part of it can be in the form of energy storage plants that are charged by inexpensive, off-peak power (usually at night) and discharged during the periods of high demand. Estimates of the fraction of capacity that could be in the form of energy storage range up to 15% of the total generating capacity, though 5% might be a more reasonable projection. The installed generating capacity in the U.S. is expected to 750,000 MW in the 1990's[1]. Five percent of this, 37,500 MW, could be in the form of energy storage.

At present about 2% of the generating capacity in the U.S. is in the form of pumped hydro units, some of which date back to the 1930's.[2]. These units have been of great value to those utilities fortunate enough to have the necessary geological and other conditions, namely an available location with adequate water and sites for upper and lower reservoirs with a differential height of several hundred feet or more. We are now running out of such favorable sites, and the possibility of using underground caverns for the lower reservoir has been proposed.[3]

To satisfy the need for peak power several new technologies,[4,5] including compressed air[6], underground pumped hydro[3], batteries[7], and Superconducting Magnetic Energy Storage[8-11] (SMES) show promise for possible future applications. Some have already seen limited use, though they are all still developmental. In each of these technologies, except SMES, the electrical energy is converted to another form, mechanical or chemical, through several tranformations, and then back to electrical. The conversion processes are inherently inefficient. As a result pumped hydro, compressed air, and battery energy storage are all only 65 to 75% efficient. (Efficiencies approaching 80% for pumped hydro plants with large heads have been reported[12]). SMES may be as high as 95% efficient. With technical development and cost improvements in these emerging technologies the electric utilities will someday be able to select from several options the type of plants that will optimize their power generation capability in terms of cost and performance.

SMES SUMMARY

Here we address Superconducting Magnetic Energy Storage, which is inherently very efficient and has siting requirements that are somewhat different from other technologies. SMES has the potential of finding application in systems with large energy storage requirements and/or rapid power changes. It will meet many of the requirements for diurnal storage. An unusual feature of SMES is the cost scaling with size as shown in Fig. 2, which is different from that for other storage devices[13-15]. For a given design, the cost of a SMES unit is roughly proportional to its surface area and the required quantity of superconductor. The stored energy is roughly proportional to the volume; thus, the cost per unit of stored energy (MJ or MWhr) decreases as storage capacity increases.

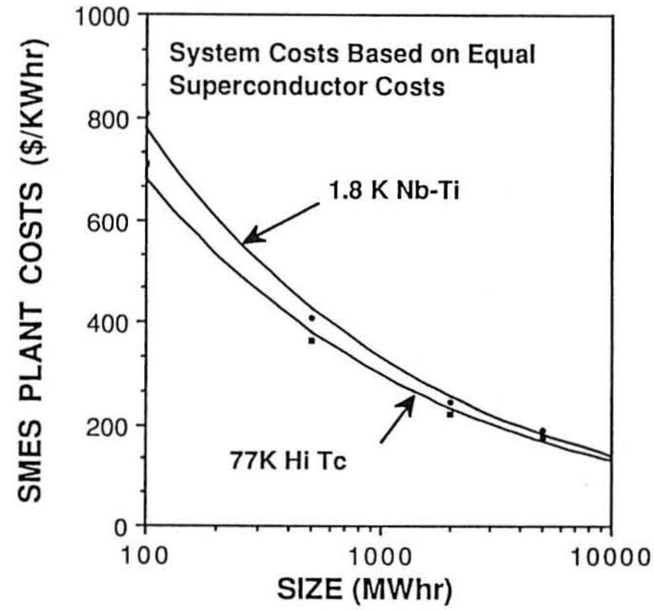

Fig. 2 Costs of SMES plants of various sizes per unit of stored energy. The impact of high temperature superconductors is included for the case of equal material and fabrication costs.

The SMES plant is charged and discharged through a multiphase converter, which allows it to respond within tens of milliseconds to power demands that could include a change from maximum rated charge to maximum rated discharge[16-17]. This rapid response should allow a diurnal storage unit to provide spinning reserve and to improve system stability, thus giving a substantial cost credit to this technology. Both the converter and the energy storage in the coil are highly efficient as there is no conversion of energy from one form to another. The major loss during storage is the energy required to operate the refrigerator that maintains superconductivity in the coil. Because of these characteristics and because it can be easily sited, is likely to be quite competitive with other storage technologies. Superconducting Magnetic Energy Storage, has the potential of finding extensive application on utility systems.

Several institutions have supported the development of SMES. Most recently, SDI and EPRI have jointly initiated a program to design and build an Engineering Test Model, ETM, with an energy storage capacity of about 20 MWhr. The power capacity for the two applications will be different: about ten MW for EPRI's utility application and several hundred MW for SDI.

In early 1987, there were many who suggested there would be great and glorious improvements should high critical temperature superconductors be used for SMES. The potential impact of high temperature superconductor on SMES have been considered in detail elsewhere.[18-20] Based on the remote chance of a 1 for 1 replacement of the superconductor and operation at 77 K, the capital cost will decrease by about 8% and the efficiency will increase by about 2%. Neither of these is significant enough to change the relative competitiveness of this technology, though it may make smaller units more attractive.

HISTORY OF SMES

The development of SMES can be traced to an early paper by Ferrier[21] that considered a single large diurnal energy storage coil for France. The coil was to be in the shape of a torus, which contains essentially all the field within the toroidal shell formed by the superconductor. Only one unit would be built and both capital and development costs appeared high so the idea was not pursued.

Studies of SMES in the U.S. began at the University of Wisconsin in 1971 under the direction of Boom and Peterson[22]. The fundamental interaction between an energy storage unit and an electric utility system through a multiphase bridge was studied in detail,[23,24] including an evaluation of the stabilizing effects of the rapid response of the converter on electric utility variations.

In 1972 the Los Alamos Scientific Laboratory was asked by the U.S. Atomic Energy Commission to look into SMES and, if it appeared economical, to outline a development program to the newly formed Division of Applied Technology. Two major areas were immediately addressed. The first was to determine the relative value of SMES compared to other technologies[15]. The second was to determine the utility conditions in which such a technology would have to operate. Even at that early date the evaluation[25] of this technology was quite straightforward and showed that the level of development of some of the components was adequate for large scale units. Discussions with representatives of the electric utilities showed a keen interest in the new technology, with the ever present reservation that if it were developed, the resulting units must be cost effective (cheap), efficient, reliable, easily sited, and environmentally acceptable.

An early analysis of costs[15] based on standard techniques for building superconducting magnets showed that, by itself, the structure required to contain the Lorentz forces would be sufficiently expensive to eliminate SMES from consideration for utility application. This is a result of the fundamental relations between stress and energy, sometimes referred to as the Virial Theorem. About 16 kg of stainless steel support structure would be needed for each MJ of stored energy. This quantity is so large that the cost per unit of stored energy would be $50/MJ whereas the cost of the pumped hydro plant at Ludington was only 6.9$/MJ. Hassenzahl, recognized the economic requirement of a warm structure such as "in situ" rock in place of cold structure, as referenced in the article by Power & Bezler[26] who had studied the costs of supports for superconducting magnets for fusion and found that warm support would reduce the costs of fusion based power plants.

Other energy storage technologies[27-29] were being considered at the time, and there were many similarities between the applications of batteries and SMES to a utility system. Both require ac-dc converters and can thus respond quickly to changing power demands. The cost of the converter was well established by commercial and utility application and was known to be relatively inexpensive based on applications on dc transmission lines[30]. Through comparison with cost estimates for other new technologies[15,23] and discussions with the electric utilities it was found that a significant cost credit could be assigned to SMES if the converter were oversize, because the relatively inexpensive, increased power capability that came with additional converter capacity was quite valuable for accommodating rapid power swings.

Thus, the converter is seen to contribute two inherently attractive features to a diurnal storage unit: first the fast response time of the converter allows the SMES unit to improve system stability and second the low cost of the converter permits the SMES unit to provide the system with inexpensive spinning reserve, the extra power capacity that must be available on any operating power system.[35,36]

As mentioned above, the major cost item in a very large superconducting coil with all components at cryogenic temperatures will be the reinforcing structure. There are magnetic field configurations (used in plasma physics mainly) in which the fields and currents can be configured to be force free. Mawardi[31] and others have proposed a force-compensated SMES system consisting of toroidal and poloidal coils in which the Lorentz forces cancel for the combined system. The total structural requirements would be reduced, even though the forces in each coil type appear as expected. Several studies of this concept[32-34] have led to the conclusion that a strict relationship between stored energy and the support structure exists.

Because the early cost estimates showed that only a very large SMES unit would be economical, some effort had gone into searching for other applications of SMES to utility systems. Late in 1976 a collaboration of the Los Alamos group and the Bonneville Power Administration[17,37] suggested the use of a small, rapidly cycled energy storage unit to aid in stabilizing the power flow from the Pacific Northwest to Southern California. The motivation for this effort was an instability at a frequency of about 0.3 Hz that limited the maximum north to south power flow under certain conditions.[38]

This project was carried through to completion including tests of the unit on the power grid[39-42]. The need for this unit, which existed in 1976 when it was proposed, was reduced by adding power control to an existing dc transmission line to provide the necessary damping. Had there not been another possibility available, the 30-MJ SMES unit might still be operating. Cost estimates have suggested the economic payoff would have been reached in about two years.

In 1980 a point reference design[43] for a deep 1 GWHr SMES unit was developed by the Los Alamos National Laboratory. The conclusion was that an economically competitive unit would be in the size range 1 to 5 GWhr. In 1981 the Electric Power Research Institute initiated a study by Bechtel[44] to evaluate the technology. The conclusion of this study was that a plant closer to the surface would be more practical, but the cost estimate was consistent with the earlier LANL study. In subsequent years both EPRI and DOE supported work at Bechtel[9,45,46] to improve the design.

In 1986 EPRI proposed that the next step in this technology should be the construction of an Engineering Test Model, which would store about 10 MWHr and be about 100 m in diameter.[47]

Some work on SMES has been carried out in Japan[48], including two workshops held to evaluate the status of the technology and to discuss future projects. The designs preferred by the Japanese seems to be driven, at least in part, by considerations associated with their high cost of helium.[49-51]

THE COMPONENTS OF A SMES SYSTEM

Here we describe a general SMES system and then give some details of each component. Because of the sensitive nature of the present competition for the construction of an ETM, the recent developments of the two teams will not be discussed here but are included partially in separate papers in the Proceedings of this conference.

The components of a SMES system are shown schematically in Fig. 3. The heart of the system is the superconducting coil. The dimensions of the coil are determined by the energy storage capacity desired and the coil design chosen. A 5000 MWhr plant is considered here as a reference point. One set of possible characteristics are listed in Table I. The coil radius can vary from about 150 m to 500 m, depending on the peak field and the ratio of height to diameter. As mentioned before, if the system is to be economical, the magnetic forces that tend to expand the coil must be transmitted to a structural material such as "in situ" rock. This is accomplished by means of a structural material like Fiberglas reinforced epoxy[52,53] that has high strength and low thermal conductivity.

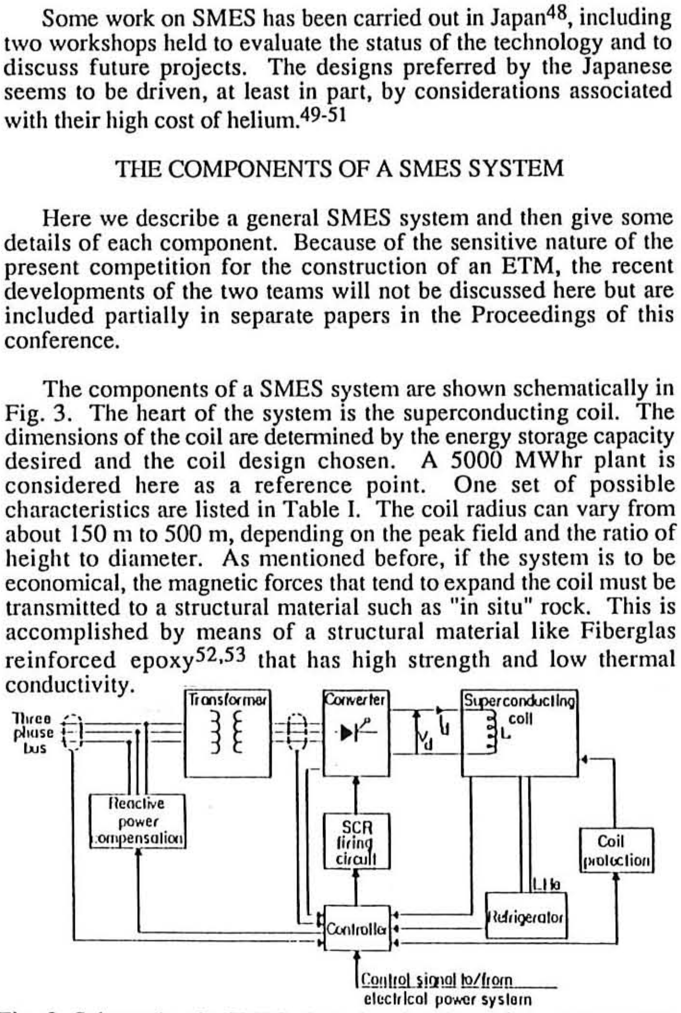

Fig. 3 Schematic of a SMES plant showing the various components and their interrelationships.

TABLE I

Characteristics of a 5000 MWhr SMES Plant

Peak Stored Energy (MWhr)	5250
Peak Power (MW)	1000
Coil Height (m)	19
Coil Diameter (m)	1000
Aspect Ratio	.019
Operating Temperature (K)	1.8
Current (ka)	200
No. of Turns	556
No. of Radial Layers	4
Maximum Wall Pressure (MPa)	1.92
Peak Magnetic Field (T)	6.69
Midplane Magnetic Field (T)	5.18
Strut Spacing (m)	4.75
Cooldown Hoopstress (MPa)	345
Refrigeration Load (MWhr/day)	120
Construction Time (yrs)	7
Land Requirement (acres)	5300

The superconducting coil is contained in a cryostat or dewar that consists of a vacuum vessel in intimate contact with the rock and a helium vessel that encloses the superconducting coil and contains the liquid helium that cools the coil. It is possible to consider a SMES conductor that contains the helium. The advantage is the elimination of the helium vessel and reduction in the amount of helium. The disadvantages are the need for many helium access points, the question of stability, and possibly extended cooldown times.

Heat generated within the coil or conducted to the helium, along either the supports or the power leads, is removed by a refrigerator.

The current in the superconducting coil passes from room temperature to the coil along a set of special low loss power leads. At the room temperature end the leads are connected to busses that go to the converter. The heat conducted from room temperature to the coil is absorbed in a helium bath at 4.4 K.

The power demand, the timing of the three phases on the ac system, and the current in the conductor (or equivalently the stored energy in the coil) are used by the controller to calculate the firing angle for the SCR firing circuit. This in turn controls the direction and magnitude of the power flow through the converter.

The current in the superconducting coil will be on the order of 100kA. Power systems normally operate at much lower current levels so a transformer is needed to convert the high voltage and low current of the ac system to the low voltage and high current required by the coil. The individual semiconductor elements can only carry a few thousand amperes so many must be used in parallel.

The superconducting coil, as seen through the converter, appears as a reactive load to the ac system. The reactive power created in the system is canceled by the reactive power compensation system that is in essence a variable capacitance. More recent developments of GTOs suggest that full reactive power control can be achieved. However, GTO-based converters may not be as efficient as those using SCRs.

<u>Superconductor and Coil</u>

The superconductor will likely be a Nb-Ti/copper composite stabilized by high purity aluminum. The copper serves several purposes. First, it provides a matrix that mechanically supports and separates the individual filaments of Nb-Ti, which in the final conductor are tens of microns in diameter. Second, because of its high resistivity relative to the superconductor, it electrically isolates the Nb-Ti filaments by providing a resistive barrier that reduces losses during charge and discharge. Third, the copper can stabilize the superconductor by conducting current during short periods when the superconductor undergoes a transition to the normal state. The composite conductor is formed of long strands of this conductor and the aluminum stabilizer. The individual strands can be spliced so that conductor and system performance are not degraded by finite conductor length. The total conductor cost is minimized by grading the quantity of superconductor in the cable to have the superconductor in all parts of the magnet operate near the critical current. The usual Nb-46.5% Ti conductor may be replaced by a 50-55% Ti alloy that can maintain a higher current density at low fields and low temperatures. The critical current used to estimate costs below is 7000A/mm^2 at 1.8K and 5T. The grading is adjusted so that the conductor operates at about 90% of critical current in the local field.

The cross sections of high purity aluminum in the conductor and the heat absorbing "enthalpy" material are determined by a local voltage requirement and a limit on temperature rise in case of an emergency internal energy dump.[54-58] The issue of coil safety and protection cannot be discussed in detail here. However, any viable design must assure the safe energy conversion from magnetic field to heat in the structure. This requires removing helium and spreading the normal region.

As anyone who works with electrical wiring knows, aluminum and copper are not metallurgically compatible, which suggests that one or the other be used but not both. However, there is considerable recent experience with aluminum stabilized conductors. Aluminum of high purity has a low temperature resistivity about one tenth that of good copper, its resistance is less affected by the magnetic field, and it is less expensive; thus aluminum may be preferred for the major part of the stabilizer. In the event of a quench the safety of the unit will depend on having a large fraction of the coil normal in a very short time to limit voltages and to reduce temperature variations. The addition of massive amounts of stabilizer and enthalpic material to the conductor reduces the quench propagation velocity. Thus some method is generally needed to accelerate the quench or to cause multiple normal regions.

In most designs, the conductor and the supports that transmit the forces between turns and to the cryostat wall are submerged in liquid helium at about 1.8 K. This bath removes heat from the conductor and carries it to the refrigerator via a set of heat exchangers. The choice of 1.8 K as an operating temperature is based on a trade off between several factors. As the temperature decreases, current density increases, refrigeration costs - capital and operating - increase, enthalpy to the lambda point increases, and the heat transfer/thermal conductivity has a maximum near 1.8 K. The low cost of refrigeration relative to the superconductor generally suggests operating in the 1.7 to 2.0 K range.

Dewar and Structure

The dewar and the structure that supports the windings and transmits forces to the rock are designed together to form an integrated system in which the structural components support multiple loads. The Lorentz force has a net radial outward component and an axial component that is symmetrical about the vertical centerline. Though these are the major forces, the weight of the magnet must be supported at the bottom by struts that can accommodate the thermal contractions of cooldown. In addition, there is the force of the atmosphere on the vacuum vessel and the internal pressure of the helium on the helium vessel. The struts proposed use a cryogenic grade glass-fiber reinforced epoxy (G-10CR) and may be graded in thickness to take advantage of increased strength at low temperature.

Two vessels are generally required. First, an outer vacuum vessel, most likely made of a seam-welded aluminum sheet, will enclose the coil, helium vessel and the support structures. Care must be taken to assure that welds are centered between supports in the most accessible region where the maximum deflection occurs. The aluminum material may have to be thickened in the weld areas to compensate for reduced strength due to heating during the welding process. The difference in pressure across the aluminum, causes the aluminum to deflect. The amount of deflection allowed and the support spacing are chosen to reduce the amount of aluminum required in the wall and to minimize cost.

In a full scale device with a helium vessel, the fabrication of the cryostat may be sequenced with the coil winding process. The vacuum vessel, the support struts, and the outside wall of the helium vessel are fabricated in place in the excavated tunnel. The coil is then wound onto the inside of the outside wall of the helium vessel. After each segment of the coil is completed the inside wall of the helium vessel for that segment is fabricated in place and the helium vessel is sealed. Because of the possibility of extensive winding time several segments can be assembled simultaneously. The final stage of assembly is the installation of axial supports between the helium vessel and the inside wall of the vacuum vessel. For a coil with cable in a conduit conductor there is no helium vessel so the assembly process is simpler and faster, but the tube connections for liquid helium and for heat removal and cooldown may be complicated.

Tunnel and Excavation

At present a device near the surface and in mild rock is preferred[44]. Generally this will require trenching rather than tunneling and the coil/cryostat assembly will be constructed inside this trench. The time required for trenching and site preparation will be two to three years. Some recent estimates show that very weak rock, maybe even alluvium, will be acceptable for the construction. This will considerably expand the range of potential sites and increase the likelihood of application.

Cryogenic System

In most systems proposed the coil operates in a 1.8 K helium bath at atmospheric pressure. Sub 4.2 K operation is chosen because the current density possible in the superconductor is higher at lower temperatures. As discussed above, 1.8 K and atmospheric pressure are chosen because of the maximum in heat transfer and thermal conductivity of HeII. This condition is maintained by means of a heat exchanger between the subcooled superfluid helium and a HeII bath at the equilibrium vapor pressure of about 12.5 torr. In addition, a high thermal resistance fluid path is needed between the coolant bath and a 4.2 K helium bath. This technique of producing a non-equilibrium cooling bath was developed by Claudet et al.[59] and is now widely used in low temperature experimental facilities[60-61]. The working fluid in this system is helium, which is completely sealed so that no air enters the system and so that little helium is lost.

In addition to maintaining the coil at 1.8 K, the cryogenic system provides coolant at several intermediate temperatures. The first is a bath at about 4.5 K that maintains a constant pressure in the 1.8 K bath and intercepts any heat flow through the power leads that carry current from ambient temperature to the coil. The choice of current has a significant impact on the 4.5 K heat load. Reducing the current, in particular on small devices can have a major impact here. In addition, heat that travels along the support struts is removed at intermediate temperatures by helium gas at high pressure.

The compressor and other moving parts of the cryogenic system must be as close to the coil as possible to improve efficiency and reduce cost. At the same time this equipment must be in a low magnetic field. It appears that the best option is to have this equipment at fields less than 200 G, where limited personnel access may be possible, and to shield the equipment if necessary to have it perform effectively.

Power Conditioning System

The electrical interface between the superconducting magnet and the electric power system is a converter as shown in Fig. 3. The converter is an ac to dc rectifier and dc to ac inverter that changes the alternating current from the utility into the direct current that must flow continuously in the coil.[62-64] To charge or discharge, the voltage across the coil is made positive or negative. When the unit is on standby, independent of storage level, the current is constant and the average voltage across the superconducting winding is zero. The possibility of a persistent mode switch has been discussed, as there are losses in the converter in the idle condition. However, the need by the utility for rapid response of the SMES plant will likely be more important than the losses.

The basic 3-phase bridge consists of 6 thyristors (SCRs) or 6 GTOs, which are controlled by a firing circuit. (We describe here the operation of this simple circuit; the actual converter will be much more complicated and contain multiple bridges.) Voltage pulses from the firing circuits cause the SCRs to conduct. The voltage pulses cause each SCR to begin conducting at a prescribed time and sequence in the 16 ms cycle to maintain the desired average voltage across the coil. By changing the relative phase, of this pulse through a range of 0 to 180°, the voltage across the coil can be made to vary from its maximum positive value to the maximum negative value.

The average voltage is given by

$$V = V_0 \cos \alpha.$$

The maximum and minimum values of α are controlled by the characteristics of the thyristors and the design of the circuit. Generally the limits are about 5° to 165°, instead of 0° to 180°. This restriction does not cause any practical limitation on charging and discharging the coil or on the power during charge and discharge.

The 6-pulse bridge, which is the simplest possible for a 3-phase system, produces harmonics on the ac bus and in the output voltage to the coil and causes a phase shift of current and voltage on the ac bus, thus introducing reactive power. Neither harmonics nor reactive power are desirable. Both must be reduced or eliminated by the addition of filters or by increasing the complexity of the converter.

The harmonics that appear across the coil also appear on the ac side of the bridge and will propagate into the ac system if no damping is provided. Generally, large scale converters such as those now used on dc transmission lines have filters on the ac side that remove a large fraction of the unwanted harmonics. By using GTOs these can be reduced further, and by using two or more 6-pulse bridges that fire in different sequences, the reactive power can be reduced. Because the gate turn off devices are more complicated components a given silicon wafer size will carry less current than if it were mode into an SCR. Thus, more GTO's, which are more expensive per unit, will be required than SCR's. In addition, the circuitry needed to make a GTO converter work properly also impacts the overall efficiency of the ac-dc conversion process. Thus a SMES plant with GTO's may be 88% efficient whereas one with SCR's would be 92% efficient, for example. Further analysis is needed in this area.

The response of the control and firing circuits to a new demand signal are so rapid that a new firing angle may be chosen for the very next SCR to be pulsed, say within a few milliseconds. This rapid response to power demands that may vary by hundreds of megawatts is a unique capability of SMES relative to other energy storage systems such as pumped hydro and compressed air. Though an almost similar capability is possible with batteries, they are essentially constant voltage devices whereas the SMES unit is constant current. The response time of the SMES is generally better. Note also that to reverse power on a battery the current must be reversed. This ability to respond quickly allows the SMES unit not only to function as an energy storage unit, but also to act as spinning reserve and even to provide stability in case of disturbances on the utility system.

SMES SYSTEM COSTS

The costs of a SMES system can be separated into two rather independent components. One is related to the energy storage capacity, the other to the power capacity. As mentioned earlier, the cost of a SMES plant will depend on the size -storage capacity- with larger units being more economical. We use here a reference plant with 5,000 MWhr storage capacity and 1000MW power capacity. This implies the nameplate rating would be 1,000MW for 5 hours. The costs of this reference unit have been determined by several groups, some of them more than once. Here the Bechtel work in reference 44 is used as a basis.

Each of the major components described in the previous section have an associated cost. Because the storage capacity of the plant and the power capacity are to a certain degree independent the costs of these items can be considered separately. The actual cost of the conductor assembly will depend on the unit cost of materials at the time of construction and on the cost of labor at the site. The values here are a few years old and it is clear the costs of certain components have changed considerably since that time. For example aluminum costs have increased much faster than those of copper or Nb-Ti alloy. Nevertheless, we can look into the costs of each major component. These are summarized in Table II, which also includes the possible impact of high critical temperature materials on SMES, as described below. The conductor assembly has Nb-Ti, Cu, high purity Al, and high strength Al; it must be partially assembled at the factory (generally factory work is less expensive and more efficient than field work), then delivered to the site for final assembly. This includes welding, introducing a ripple if included in the design, etc. To accomplish this a special train car with conductor components moves around the site at ground level and lays the cable into the trench.

TABLE II

A Comparison of 5000 MWhr SMES Plant Costs for Different Supercondutor Characteristicsd and Costs
(Millions of Dollars)

Operating Temperature (K)	1.8 K	77 K	77 K	77 K
Material	Nb-Ti	HTSC	HTSC	HTSC
J_{op} (Base = 7000 A/mm^2)	Base	1000 A/mm^2	Base	Base
Cost (Base = Nb-Ti at 1.8 K)	Base	Base	$22/kg	Base
Storage Related Costs:				
Conductor	121.0	443.2	75.2	121.0
Coil Structure Components	196.9	196.9	196.9	196.9
Radial and Gravity Supports	14.4	5.0	5.0	5.0
Cryogenic Vessel	2.7	2.0	2.0	2.0
Thermal Shields	12.4	4.7	4.7	4.7
Coil Protective System	16.1	15.0	15.0	15.0
Vacuum Enclosure	21.3	15.5	15.5	15.5
Refrigeration System	16.3	6.3	6.3	6.3
Vacuum Pumping System	1.4	1.4	1.4	1.4
Control Room Equipment	2.0	2.0	2.0	2.0
Other Items	3.1	3.1	3.1	3.1
Subtotal	407.6	695.1	327.1	372.9
Power Related Costs:				
Power Conditioning System	68.3	65.0	65.0	65.0
Switchyard	10.6	10.6	10.6	10.6
Subtotal	78.9	75.6	75.6	75.6
Total Capital	486.5	770.7	402.7	448.5
Construction - Storage Related	93.7	159.8	75.2	85.7
Construction - Power Related	24.4	23.3	23.3	23.3
Indirect - Storage Related	21.2	36.2	17.0	19.4
Indirect - Power Related	7.8	7.5	7.5	7.5
Total Construction	633.6	997.5	525.7	584.4
Facilities and Engineering	38.6	49.7	35.3	37.1
Contingency	156.4	201.1	143.1	150.3
AFUDC	88.0	113.3	80.5	84.6
Other	42.3	27.3	27.3	27.3
Total	958.9	1388.9	811.9	883.7
Relative Cost (%)	100	145	85	92

The total direct capital costs of the conductor and the coil related structural components is $315.9M. The costs for other storage related items in this design amounted to only $91.7M. More recent design effort have led to a reduction of the fraction of the total costs related the coil and conductor.

The total direct capital cost of the power conditioning system, including a switchyard for the incoming ac power, is $78.9M. If a larger power capacity were required to accommodate a spinning reserve requirement for example, it would be possible to increase the power capacity with little or no impact on the storage related costs. With contingency etc., the power related costs are about $125/kW. The value of spinning reserve and other credits could be as high as $250/kW. Thus the addition of power capacity might well be considered by any utility purchasing such a device.

The total estimated cost to construct is $633.6M. In addition there are engineering costs, contingency-those costs that are expected but not known in detail-, interest during construction on the costs already incurred, and other miscellaneous costs. These raise the total to $958.9M.

This cost is less than a coal fired power plant of the same capacity, but more than an equivalent pumped hydro storage plant. Several comparisons with other systems have been made and the general result is that SMES will be marginally competitive with pumped hydro. There is an assumption required to arrive at this conclusion. It is that there are sites available for both. In fact, there are few remaining sites where pumped hydro can be installed. Also there are siting issues for the SMES plant due to the stray magnetic field.

POSSIBLE IMPACT OF HIGH CRITICAL TEMPERATURE SUPERCONDUCTORS ON SMES

If effective HTSC materials are developed then both the design and the cost of a SMES plant will be affected. Based on several assumptions regarding the performance of these materials, and using the 1.8 K system described above as a benchmark, one can ask how the design would change if HTSCs were available. Several interrelated technical factors need to be considered. These are summarized in Table III.

TABLE III

ISSUES IN THE USE OF HIGH TEMPERATURE SUPERCONDUCTORS FOR SMES

Item	Consideration
Operating Temperature	Determines Cryogen, J_c, and H_c.
Current Density	Affects quantity of material required.
Stability	Determined by material characteristics and operating conditions.
Safety/Reliability	Ability of the system to absorb all the stored energy without damage to the plant.
Strut Characteristics	Strength of the structure and material requirements.
Friction	Forces that hold the assembly together and cause motion leading to quenches.
Stress/Strain	The existing SMES design allows a conductor cyclic strain of about 0.4%.

The operating temperature chosen for a superconducting device is a compromise based on achieving the lowest cost while meeting operational requirements. This is accomplished with a good engineering understanding of the materials and subsystems. It has been suggested[65] that a "rule of thumb" exists for operating a superconductor at 75% of T_c. In fact rules of thumb are generally based on engineering practice, and are usually applicable over a small range of variables.

A strong argument can also be made for operating in liquid nitrogen if the materials allow it. If this selection is made, then, the heat of vaporization of the nitrogen also provides considerable enthalpy, and thus increases stability. It also reduces the propagation velocity of a quench, should the coil go normal, and increases the energy required to heat the conductor into a normal state in the case of an energy dump. Both of these can have a very negative affect on the safety of the plant. An option that should be reconsidered for the HTSCs, at least for large magnets, is to use indirect cooling and forced flow. Properly selecting the operating temperature and isolation from the liquid nitrogen may simplify the safety and protection systems and still provide a reasonable operating margin.

Once the storage capacity of a coil of a given geometry and peak field is selected, the quantity of superconductor measured in Ampere meters (usually kAm) remains the same independent of current or operating temperature. The volume of superconductor on the other hand depends not only on the application but also on Jc and whether it is possible to "grade" the superconductor, i.e. use less in regions where the magnetic field is less.

The total volume of superconductor thus depends on the quantity Q_{sc} in kAm required by the design and the working current density J_{op}

$$V = Q_{sc}/J_{op}.$$

The total cost of superconductor in an application is the sum of the raw material and the fabrication costs. For the ductile conductor alloy Nb-Ti these costs are about equal. In Nb_3Sn, which is a brittle compound, the costs of conductor fabrication and the additional costs of coil fabrication and assembly to accommodate the brittle nature of the material and the extra costs of high temperature processing are much higher than the cost of the material. As a result, the use of Nb_3Sn has been minimal in large scale applications. A comparison for accelerator magnets used a factor of 1.25 for the relative fabrication cost of Nb_3Sn vs. Nb-Ti magnets[66].

The question that must eventually be addressed is how to incorporate a material with low ductility into a design that naturally subjects the materials to extensive cyclic strain? However, should the high T_c materials ever meet current density requirements and the strain limits be studied and understood, it should be possible to adjust the design to accommodate them.

Two easily applied assumptions will be made regarding the current density in the HTSCs. The first is that the new materials can be substituted directly for Nb-Ti at the chosen operating temperature, with an operating current density of 7000 A/mm^2. The second is that the critical current density at 77 K will reach the goal proposed by the National Academy[65], 1000 A/mm^2. These two assumptions will have a major impact on SMES costs.

The DOE has established some cost guidelines for the HTSC's[67], and the National Academy[65] in its evaluation used another. Three scenarios are considered here: first, the cost and performance of coil and conductor, materials and fabrication, are projected to be equal to that of Nb-Ti; second, the current density of the high T_c materials is assumed to be 1000 A/mm^2 and the costs equal to those of Nb-Ti; and third, the current density is assumed to be that of Nb-Ti, 7000 A/mm^2, and the cost a low, $22/kg.

The costs of the "mechanical" components of the SMES plant operating at high temperature will change somewhat from those for a 1.8 K plant, but the total impact on system costs will be small. The struts that transmit the load from 1.8 K to ambient temperature have been optimized with two intermediate thermal intercepts. One of these is at about 77 K. As a conservative estimate we set the strut length and material requirements equal to the segment of the original strut that spans from 77 K to room temperature. This estimate allows a narrower cryostat and trench and the strut has a larger cross section than is needed, as the buckling limit is less and no intermediate heat shields are required. However, the brittle nature of the superconductor may require a smaller strut spacing, so this should be a reasonable estimate.

The cryostat can be changed considerably as it may be possible to insulate it with a type of styrofoam or perlite, so the heat shields and much of the multilayer thermal insulation can be eliminated. If a gas could be used in the space between vessels the structural requirements could also be reduced. Whereas much of the heat is removed at 77 K in the conventional SMES unit, all the heat load will be removed at this temperature in a HTSC unit. The effect on the load at 77 K is minimal, but the effect on room temperature power is very large.

The cost of the struts for a 77 K system will scale from those for a 4 K system based on the length to the 77 K intercept point. For the 5000 MWhr design this was 0.66 m out of a total length of 2.0 m, so the struts will cost about one-third as much. Eventually this length will have to be optimized with the cost of materials, trench width, and refrigeration included in the analysis. The original trench was about 5 m wide. Theoretically, it would be possible to have a 2 m wide trench, but access requirements will probably set the minimum width at about 3 m.

The cost of the refrigerator depends on the room temperature power requirement more than any other factor. The costs of the refrigerator are scaled from the 1.8 K, 5000 MWhr plant based on the power ratio raised to the 0.75 power.

There are two ways to consider the energy required to operate the refrigerators. The first is to attribute it to an operational cost, and the second is to take a penalty in the efficiency of the plant. The final choice between these for an operating SMES plant will be made by the utility and may be different in operation from that used during the proposal and design stage. Here we assess the refrigeration cost as an increment on the efficiency. The remainder of the operational costs will be reduced by some fraction because of the decrease in refrigeration power requirement. Other operating costs will remain essentially unchanged.

Cost comparisons based on the above discussion are given in Table II. The savings that can be expected for the case of direct replacement, which I believe to be the fairest, though still very optimistic comparison, shows a potential decrease of about 8% in cost for the plant. Considering that SMES is now marginally competitive this would improve its chances for use, but would not make it a certainty. If in fact the superconductor does cost less in the fabricated state then a considerably larger savings can be realized. If, on the other hand, the critical current density cannot be improved to match that of Nb-Ti at 1.8 K then the high critical temperature materials are not likely to see significant application on SMES.

One potential advantage of the use of HTSCs is the possibility of decreasing the unit cost of smaller plants. As mentioned above, the amount of superconductor and the cryostat materials scale as the $E^{2/3}$ for large sizes. This is to be compared to most systems that scale directly as the stored energy. As a result, the decreasing unit costs of SMES will drop below those of other systems as the sizes get sufficiently large. By reducing the unit cost of the SMES plant, the effect of the HTSCs will be to move the crossover to smaller plant capacities as shown in Fig. 2. Another possible area of application could be to reduce the losses associated with the power leads.

In assessing SMES and other potential applications, it is worth noting that the HTSCs will have the most significant impact on technologies in which the refrigerators are a major part of the capital cost and/or where refrigeration power/operating costs are high.

The Present ETM Program

Near the end of the Bechtel studies it became apparent that in addition to the utility requirements for stored energy there was a military need for very high power, repetitive pulsed energy sources for a nmber of advanced weapons systems.[68,69] The same type of evaluation that shows the relative advantages of SMES for electric utility use shows similar advantages for these new applications. In particular, since the power requirement may be very high and last only about 30 minutes, the arguments for spinning reserve apply.

The really interesting blend is to consider a unit that can meet the diurnal storage needs of both the electric utilities and the pulsed power requirements of the Strategic Defense Initiative.

Consider the 5000 MWhr unit described above. It could be installed as a working plant on a utility grid and satisfy the diurnal energy storage requirements, provide system stability and spinning reserve. Operating on a day-to-day basis it could be dispatched by the local utility to provide the most economical operation. With very slight modifications to the power conditioning system it could also be made to connect to, or be switched to, some firm of pulsed energy weapon such as a ground based laser (GBL). The requirements for a GBL are not fully understood at present, but could be on the order of 2000MW for a half hour. Having additional power capacity on the plant would increase the operating voltage but would not require any major plant design changes,.except for those in the PCS itself. Depending on various issues it might be necessary to separate the converter into two units, one for the utility and the other for SDI. The stored energy in the plant would always be maintained above a certain level to maintain readiness of the power source for the GBL.

Knowing that such an options might be possible, and perhaps even the best solution to a joint problem, in 1987 the SDIO, with EPRI as a collaborator, started a program to develop an Engineering Test Model. EPRI had already outlined a plan[47] to design and build an ETM over a 5 or 6 year period and was exploring funding alternatives. The timetable for the SDIO was much shorter, with a goal of construction within a 3 year period after project initiation.

The request for proposals for this program was issued by the Defense Nuclear Agency DNA on behalf of the SDIO in June of 1987 and two teams, one led by Bechtel and the other by Ebasco, responded. Both are involved in the design of independent ETM devices with somewhat different approaches to the various technical issues. Two sessions at this conference are devoted to the work of these two teams. Some detail, of their work is reported there.

The management of the effort is by several levels of review teams that consist of representatives from the government and EPRI. Each team is to select a preferred site and to design their system to operate either at this site or at White Sands, the site the first military application. The site selection is needed early due to the requirement for an environmental impact evaluation.

The program is to be completed in a total of about 4 years and is expected to cost upwards of $150M. This will cover the costs of the development work by the two teams during the "horserace" phase and the construction of one ETM unit with storage capacity in the range 10-30 MWhr.

CONCLUSION

SMES appears to marginally competitive with other storage technologies and is likely to remain so. There is a large market for additional energy storage capacity in the U.S. Some 25,000 MW would be possible if a sufficiently cheap yet reliable plant was developed. The SMES ETM program in progress may lead to the construction of a model that will prove the principles so that utilities will begin to install SMES plants early in the 21st century.

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