An Assessment of High-Temperature Superconductors for High-Field SMES Systems

TR-110719

Final Report, December 1999

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REPORT SUMMARY

This study evaluated superconducting magnetic energy storage (SMES) systems made of different high temperature superconductor (HTS) materials. The research addressed a broad range of practical issues associated with building a high-field HTS SMES system.

Background
A number of groups around the world have investigated the concept of using high temperature superconductors for SMES. Early HTS material performance in the magnetic fields required for SMES magnets suggested that they were not viable materials for this application. Fortunately, HTS materials have improved significantly in the past two years. Generation I materials are commercially available today in kilometer lengths and are already used for several applications. Generation II materials have much better intrinsic performance, but they are still in the early stages of development.

Objective
To evaluate and compare costs and complexities of SMES systems made of different HTS superconducting materials.

Approach
The project team based its approach on knowledge of previous SMES system analyses, which allowed assumptions to be made that simplified the current investigation. Following a stepwise approach, team members

1. evaluated previous studies of HTS SMES and used those results to guide study developments.
2. evaluated performance of HTS materials and established a set of design criteria for different operating conditions for each material.
3. developed costs of HTS conductors from known material costs and from projected labor costs based on large-scale conductor production.
4. determined or estimated material and fabrication costs for HTS conductors.
5. established conceptual designs of SMES systems (solenoids and toroids).
6. calculated SMES system costs based on material capabilities.

Results
Based on the relative costs of different SMES systems, the study identified Generation II materials as likely candidates for the lowest priced, future HTS SMES systems. The study further predicted significant cost reductions over present costs for low temperature superconductor

(LTS) SMES, if performance and cost assumptions for the HTS Generation II conductors prove attainable. The study cited, among other factors, material costs, operating temperature range, and use in a variety of other applications as major strengths for Generation II materials. SMES systems made of Generation I materials can become competitive with LTS-based SMES systems if fabrication costs can be reduced or silver content reducedThe study made 15 suggestions for additional efforts to develop HTS based systems. These recommendations related to either system parameters or to HTS technology improvements.

EPRI Perspective

Two factors provided the major impetus for this study of high-field HTS SMES: (1) recent improvements in HTS material that will allow construction of practical HTS magnet systems, and (2) the higher the magnetic field, the smaller the footprint of the SMES coil. Further, these factors combine in a multiplicative fashion because high magnetic fields have a smaller impact on the current carrying capabilities of HTS materials than on those of the frequently used LTS material Nb-Ti. Thus, the amount of superconductor required for HTS magnets does not increase rapidly with operating field. The results of this study hold out the promise that practical, high-field SMES devices using HTS superconductors are achievable and that economic applications for high power SMES (such as FACTS devices) could become reality within a few years. These promises should provide strong motivation to pursue the necessary development of conductors and cables for high-field applications.

TR-110719

Keywords

Superconductivity
Superconducting magnetic energy storage
High temperature superconductors
Energy storage
FACTS

EXECUTIVE SUMMARY

S-1 Rationale

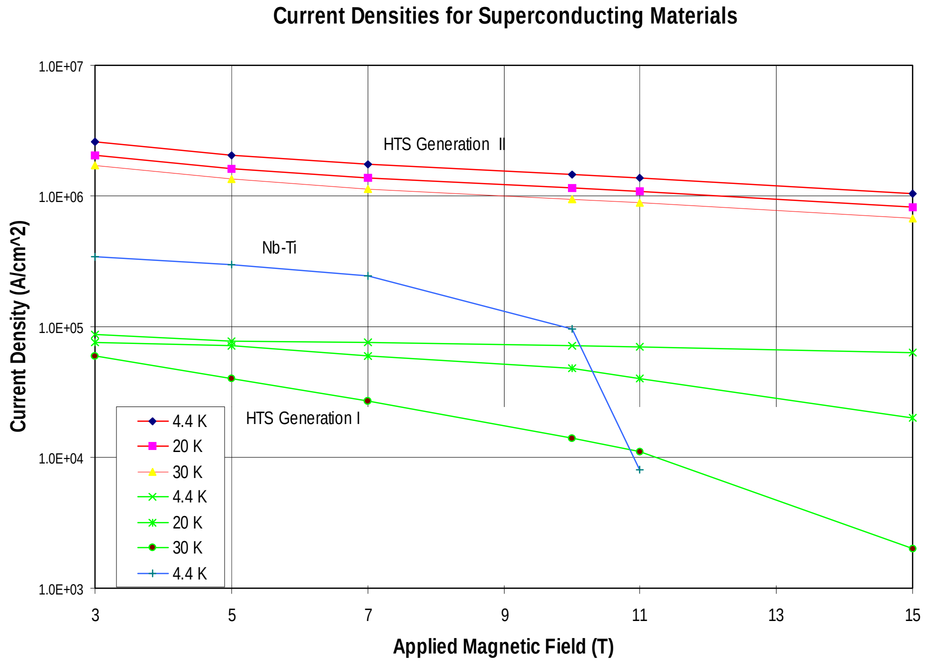
The concept of using high temperature superconductors (HTS) for SMES has been investigated by a number of groups around the world. The earliest studies were carried out within a year after this type of superconductor was discovered. They were based on large SMES systems, with cost and operating characteristics scaled from the known performance of low-temperature SMES systems under development at the time. However, the performance of the early HTS materials in the magnetic fields required for SMES magnets suggested that they were not viable materials for this application.

Fortunately, HTS materials have improved significantly in the past two years. In particular, they perform very well at fields above 10 T, even at intermediate temperatures well above the boiling point of helium, e.g., between 10 and 30 K. This can be seen in Figure 1, which compares the current densities (A/cm^2) in HTS and conventional superconductors. Two different types of HTS materials are shown. The Generation I materials are commercially available today in kilometer lengths and are already used for several applications. The Generation II materials have much better intrinsic performance, but they are still in the early stages of development. Gen II materials also require more companion materials to form a conductor. As a result, their engineering current density is not as much improved as the intrinsic current densities shown in Figure 1 would make it appear.

Two factors provided the major impetus for study of high-field HTS SMES described in this report.

- The recent improvement in HTS material will allow the construction of practical HTS magnet systems.
- The higher the magnetic field, the smaller the footprint of the SMES coil, as shown in Figure 2.

Further, these factors combine in a multiplicative fashion because high magnetic fields have a smaller impact on the current carrying capabilities of HTS materials than on those of the frequently used LTS material Nb-Ti. Thus, the amount of superconductor required for HTS magnets does not increase rapidly with operating field.



Note that the low packing factor for Generation II materials causes the practical engineering current densities to decrease by a factor of 4 to 5, rather than a factor of 2 for the other materials

Figure 1
Current densities for HTS and LTS materials

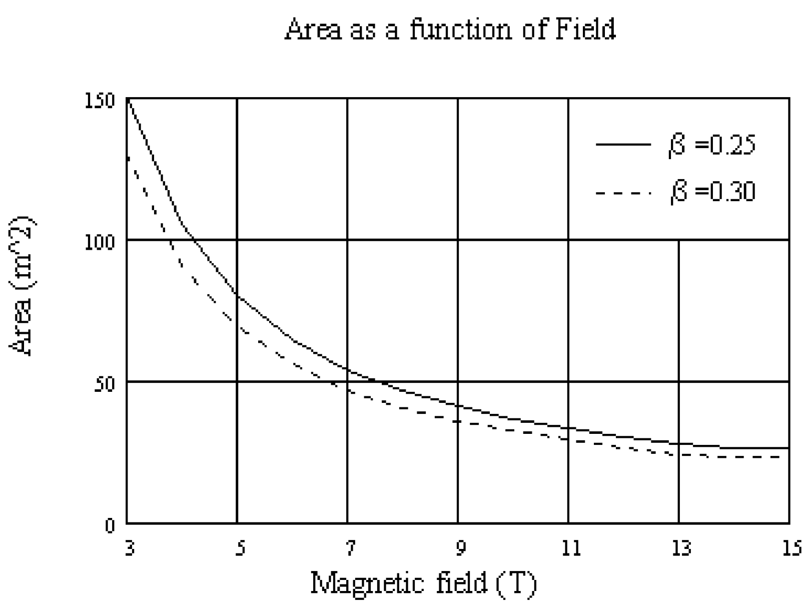


Figure 2
Relation between coil footprint and maximum magnetic field for a toroidal 1500 MJ SMES coil

S-2 Goals

The goals of this study of high-field HTS SMES were to evaluate and compare the costs and complexities of SMES systems made of HTS superconducting materials. The emphasis in the study was on high-fields and on temperatures well above the temperature of boiling helium, nominally 4 K or 4 degrees above absolute zero. The combination of smaller devices and reduced refrigeration loads were expected to lead to lower system costs. Cost estimates are based on existing performance and cost for the Generation I materials and on projected material improvements and large-scale production for the Generation II materials. The scope of the effort was extended during the study to include LTS-based SMES systems and to compare HTS and LTS SMES system costs.

S-3 Approach

Several procedures could have been used to study SMES systems made of HTS materials. The path chosen for this work was to address a broad range of practical issues associated with building a high-field HTS SMES system. The approach followed was based on a knowledge of previous analyses of SMES systems. Experience from those efforts allowed assumptions that simplified the analysis. For example, the combination of current and voltage for the various applications were based on the results of previous studies of low-temperature SMES systems. Certain choices were made early in the program. The first was to select three potential energy storage applications with different power and stored energy capacities. Theses applications and device capabilities are given in Table 1.

Table 1
SMES Coil Design Parameters for HTS Comparison

Parameter	Case 1	Case 2	Case 3	Case 4
Stored Energy	4 MJ	100 MJ	1500 MJ	1500 MJ
Power level	2 MW	50 MW	100 MW	100 MW
Configuration	solenoid	solenoid	solenoid	toroid
Aspect ratio *	.25	.25	.25	.55
Operating field	3-15 T	3-15 T	3-15 T	3-15 T
Conductor shape	cable	cable	cable	cabled tape
Duty Cycle	2-4 cycles/month	1 cycle/month	5 cycles per event one event per month	5 cycles per event, one event per month

*The value given here were the initial aspect ratio used for system optimization.

The second choice relates to system costs. The resources available to the study limited the scope to an evaluation of cost differences among the systems based on the various conductors. A bottoms-up cost estimate was made for the Generation II materials because, at their early stage of development, no reliable cost data are available. To the extent that projected costs are available for LTS SMES systems, they are used as a basis for HTS SMES system cost estimates.

The third choice was to exclude the power conditioning system from the system costs. The rationale for this decision was primarily that the cost and performance of the PCS is not likely to depend on the differences encountered in the SMES systems studied here.

This study followed a stepwise approach that is summarized below.

1. Previous studies of HTS SMES were evaluated and results were used to guide the developments in this study.

2. Performance of HTS materials were evaluated and a set of design criteria for different operating conditions were established for each material.

3. Costs of HTS conductors were developed from known material costs and from projected labor costs based on large-scale production of the conductors.

4. Material and fabrication costs were determined or estimated for HTS conductors.

5. Conceptual designs of SMES systems (solenoids and toroids) were established and were programmed using Mathcad® software.

6. SMES system costs were calculated based on material capabilities. The following sub-elements were estimated in developing the system cost.

   a. Superconducting material
   b. Normal conductor and superconductor support
   c. Coil fabrication
   d. Structure
   e. Cryostat
   f. Fabrication and assembly
   g. Refrigerator
   h. Miscellaneous components

S-4 Results and Conclusions

Figures 3 and 4 provide a great deal of insight into the relative costs of different SMES systems. They support the following conclusions.

1. The cost of SMES systems made of Gen II conductors is predicted to eventually reach 50 to 70% of the cost of LTS based SMES systems.

2. As a result, if practical conductors can be made of the Generation II materials, it will be an ideal material for HTS SMES as well as a variety of other applications.

3. The results indicated that the lowest priced SMES systems will be made of Generation II materials and will operate at temperatures of 30 K (or higher).

4. Because of their higher operating temperature these systems will also have the lowest operating costs. (Operating costs were beyond the scope of this study.)

5. SMES systems made of Generation I materials can become competitive with LTS based SMES systems if fabrication costs can be reduced or silver content reduced.

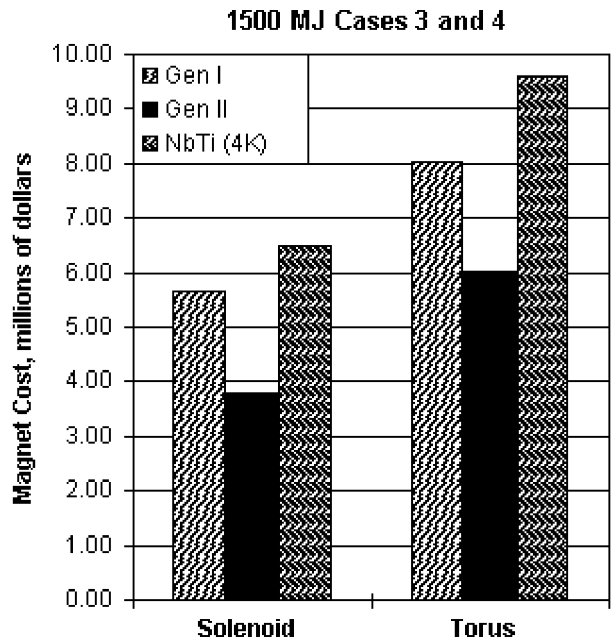


Figure 3
Cost comparison for 1500 MJ SMES systems—Cases 3 and 4 in this study

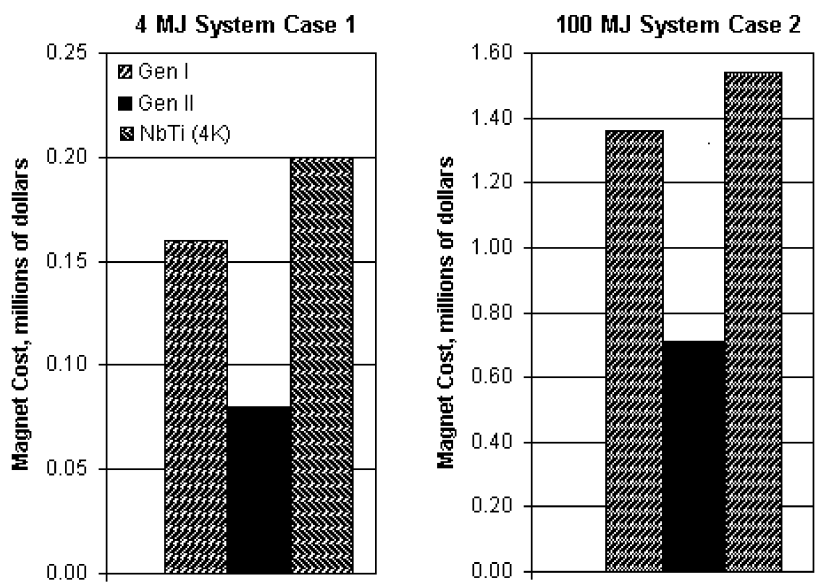


Figure 4
Cost comparison for 4 and 100 MJ SMES systems—Cases 1 and 2

S-5 Recommendations for further work

As a result of this study, the following suggestions are made for additional effort to develop HTS based systems. These recommendations relate to either system parameters or to HTS technology improvements.

Programmatic—system or application related

1. Develop SMES system costs as a function of temperature to determine the minimum capital cost system.

2. Develop SMES system costs for fields higher than 15 T, where applicable.

3. Explore cost details of Generation I and Generation II conductor fabrication.

4. Estimate operating costs of the SMES systems at different temperatures and develop a total life-cycle cost based on expected lifetime and performance. This should include operation of the refrigerator, PCS, maintenance, etc.

5. Assess the impact of device size and footprint—depends on allowable magnetic field—on value and potential market.

6. Carry out a sensitivity study of the cost of HTS SMES systems should some of the improvements listed below come to pass. This effort will establish priorities for further developmental work.

7. Carry out a complete evaluation of existing data on the effects of strain on HTS conductor performance. The effort should include both axial tension and transverse compression.

HTS Technology Advances

1. Evaluate existing approaches for conductor production and superconducting device requirements to determine the optimum form for HTS based conductors, e.g., cable in conduit conductors or multistrand tapes.

2. LTS wires are internally subdivided into thousands of filaments, which reduces hysteretic losses. In addition, independent current paths add stability and robustness to the system design. Various concepts should be explored to determine approaches that may provide similar subdivision in HTS materials.

3. Establish methods for sharing current among the different wires in the conductor and the different current paths in individual wires.

4. Develop conductor designs that incorporate a sufficient number of individually produced HTS conductors to carry 10,000 to 40,000 A.

5. The most expensive part of the Generation I material is the silver sheath. Alternative materials and methods for lowering the fraction of silver needs to be investigated.

6. Develop approaches for increasing the thickness of the YBCO layers in the Generation II conductors. Thicknesses of 1 μm are common today, but this needs to be increased by a factor of 5 or more to achieve the economics predicted in Figures 3 and 4.

7. There is little data on the performance of HTS materials at temperatures other than 4 and 77 K, and in self field. An effort to provide data at intermediate temperatures and at fields up to 20 T, and to have a facility available for the measurement of new materials would be a useful contribution to the development of future HTS conductors.

8. Carry out a sensitivity study of the cost of HTS SMES systems should some of the improvements listed above come to pass. This effort will establish priorities for further developmental work.

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1
INTRODUCTION

1.1 Background

Superconductivity was first discovered by Kammerlingh Onnes in Holland in 1911. [1] The first superconducting material was mercury, which was found to have zero electrical resistance near the temperature of liquid helium. The following three quarters of a century saw the discovery of many other low-temperature superconductors (LTS), a gradual improvement in performance, and the development of several technical applications. [2] In addition, a fundamental understanding was developed that described the mechanisms that allowed some materials to be superconducting. This effort suggested that some materials could be superconducting at room temperature or even higher. However, until 1986, the experimentally observed record temperature was 23 K. [3]

A new type of superconductor was discovered in the summer of 1986 by two researchers in Switzerland. [4] The material was crystalline and exhibited superconductivity at temperatures over 40 K, well above the previous record. During the following year a host of materials with other constituent elements [5, 6, 7], but having similar structure, were also found to exhibit superconducting characteristics at elevated temperatures. Some were superconductors above 100 K. [8] Since that time there has been considerable development of different materials and material-fabrication processes. Several books, journals, and proceedings of recent conferences describe these developments in great detail [2, 9, 10].

Perovskite is the class of materials that exhibit high-temperature superconductivity (HTS). The most familiar naturally occurring perovskite is mica. It is made of crystal layers that can be easily cleaved into sheets that have surface areas measured in square centimeters but with thicknesses as small as a few microns. Mica was used extensively in radio applications because it is a good insulator and it is relatively soft. The HTS superconductors have many physical characteristics similar to those of mica. At room temperature, they are insulators, they are very soft and can be fractured or compressed. As a result, the superconductors made of these materials are fabricated with a structural matrix, which provides support and often contributes to both fabrication and to operation.

The concept of using high temperature superconductors (HTS) for SMES has been investigated by several groups. Some studies were carried out within a year after their discovery. These studies were mostly based on previous estimates of very large SMES systems storing megawatt hours of energy. However, the projected production capabilities and the observed performance of the early HTS materials in the magnetic fields associated with SMES magnets suggested that they were not viable for this application.

Fortunately, the fabrication process and the performance of HTS materials have improved significantly in the past two years. In particular, they perform very well at magnetic fields greater than 10 T, even at intermediate temperatures well above the boiling point of helium, e.g., between 10 and 30 K. In addition, the need for smaller energy storage systems, e.g., for power quality has lead to the development of practical SMES systems that store a few megajoules of energy.

1.2 Recent HTS Development

Two HTS materials have become commercially available in wire form during the past few years. Both are fabricated via a powder-in-tube (PIT) process, [11] which begins with placing precursor powders of the materials in hollow silver tubes. The tubes are compacted to eliminate voids and drawn into a rod form. A large number of these rods are placed together in a larger silver tube and the entire assembly is drawn and/or rolled several times to obtain wires or tapes with dimensions of about 1 mm. The final size and shape depend on the material and the application.

Both of these HTS superconductors contain bismuth, strontium, calcium, copper, and oxygen. As a result they are referred to as BSCCO materials. The difference is the ratio of the different elements listed above, which is indicated by BSCCO-2212 and BSCCO-2223. These compounds require quite different processing procedures and have different ranges of application. Because they are the first HTS materials widely available for superconducting magnets they are often referred to as Generation I HTS superconductors (sometimes called Gen I materials).

In addition a separate material is under development that carries more current than the BSCCO materials, especially at temperatures above 20 K and when exposed to a magnetic field. This material is made of yttrium, barium copper and oxygen. It requires a different process for fabrication from that of the BSCCO materials. Though several approaches to fabrication of this material are possible, none are commercialized at this time. Because the material appears to be promising and there is considerable effort to produce it commercially today, it is referred to as Generation II (Gen II) material.

The status of the development of each of these materials including their physical characteristics costs are described in detail in Section 3.

1.3 Introduction to SMES Systems

1.3.1 SMES system Characteristics

A SMES system is composed of several components, as shown in Figure 1-1. The four major components are the superconducting coil, the cryostat, the refrigerator, and the power conditioning system (PCS), which connects the coil to the electric power system. The pcs may be thought of as the enabling technology in the recent development of SMES and other energy storage technologies that are under consideration today.

Several characteristic of the SMES system are notable.

1. SMES has the potential to be highly efficient in large-scale systems (as high as 95% for large diurnal applications).

2. The ability to change power levels in a fraction if a 60 Hz AC cycle is inherent in the design of the PCS.

3. SMES systems can operate at power levels that may discharge the entire system in one or a few seconds.

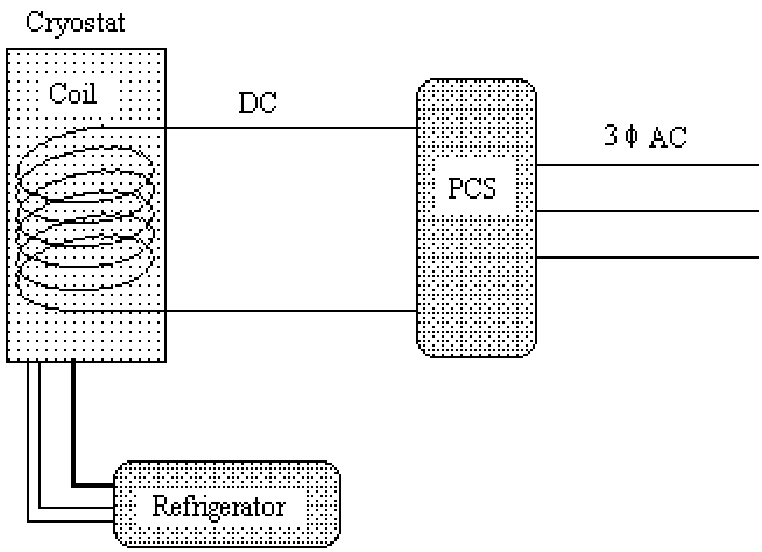

Figure 1-1
Block diagram of the principle components of a SMES system

1.3.2 History

The development of SMES can be traced to an early paper by Ferrier [12] that considered a single large diurnal energy storage coil for France. The coil was to be in the shaper of a torus, which contains essentially all the field within the toroidal shell formed by the superconductor. Only one unit would have been built and both capital and development costs appeared high so the idea was not pursued.

Studies of SMES in the U.S. began in 1971 and Peterson [13] suggested that a multiphase bridge should be the fundamental connection between an energy storage unit and an electric utility system. In 1972 the Las Alamos Scientific Laboratory outlined a development program for large-scale application of ht technology and developed costs for comparison with other energy storage systems. The effort suggested that, based on standard techniques for building superconducting magnet the structure required to contain the Lorentz (magnetic) forces would be sufficiently expensive to eliminate SMES from consideration for utility application. The economic advantage of a warm structure, such as “in situ” rock in place of cold structure [14] was discovered.

Through 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 quire valuable for accommodating rapid power swings and providing spinning reserve.

Late in 1976 a collaboration of Los Alamos and the Bonneville Power Administration 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. [15] A 30 MJ unit was constructed, installed at the Tacoma, WA substation and was tested on the electric power grid.

In the early 1980's EPRI and Los Alamos supported studies of the economics of SMES for diurnal energy storage, and in 1986 EPRI proposed that the next step in this technology should be the construction of an Engineering Test Model (ETM), which would store about 10 MWh. This proposal eventually lead to a joint effort by EPRI and the U.S. military to develop a dual-use ETM. The proposed system would supply energy to the electric utilities and would also supply pulsed power for directed energy weapons for the newly formed Strategic Defense Initiative Organization (SDIO).

Parallel to the effort of the ETM design, a new company, Superconductivity Inc., began to develop small SMES systems for power quality applications. As the use of computers increased and it became apparent that many processes needed continuous clean power, the beginning of the power-quality movement. Several of the SI units have been installed and tested at a variety of sites.

SMES has also been proposed as a system that can supply energy in short bursts for a variety of applications for the electric utilities. There are discussed in Section 2.

1.4 Summary of previous HTS SMES Studies

Several studies have addressed the concepts and economics of SMES systems based on high temperature superconductors. Eighteen such studies are described briefly in Appendix C. Many of these had some funding from EPRI.

Most of the previous studies focused on cost savings resulting from operation at higher temperature than conventional superconductors (i.e., NbTi at 1.8 to 4 K). These savings could be most significant for small systems where the refrigerator represents a significant fraction of the system cost.

In the absence of real performance or cost data for lengths of HTS wire, many of the studies either assume performance values, such a $/kA-m, or prices equivalent to those of conventional superconductors and then proceed with parametric studies. The common conclusions from these studies are:

1. The working critical current density needs to be at least 20,000 A/cm^2
2. The conductor cost needs to be less than 10 $/kA-m, , or equal to LTS cost on a $/volume basis.
3. The larger the system, the less significant the refrigerator savings by operating at higher temperatures.
4. Early systems will be small because of wire length limitations.

1.5 Outline

The body of this report consists of an introduction and six sections. Section 2 includes descriptions of the three different SMES sizes that are evaluated in this study and the rational for the choice of their operating power, voltage, and current. Because the largest size, 1,500 MJ of storage, will have an extensive external field if it exists as a solenoid, a fourth case, a 1,500 MJ toroidal design has been included.

Section 3 describes the status of HTS material performance and fabrication today and projects them to the near-term future, approximately 2 and 5 years hence. In addition, Section 3 expands on the description of HTS fabrication given above. Section 3 also addresses the effect of strain (or stress) on the performance of the different types of materials. The costs of HTS materials and SMES subsystems are developed in Section 4. The HTS costs are based on projections of expected manufacturing capabilities two years and five years hence. These costs are also based on the assumption that HTS materials are fabricated in large quantities and are used in multiple technical applications. Section 5 presents the costs of the different SMES devices and some of the subsystems. The values given there are based on the material and subsystem costs given in Section 4.

Conclusions of the study and recommendations for further work are presented in Section 6.

Several Appendices are included in the report.

Appendix A provides the references cited in the report.

Appendix B briefly describes the critical-current densities that can be used in HTS SMES.

Appendix C includes brief summaries of previous HTS studies.

Appendix D includes parts of translated reports on SMES from a Japanese workshop held in December of 1997.

2
SMES SYSTEMS EVALUATED

SMES has been proposed as a solution to many problems within all areas of the electric system, from support at the generator to customer-side end use. Numerous workshops sponsored by EPRI, DOE, DOD and industry trade groups have addressed the match of SMES with utility needs. Case studies have examined the benefits of SMES in these applications. Some of the most frequently-mentioned applications and benefits are described later in this section.

2.1 Cases Selected

These different applications call for SMES units of vastly different sizes—both power rating and duration—leading to a range of storage capacity over many orders of magnitude. These ranges are shown graphically in Figure 2-1. A set of HTS SMES sizes to study in detail was drawn from previous analysis and is listed in Table 2-1. Three typical sizes/applications were selected for end-use power quality, transmission system power quality, and transmission stability support.

These different sizes are optimized with different coil configurations. The smaller units are best suited for solenoidal configuration. The largest one could also be built as a solenoid, but will have a much smaller magnetic footprint if built as a torus. These considerations lead to the set of coils studied in detail, as listed in Table 2-2.

The current chosen for each of these cases was determined by the presumed maximum voltage of 5000 V. The duty cycle determines the ac losses which contribute to the heating in the coil.

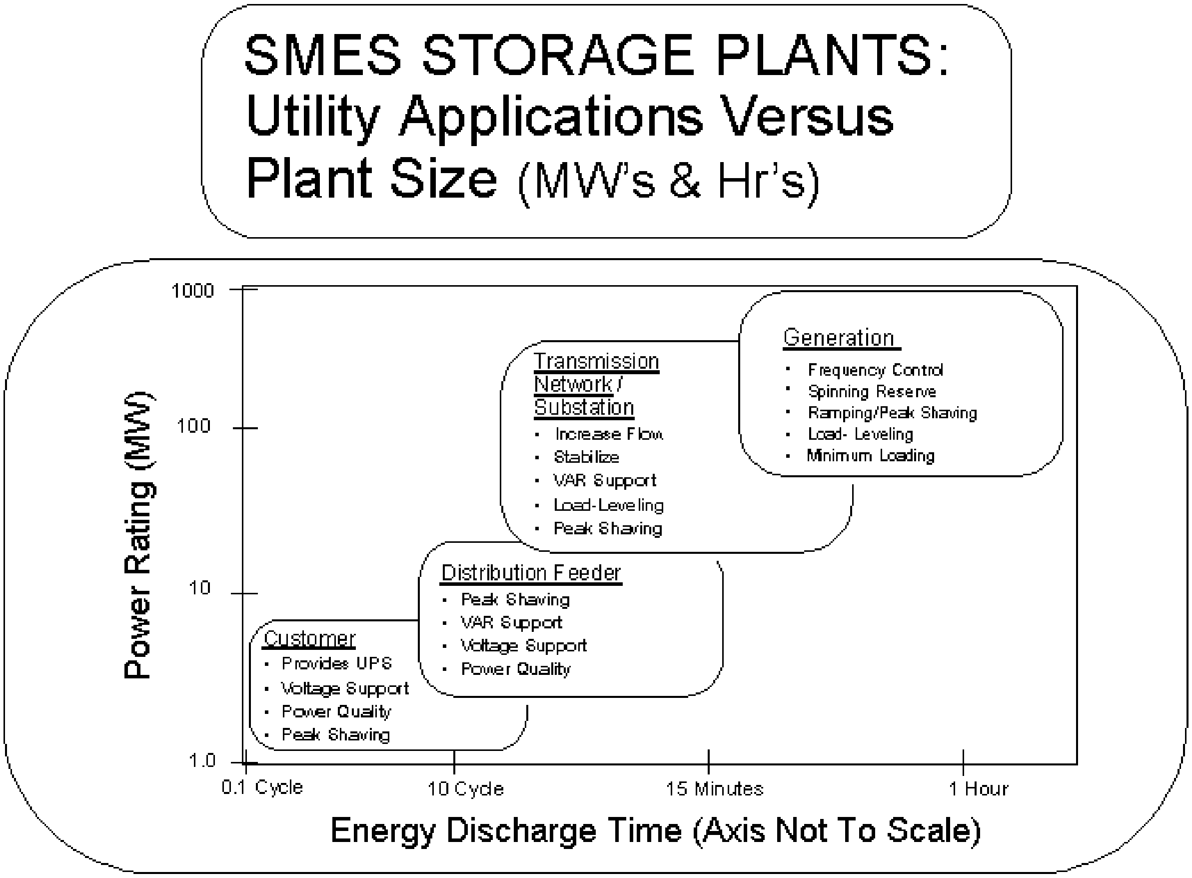

Figure 2-1
A comparison of applications and performance characteristics of SMES systems (Figure generated by Dr. R. Schainker, EPRI).

Table 2-1
Utility Applications Selected

Parameter	Case 1	Case 2	Case 3	Case 4
Area of Application	Power Quality	Power Quality	Transmission Stability	Transmission Stability
Stored Energy	4 MJ	100 MJ	1500 MJ	1500 MJ
Power level	2 MW	50 MW	100 MW	100 MW
Discharge Time	2 s	2 s	15 s	15 s

Table 2-2
Representative Coil Design Assumptions

Parameter	Case 1	Case 2	Case 3	Case 4
Area of Application	Power Quality	Power Quality	Transmission Stability	Transmission Stability
Stored Energy	4 MJ	100 MJ	1500 MJ	1500 MJ
Power level	2 MW	50 MW	100 MW	100 MW
Discharge Time	2 s	2 s	15 s	15 s
Configuration	solenoid	solenoid	solenoid	toroid
Initial Aspect Ratio	.3	.3	.3	.3
Initial Operating field	3.5T	3.5T	3.5T	3.5T
Maximum Coil Voltage (V)	5000	5000	5000	5000
Coil Current (A)	1000 nom	20000	40000	40000
Conductor shape	cable	cable	cable	cable
Duty Cycle	2-4 cycles/month	1 cycle/month	5 cycles/yr	5 cycles/yr

2.2 Utility Applications for Energy Storage

The principal applications for energy storage in utility systems have been categorized as 1) generation and ancillary service, 2) transmission systems, 3) capacity deferral, 4) wide area power quality enhancement and 5) black start capability. [16] SMES will principally have application in numbers (1), (2), and (4).

In generation and ancillary services important applications are spinning reserve, frequency regulation, and load following. Energy storage systems can provide dynamic reserve capability at their full rated power in the critical first moments of a loss of generation incident. Similarly, energy storage units can absorb or supply energy as required for frequency regulation and load following freeing other generation source from frequency regulation duties.

A key transmission system application is transmission line stability. Transmission line stability may be improved with the addition of an energy source which can supply or absorb energy from the transmission system. Studies completed to date generally show that many transmission system requirements can be effectively provided by a FACTS controller alone, without an energy source. For example, dynamic-voltage-regulation and power-flow-control benefits will accrue from the FACTS controller alone. An energy storage module is required only if other transmission requirements, such as transmission line stability or short-term energy injection are required.

For wide area power quality enhancement an energy source coupled with the appropriate electronic power conditioning system could isolate critical loads from voltage sags and power outages on the transmission or distribution system.

Table 2-3 provides a more comprehensive list of potential applications for energy storage. [16]

Table 2-3
Potential Applications for Energy Storage

Potential Applications	Power MW	Discharge Time	Energy Capacity MWh	Estimated Market Size (units)
UTILITY APPLICATIONS				
System and Generation				
Area Control	100 - 1000	10 - 100 s	0.1 - 10	100
Frequency Control	100 - 1000	10 - 100 s	0.1 - 10	100
Peak Shaving	100 - 1000	15 min - 4 h	30 - 350	100
Load Leveling	100 - 10000	4 - 10 h	100 - 10000	100
Spinning Reserve	30 - 1000	5 - 30 min	10 - 350	200
Transmission				
Peak Shaving	20 - 300	5 - 30 min	5 - 100	100
Stability	50 - 500	1 - 5 s	0.02 - 1	50
Distribution				
Peak Shaving	1 - 20	5 - 20 min	1 - 3	1000
Power Quality	10 - 50	1 s - 1 min	0.01 -2	1000
INDUSTRIAL APPLICATIONS				
Arc Furnace	10 - 100	5-20 min	1-30	50
Textile Mills	5 - 40	2-10 s	0.01 - 0.1	5000
Paper Mills	10 - 30	1-5s	0.004 - 0.02	200
Auto Plants	10 - 30	2 s	0.003 - 0.02	200
Silicon Wafer Mfg.	20 - 60	0.1 s	0.001 - 0.01	50
Financial Institutions	20 - 60	0.1 s	0.001 - 0.01	50
General Power Quality	0.5 - 2	0.1 s	0.0003 - 0.01	1000
Steel Finishing Mill	1	8 h	8	100
Welding/Bonding-Large	1-10	0.1-5 s	0.003 - 0.01	1000
Oil Refinery	300	5 s	0.1 - 0.5	20

3
SUPERCONDUCTOR PERFORMANCE

Three different types of superconducting materials are considered for SMES coil construction in this report.

- The first is the HTS material BSCCO, which is made of Bismuth, Strontium Calcium, Copper and Oxygen, and is often referred to as a Generation I material because it was the first HTS material to be used as wires in commercial applications. Three types of BSCCO are commercially available today—two of which are considered appropriate for coil construction.
- The second is the HTS material YBCO, which is made of Yttrium, Barium, Copper and Oxygen, and is referred to as a Generation II material. Several different approaches are being developed for YBCO fabrication. It is an extremely promising material for magnet applications as the current density remains high at fields of several tesla and temperatures of 20 to 30 kelvin. However, it is not available in sufficient quantities for coil fabrication today.
- The third is the LTS material Nb-Ti, which is used in many liquid helium cooled coils today. This material is used as a reference point for the evaluation of the HTS systems. An additional LTS material is Nb_3Sn, which is used for some high-field applications today and can be used at higher temperatures than Nb-Ti. Though it is not used in the comparisons of SMES systems, its critical current at 4.4 K is given in this section to establish a benchmark.

Figure 3-1 shows the highest current densities achieved to date in these materials. The current densities shown provide insight into the capabilities of the different materials. They are, however, considerably larger than the operating current density in a superconducting magnet. The average current density in the windings of a SMES coil is reduced below these values because of the need to include:

- normal conductor,
- insulation,
- coolant, and
- structure.

The allowable operating current densities for these various conductors were studied by reviewing the literature and private discussions with several of the manufacturers. A consultant, Dr. N. Heinig was hired to evaluate the HTS materials and the impact of ongoing research and development. The report on this effort is included as Appendix C. Some of the results included in this appendix are used for material performance characteristics that are discussed below.

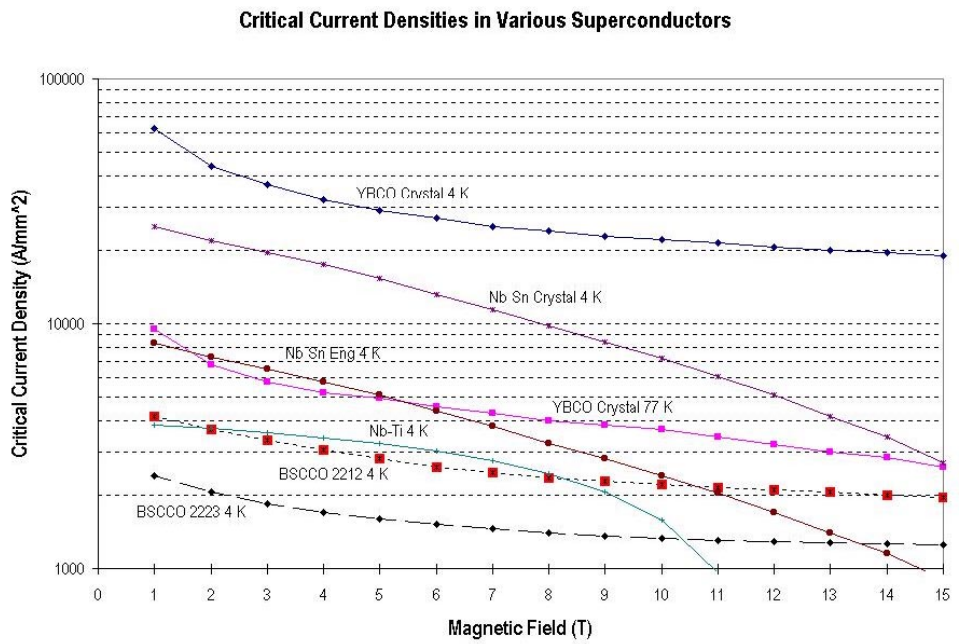

Figure 3-1
Critical current densities of various superconducting materials

3.1 Generation I Materials

Three types of generation I conductors are made for use in superconducting coils and magnets today. They are all made of Bismuth, Strontium, Calcium, Copper, and Oxygen, but their chemical structure and/or their fabrication processes are different. The chemical—crystalline—structure of the Bi-2223 material is $Bi_2Sr_2Ca_2Cu_3O_{10}$. Conductors made of Bi-2223 are available in the form of tapes "flattened wires" that have many filaments of the superconductor imbedded in silver matrix. The chemical—crystalline—structure of Bi-2212 material is $Bi_2Sr_2Ca_1Cu_2O_X$. Conductors made of Bi-2212 are available in the form of multifilamentary wires and as surface coated tapes. The three conductors and their effectiveness for magnet fabrication are discussed below.

3.1.1 Bi-2223 Tapes

The Bi-2223 materials used today are multifilamentary tapes made of a silver sheath that surrounds many filaments of the superconductor. The fabrication technique is frequently referred to as the powder in tube (PIT) process. It consist of several steps. To start, the precursors of the superconducting materials are made into fine powder and placed in hollow silver tubes, which are drawn down to a diameter of a few millimeters. Assuring full compaction of the superconducting material during the drawing and all subsequent fabrication steps is critical. Several monofilament rods of silver and superconductor are stacked inside another silver tube and the entire assembly is reduced in size by drawing. At an appropriate diameter, the circular wire is further deformed by rolling into a rectangular tape. Typical finished dimensions of the tapes are 0.2 x 3.0 mm.

The rolling process affects the tape in two ways that are critical to performance. First, the contact area between the superconductor and the silver increases by flattening the conductor. This is important because micro-graphic studies show that the superconductor near the silver interface has the highest current density. Second, the conductor is textured by the rolling process so that the BSCCO crystals have the same orientation over long lengths of the conductor. This "long range order" contributes to a higher overall current density because it reduces the area where the current must pass from one crystal to another across a weakly conducting boundary.

Both the current densities and the tape lengths of Bi-2223 materials have increased considerably during the past two years. This is a result of improved processing, including the rolling process described above, the precise control of reaction temperature, and the concentration of oxygen and other gases during reaction. During the high-temperature reaction, oxygen passes through the silver sheath to produce the appropriate stoiciometry, while the Bi-2223 material maintains the textured crystalline structure produced by the rolling process.

The current density of Bi-2223 tapes as a function of temperature and field are given in Table 3-1. These values are from measurements at 4 K of multifilamentary material made by American Superconductor. The values at 20 and 30 K are extrapolations based on factors determined by Steiger et al. [17`] using magnetization techniques. These values are not appropriate for use in designing superconducting magnets. Several adjustments—mainly reductions—are necessary to determine the allowable working current densities for the materials. First, the measurements made for the materials are at a voltage sensitivity of 1 μV/cm. Magnets cannot operate with voltage gradients of this magnitude, so a standard of 0.1 μV/cm has been accepted as the operating value for magnet design. Here it is assumed that the current density at 0.1 μV/cm is 80% of the value at 1.0 μV/cm. Second, the values quoted are for short samples rather than for long lengths of wire. A additional reduction of 20% is assumed to achieve the benchmark current densities for 2223 material in Table 3-2.

Table 3-1
Critical current density (A/mm^2) of Bi-2223 tapes as a function of magnetic field and temperature

Field/Temperature	4 K	20 K	30 K
3 T	1830	1190	1050
5 T	1600	1120	840
7 T	1450	980	595
10 T	1325	805	210
15 T	1250	620	14

Table 3-2
Working critical current density (A/mm^2) of BSCCO-2223 tapes as a function of magnetic field and temperature

Field/Temperature	4 K	20 K	30 K
3 T	1171	761	672
5 T	1024	717	538
7 T	928	627	380
10 T	848	515	134
15 T	800	397	9

3.1.2 Bi 2212 Wires

One of the Bi-2212 materials used today is a multifilamentary wire or tape made of a silver sheath that surrounds many filaments of the superconducting material. These wires are typically about 1 mm in diameter and have 20 to 100 filaments of superconductor. The fabrication process consists of several steps. The precursors of the superconducting materials are first ground into a fine powder and placed in hollow silver tubes. The resulting small rods are then drawn down to a diameter of a few millimeters. Assuring full compaction of the superconducting material during the drawing and all subsequent fabrication steps is critical. Several of the monofilament rods of silver and superconductor are stacked inside another silver tube and this assembly is also reduced in diameter by drawing. The eventual diameter of the wire is about 1 mm, but the specific size depends on the manufacturer and the application.

The current density of BSCCO-2212 wires is higher than that of the BSCCO 2223 wires at 4 K, especially at high fields, as shown in Table 3-3, which includes both the measured current densities [18] and projected working values. Over the past two years the current densities of long lengths of wire have increased considerably. This is a result of improved processing, in particular better compaction of the conductor and precise control of the temperature at which the wires are reacted. During reaction 2212 material is completely melted and the resulting superconductor is formed during a very short period at the melting temperature. Though the optimum temperature range for 2212 varies a few degrees centigrade from manufacturer to manufacturer, control of the reaction temperature to an accuracy of 1°C at about 897°C is required to achieve maximum performance.

Table 3-3
Measured and specified critical current density (A/mm^2) in BSCCO-2212 wires at 4.2 K as a function of magnetic field

Magnetic Field	Measured Current Density	Working Current Density
3 T	3350	1870
5 T	2800	1570
7 T	2500	1380
10 T	2200	1230
15 T	2000	1100

3.1.3 BSCCO 2212 Coated Tapes

A second form of the BSCCO-2212 conductor is a silver tape with a surface layer of 2212 material. The 2212 may be on one or both sides of the tape. The conductor is formed by pulling the silver tape through a slurry of the precursor material, which dries to form a nearly constant thickness layer. The tapes are reacted in a furnace with a partial oxygen atmosphere at a temperature similar to that of the wires, which causes the Bi-2212 to melt on the surface of the tape. These materials have special applications, but, because of loss and stability issues, do not appear to be optimal for HTS magnets of the type that will be used for SMES applications. As a result they are not discussed further in this report.

3.1.4 Generation I working Current Densities

The working current densities for the generation I materials are a combination of the BSCCO 2212 and the BSCCO 2223 capabilities. The 2212 values are used for the liquid helium, 4 K, calculations and the 2223 values are used for the higher temperatures. The values are given in Table 3-4.

Table 3-4
Working current densities in (A/mm^2) for generation I superconductors used for this analysis

Field/Temperature	4 K	20 K	30 K
3 T	1870	666	588
5 T	1570	627	470
7 T	1380	549	333
10 T	1230	451	118
15 T	1100	347	8

3.2 Generation II Materials

The Generation II HTS superconducting material in development today is YBCO, a compound made of yttrium, barium, calcium and oxygen. Only small pieces and short lengths of this material have been produced to date. However, it has the promise of very high critical current densities in magnetic fields of 10 T or greater at temperatures up to 30 K.

YBCO conductor production is very different from that of the BSCCO materials. The most critical issue is to obtain long-range order in the crystalline material. Today this does not appear to be possible with the wire process that has proved so successful for the BSCCO materials. Several fabrication procedures have successfully produced short lengths of YBCO conductors with properties that are better than the BSCCO materials by factors of 10 to 100, depending on temperature and background field. The critical current densities reported in Table 3-3 are a combination of the values from different research institutions and are used for the analysis in this report. These values have been achieved at effective voltage gradients of 0.1 μV/cm and are used throughout as the benchmark current density for the material.

Table 3-5
Benchmark critical current density in A/mm^2 for YBCO wires as a function of magnetic field and temperature

Field/Temperature	4.4 K	10.0 K	20.0 K	30.0 K
0.0 T	48100	45400	40600	35800
1.1 T	40600	37700	32400	27200
1.6 T	33800	31300	26000	22600
2.7 T	26900	24900	21400	17900
3.7 T	23100	21400	18300	15300
4.8 T	20600	19100	16300	13600
5.9 T	18900	17400	14900	12300
6.9 T	17500	16200	13800	11400
8.0 T	16650	15400	13100	10800
9.1 T	15600	14400	12200	10100
10.0 T	14600	13500	11500	9450
11.0 T	13700	12600	10800	8870
12.0 T	12900	11900	10100	8320
13.0 T	12000	11100	9420	7770
14.0 T	11200	10300	8790	7250
15.0 T	10400	9600	8170	6730

3.3 Niobium Titanium at 4.2 K

The ductile alloy niobium-titanium is frequently used in superconducting magnets that operate in the temperature regime that is accessible with liquid and supercritical helium, i.e., between 1.8 K and 6.0 K. Below 1.8 K the refrigeration costs usually become prohibitive. Above 6.0 K the Nb-Ti cost increases because more material must be used as the current carrying capability decreases. Nevertheless, there are thousands of Nb-Ti magnets ranging from small laboratory magnets for sample tests to the widespread MRI magnets and the large magnet systems associated with high energy physics accelerators. Nb-Ti is the best understood commercial superconductor used today.

Several studies have addressed the variations in the current carrying capability of Nb-Ti as a function of temperature and field. The approach used here was developed by Lubell [19] in 1988. However, the base current density J_{c00} has been adjusted to match present day Nb-Ti performance of 3000 A/mm^2 at 4.2 K and 5 T. The correlation used is given by the following relations.

$$J_c(B,T) = J_{c0}(B,T)\left(1-\frac{T}{T_0(B)}\right), \qquad T_c(B,T) = T_{c0}(B,T)\left(1-\frac{B}{B_{c20}}\right)^{0.59}, \text{ and}$$

$$J_{c0}(B) = J_{c00}\left(1-\frac{B}{B_{c20}}\right)$$

The current densities given in Table 3-6 are based on the following material parameters $J_{c00} = 7300\text{A} / \text{mm}^2$, $T_{c0} = 9.3\text{K}$, and $B_{c20} = 15.0\text{T}$. The current density at 5 T is about 3000 A/mm^2, which is a conservative value for Nb-Ti today. Typically, the working current density for this material is assumed to be 65% of the measured value for the calculations, which is used in this study.

Table 3-6
Measured and working critical current densities in (A/mm^2) at 4.2 K for Nb-Ti superconductors

Field	Measured
3	3421
4	3230
5	3008
6	2749
7	2439
8	2060
9	1585

3.4 Impact of operational conditions on conductor performance

3.4.1 Magnet stability and conductor margin

Low-temperature superconducting magnets are designed to operate with a margin of safety vis-a-vis the ultimate critical current density of their constituent superconducting materials. The extent of the margin is driven by factors associated with the fabrication of the superconductors and the physical characteristics of materials at low temperatures. These margins cannot be applied indiscriminately to the HTS materials. Instead, the rationale used to select the LTS margins must be applied to the HTS conductors to obtain an appropriate set of margins for magnet operation at elevated temperatures, i.e., above 4 K.

The production of low-temperature superconducting wires has reached a stage of maturity where the input materials and processing variables allow a very accurate prediction of critical current and resistivity of the copper sheath. For example, large production lots of SSC material were produced with less than 5% variation in critical current and 10% variation in copper sheath resistivity. Here we assume that similar results will be achieved in the HTS materials in large-scale production.

A magnet made of LTS conductors operating at liquid-helium temperature must be protected against transitions to the normal state caused by disturbances which heat the superconductor. The magnet designer must provide enough operating margin so that these disturbances do not heat the conductor above the critical temperature and thus cause a transition. The crucial element in establishing the margin is the relation between the energy of the disturbance and the enthalpy of the material between the operating temperature and the critical temperature. Ideally, both the energy spectrum of the disturbances and the enthalpy of the conductor—including other portions of the winding package—need to be calculated.

Instead, because measuring a conductor’s critical current is straightforward in most cases, the magnet designer uses the ratio of operating to critical current as the metric for selecting the margin. Typical LTS magnets operate at currents between 50 and 90% of the critical value. The fraction of critical depends on a variety of factors, in particular, on the risk associated with a transition. Magnets storing large amounts of energy, (many MJ) usually have more margin than smaller magnets.

Since the magnitude of the disturbances depends on the structural integrity of the magnet design, the energy deposited in LTS and HTS magnets of the same size and for similar purposes will be about the same. This suggests that one should equate the enthalpy margin in the two types of magnets rather than the fraction of critical current.

The LTS magnets that operate at 70% of critical have an enthalpy margin of about 1 mJ/cc, which means that 1 J will raise the temperature of 1 liter of material from 4 to 5.2 K. The energy required to raise the temperature 1 K increases rapidly as the starting temperature increases. At 20 K the energy is about 80 mJ/cc and at 30 K it is nearly 400 mJ/cc. Equivalently, 1 mJ causes a temperature rise of 0.0125 K at 20 K and 0.0025 K at 30 K. If the only requirement for stability were this stability margin, achieving the same enthalpy margin in an HTS magnet as in an LTS magnet would allow operation at about 99% of critical, rather than 65%.

The designer of a large LTS magnet is faced with the situation that the required enthalpy margin demands an excess volume of conductor. The increase can be from 25% to nearly 100% of the initial value. In any event, the amount far exceeds the amount demanded by the variability of material characteristics.

The impact of enthalpy margin on the operating current of the HTS magnet is negligible so the HTS magnet designer can ignore this requirement. Assuming the HTS materials will all perform within 5% of critical current, the magnets can be designed to operate successfully with a current margin of only slightly larger than 5%. A current margin of 6% is used for the HTS materials at 20 and 30 K, i.e., they are assumed to operate at 94% of their critical current. A margin 0f 10% is used for the HTS materials at 4 K. The LTS superconductor is assumed to operate at 65% of its critical current.

3.4.2 Effects of conductor orientation on operational current density

The critical current densities of superconductors fabricated into flat tapes depend on the orientation of the magnetic field to the wide surface. These materials often exhibit a lower critical current density when the magnetic field is perpendicular to the wide face than when it is parallel. This phenomenon was observed in early Nb tapes and was true of the Nb_3Sn tapes developed in the 1960’s and 1970’s. Orientation sensitivity appears to be even more important for the BSCCO tapes under development today. In contrast, most round multifilamentary wires made of both HTS and LTS do not have a preferential magnetic field orientation.

The field dependence of critical current on conductor orientation can be described by a trigonometric relation that depends on the type of conductor and the fabrication process. The relation used to describe the sensitivity of the critical current density to the magnetic field direction is:

$$J_c = J_{c0}[a + (1 - \alpha)\sin(\theta)],$$

where θ is the angle between the normal to the flat surface of the tape and the magnetic field and α is a measure of the angular dependence. The value of α also depends on the magnitude of the applied field.

The BSCCO-2223 materials that are formed by multiple passes through a roller are said to be textured. Above 20 K these materials have the greatest current density of all the Generation I materials. However, the texturing process reduces the critical current when the field is orientated perpendicular to their wide face. At low fields α is approximately 0.5 (the critical current is reduced to 50% of maximum) and at high fields, e.g., above 6 T, α is closer to 0.3 (the critical current is reduced to 70% of maximum). Since this study is aimed at high field magnet performance, an α of 0.3 is used for the BSCCO-2223 materials, which are the Generation I material of choice at 20 and 30 K.

The BSCCO-2212 materials that can be used for superconducting magnets today are not textured. Even though they are made into rectangular wires in some cases, their critical current densities show little dependence on θ. Since BSCCO-2212 is the Generation I material of choice at 4 K, there is no performance degradation associated with different field orientations.

The YBCO conductors are at an early stage of development so it is too early to determine the extent to which they will be affected by field orientation. To be conservative, we assume that their response will be similar to that of the textured BSCCO-2223 materials.

Sensitivity of the conductor to field orientation impacts coil design by increasing the quantity of superconductor required to achieve a specified performance. The quantity of additional conductor needed to achieve the desired stored energy depends on the type of coil, e.g., solenoid or toroid, and the winding configuration, e.g., pancake or layer winding. The four cases are discussed below.

1. Layer wound solenoids—each layer of conductor is exposed to high magnetic field levels. The outer layers see a peak field that ranges from 60 to 80% of that seen by the inner layers. All layers see significant variation in the magnetic field orientation. Conductors at the end of the coil in the innermost layer see nearly the maximum field and it is nearly perpendicular to the conductor. A performance penalty must be applied to the innermost conductors. However, the outermost layers see a much lower field and the maximum angle θ can be held to about 45°. Thus, the conductor can be graded in this type of coil.

2. Pancake wound solenoids—the peak-field variation from pancake to pancake is only a few percent and both this variation and the location of the highest field point depend on the coil geometry. However, there is a strong variation in field orientation across the pancakes. The outermost pancakes (top and bottom-if the coil axis is vertical) see the peak field, which is oriented perpendicular to the surface. A performance penalty must be applied to the conductor in this type of coil, however, grading of conductors is possible. Either smaller or fewer conductors can be used in the pancakes at the center of the coil.

3. Layer wound toroids—the magnetic field in the toroid is generally parallel to the inner surface of the component coils at the innermost part of the torus. The maximum field also occurs at this location. Some fraction of the field at the outer radius of the toroid is perpendicular to the layers of the component coils. However, the field is lower in this region. As a result, the conductor is limited by the peak field and not by the field orientation. In addition, the outer layers in each component coil sees less field than the inner layers. As a result the conductor can be graded.

4. Pancake wound toroids—the magnetic field in the toroid is generally parallel to the inner surface of the component coils at the innermost part of the torus. The maximum field also occurs at this location. Some fraction of the field at the outer radius of the toroid is perpendicular to the layers of the component coils. However, the field is lower in this region. As a result, the conductor is limited by the peak field and not by the field orientation. All pancakes, however, see the same magnetic field. Thus, grading is not possible.

A multiplier can be estimated for each of these configurations to determine how much more or less conductor must be used to reach performance goals. Since individuals conductors must be combined into bundles to achieve the required current carrying capacity, even toroidal magnets made of tapes will also affected by the field angle. The estimated multipliers are summarized in Table 3-7 below. These factors apply to the calculation of the quantity of material required for the four SMES cases at different temperatures as given in Table 3-8.

Table 3-7
Figure of merit for different coil and conductor winding configurations

Configuration	Grading Factor	Field Angle Effect	Tape Multiplier Gen II and Gen I 20 and 30 K	Wire Multiplier 4 K
Layer wound solenoid	0.85	1.5	1.3	0.85
Pancake wound solenoid	0.80	1.5	1.3	0.80
Layer wound toroid	0.80	1.3	1.1	0.80
Pancake wound toroid	0.80	1.3	1.1	0.80

Table 3-8
Multipliers for conductor requirements, excluding margin, for the four SMES cases at different temperatures

Configuration	4 MJ Solenoid	100 MJ Solenoid	1500 MJ Solenoid	1500 MJ Toroid
Gen I and Nb-Ti 4 K	0.80	0.80	0.80	0.80
Gen II 4 K	1.30	1.30	1.30	1.10
Gen I and Gen II 20 K	1.30	1.30	1.30	1.10
Gen I and Gen II 30 K	1.30	1.30	1.30	1.10

3.4.3 Effects of strain on operating current density of HTS materials

The manufacturing processes for the BSCCO and YBCO materials considered in this study are considerably different. It is likely that the differences in these processes and the subsequent treatment of the conductor affect the no-load strain condition and the strain sensitivities of the two materials. The conductor processing and the resulting strain sensitivity will be discussed briefly below. Recommendations for studies and material developments that will affect strain sensitivities of practical materials will be made in Section 6.

Before proceeding with an analysis of the strain characteristics of the HTS materials it is instructive to describe the processing of Nb_3Sn and use it as a starting point for evaluating the HTS materials. Considerable data are available on the Nb_3Sn produced by the “bronze” and the *in situ* Sn processes. Wires made in either of these processes start as billets ranging from 10 to 30 cm in diameter. The billet typically consists of an outer copper shell and an inner region that contains copper, niobium and tin. The two parts of the conductor are separated by a thin layer of niobium or tantalum. The billets are drawn down to final wire sizes of a millimeter of so. In the process, the niobium rods in the billets are reduced to filaments with micron dimensions.

Nb_3Sn

The Nb_3Sn superconductor is formed at temperatures around 700°C where the Nb reacts with the Sn. Since Cu is permeable to Sn at the reaction temperature, Sn is either leached from the bronze or diffuses across the copper matrix from tin filaments or layers. The outer copper layer remains free of tin because of the layer of Nb or Ta is impermeable to the Sn. The reaction process produces a layer of Nb_3Sn, which is a hard, brittle, glassy-like material around each Nb filament. It also causes a tin-poor bronze matrix in the inner region of the conductor.

As the conductor is cooled from the reaction temperature to ambient, the copper and bronze contract more than the Nb_3Sn. Since the Nb_3Sn is constrained as micron sized crystals between the bronze matrix and the niobium filaments, it contributes to the mechanical characteristics of the material. Thus, the Nb_3Sn is under compression and the matrix of the wire and the external copper are under tension. As a result, the overall thermal contraction of the wire lies between that of the copper based material and the superconductor.

As a coil made of this type of conductor is energized, the wire begins to stretch and the Nb_3Sn goes from a state of compression to one of tension. Measurements of the effect of tensile strain on Nb_3Sn conductors show that ability to carry current increases as tensile strain increases until the NB_3Sn reaches a state of approximately zero strain. Beyond this strain level the current carrying capacity begins to fall off. At first the reduction in current carrying capacity is small, but it increases rapidly for larger strains. The process is reversible for small strains A sample that has been subjected to a relatively small strain can still carry the maximum current when the strain is removed. As the sample is subjected to larger strains, recovery of the current carrying capability does not occur as the strain is removed. A limit is reached for the reversibility of the strain induced effects. This limit depends somewhat on the conductor fabrication process, but is on the order of 0.5%.

BSCCO

Two BSCCO materials, 2212 and 2223, are in production today. They are typically made by a powder in tube process or as a coated ribbon. The tubes and the base ribbon material is silver or a silver alloy. The superconductor is formed at a temperature of about 850°C in an oxygen-rich atmosphere. The silver is highly permeable to the oxygen and allows it to react with the BSCC materials. In both production processes the silver is soft and the superconductor is in a state of low strain after the reaction process. As the conductor cools the superconductor is compressed by the silver matrix. However, there are voids in the filaments in the tube PIT process and there is no surrounding constraint on the coated tape process. In addition, the superconductor is soft and is much like mica, which has slip planes between layers of material. The observed thermal contraction observed in both the tapes and wires is essentially identical to that of the silver alone. Since the BSCCO is weak and does not contribute to this property, it must be in a neutral state, i.e., it has zero tension/compression.

As the superconductor is wound into a magnet, parts of the material experience a tensile strain associated with the bending of the wire. As current is passed through the conductor the tensile strain increases.

Tests have been carried out with BSCCO materials to determine the effect of tensile stress on current carrying capacity. The current carrying capacity decreases very little for small strain levels. However, especially in early tests, above about 0.1% strain the current carrying capacity decreases rapidly and above about 0.2% strain the reduction in current carrying capacity is irreversible. This suggests that there is some irreversible damage to the material above 0.2% strain. More recently, as Gen I materials have become more consistent in their performance, the irreversible effects of strain have been reduced. As a result, it not appears that the Gen I materials can withstand operating strains of about 0.3%, and, under controlled conditions, up to as high as 0.5%.

Materials in a superconducting magnet are exposed to transverse compressive loads in addition to the tensile loads. Because the layers in BSCCO slip past each other and there are often voids in the structure, the superconductor can be deformed with very low compressive loads. Since the ability of the HTS materials to carry current is limited by the contact between crystals—in which the layers may fall at different angles—any motion at the boundaries causes the current carrying capacity to decrease. Also, once the boundaries have shifted the stress is relieved and the new and often less desirable orientation becomes permanent.

The allowable strain in the HTS materials is assumed to be 0.3%. However, a goal should be to establish a practical strain level for magnet operation with BSCCO materials.

YBCO

Material is made by a variety of processes that tie the crystal structure of the superconductor to a prepared layer of material in which the crystal lattice is close to that of the superconductor. At present the YBCO is made in a thin layer that is prepared on a substrate. Since practical YBCO materials do not exist at this time, there is limited relevance of the small amount of data on the strain sensitivity of the laboratory specimens. However, the data that are available suggest that the allowables for this material are high. Measured degradation initiation of deposited YBCO materials appears to 0.5% tensile and 1.0% compressive strain.

3.4.4 AC Losses

The magnitude of the AC losses in a superconducting magnet depends on the conductor type and geometry and the frequency and magnitude of the charge discharge cycle. If the system is charged infrequently, the average AC loss may be very small, but the instantaneous heating may be enough to cause a significant temperature rise, even if the overall power requirement is not affected. Thus there are two regimes to be evaluated. The first is the average heat input to estimate refrigerator capability and overall power requirements. The second is the ultimate temperature increase associated with a single rapid discharge.

The SMES systems evaluated here are assumed to see limited use. That is, they will experience on the order of 100 few cycles per year. Thus, the AC loss contribution to the total refrigeration heat load is small compared to conduction and radiation losses. However, they all discharge quickly so the temperature rise during discharge, particularly is they are sequential, can be a concern. As a result, the conductors for any SMES application must be designed to limit AC losses. This is accomplished by subdividing the conductor in one or more stages, e.g., cables that contain subcables made of wires that consist of many filaments of superconductor imbedded in matrix of normal conductor.

The AC losses in a conductor are a sum of different terms that depend on the superconductor, the normal stabilizing conductor, and the current paths between these two materials. Since the details of HTS conductors for SMES coils await further development, the approach used here was to assign an average refrigeration load of 25 watts to the 1500 MJ toroidal SMES system and to scale the load for the other systems based on the quantity of conductor.

3.5 Protection and stability of HTS superconducting magnets

The design criteria for superconducting magnets include many items that are not required for conventional electrical systems. Some are obvious, such as the refrigerator, the vacuum system, the cryostat, and the current leads that transfer the current from ambient to the operating temperature. In addition, the inherent characteristics of the superconducting material and the overall conductor lend a special set of problems that must be faced by the superconducting magnet designer. The two that are most critical are stability and protection. There is a wealth of literature with the goals of assuring stable superconductors and of making superconducting magnets safe [2]. These two requirements are discussed below, where it will become apparent that the two can be met simultaneously only with considerable understanding of the superconductor itself and its integration into the magnet system. As stated in Section 3.4.1, the bases for the choices that have been made for LTS magnets must be applied to the HTS systems, rather than indiscriminately applying the resulting design choices themselves.

Since many superconducting magnets function perfectly well today, it is clear the problems of stability and protection are understood and have been solved—at some level—for the low-temperature materials. However, neither magnets made of high-temperature superconductors nor the high-temperature superconductors themselves are at a level of development today where these critical issues require practical solutions. Explained simply, the physical size of HTS devices built today and the stored energy per unit of superconductor in these devices are both small when compared to existing LTS devices.

If HTS energy storage devices (and large coils for other applications) are to become economically competitive, the HTS materials and the normal conductors that are associated with them must carry current densities that are similar to those encountered for LTS materials. As a result, the issues of stability and protection for HTS materials will achieve the significance that exists in LTS devices today. The approach used here to address the issues of stability and protection for HTS systems is to begin with a description of the solutions to these issues for LTS systems and then to extend the analysis to the anticipated HTS systems.

Since operating regimes for the HTS materials may range from below 4 K, the temperature of liquid helium, to above 77 K, the temperature of liquid nitrogen, the first consideration in the analysis is the changes in material characteristics as the temperature increases. In addition to the superconducting parameters, two material characteristics are critical to the safety and protection of a superconducting device. These are the specific heat and the normal state resistivity of all the materials in the magnet, including the insulation. The specific heat of all the materials in the coil increase by a factor of 100 or more as the temperature goes from 4 to 77 K, and the resistivity of copper used in LTS conductors increases by a factor of 20 to 50, depending on its purity and state of mechanical strain.

Protection of LTS systems depends on maintaining safe levels of voltage and temperature within the magnet should all the stored energy require immediate discharge for any reason. Several different conditions must be met.

The first is often referred to as the adiabatic condition, i.e., the event is rapid and all or most of the energy is absorbed by the magnet components. The result of this requirement is that the enthalpy of the cold mass between the operating temperature and the maximum allowable temperature must be greater than the stored energy. The maximum temperature can range from 70 K to 500 K.

The second is the temperature variation across the coil must both be held below an acceptable level that is determined by the magnet structure. The maximum temperature can variation can be from 0 K, i.e., the entire system must be at essentially the same temperature, to 500 K.

The third is that the maximum voltage across the entire magnet, and the maximum turn-to-turn and layer-to-layer voltages must be maintained below predetermined values. These voltages depend on magnet and insulation design, and can range from a few hundred to a few thousand volts.

The maximum voltage across the entire magnet is usually determined by an external resistance. If the resistance is constant throughout the discharge, the voltage is at its highest level when the current is maximum, $V=I_{max}R$. The maximum voltage and temperature within the windings of the coil is dynamic and depends on a variety of parameters including:

- the starting point of the transition,
- the speed with which the transition moves through the magnet,
- the size of the magnet, and
- the winding pattern.

This same set of parameters determines the maximum temperature within the windings.

Computer codes available today can analyze the transition process and can successfully predict the peak voltages and temperatures in superconducting magnets. These “quench” analysis programs use the design parameters of the conductor to determine the speed of propagation of the transition, the so-called quench velocity. They then combine the quench velocity with the magnet geometry, and the material characteristics to determine voltages and temperatures.

The critical element of the analysis and of the protection of the magnet is the calculation of the three-dimensional quench velocity:

- along the conductor
- between turns, and
- from layer to layer.

Martin Wilson [20] developed much of the early analysis of the quench process. Parts that allow a comparison between HTS and LTS systems are included here. The quench velocity along the conductor depends on the material characteristics and the difference in the operating temperature and the temperature above which the conductor can no longer carry the operating current.

$$v_q \propto \frac{I}{\gamma \cdot C \cdot A}\sqrt{\frac{\rho\kappa}{\Delta T}} \times f(T - T_{Bath}) \propto \frac{I}{\gamma \cdot C \cdot A}\sqrt{\frac{L_0 T_{avg}}{\Delta T}} \times f(T - T_{Bath}), \qquad \textbf{Eq. 3-1}$$

where ρ is the resistivity of the conductor material, κ is the thermal conductivity, C is the specific heat, A is the area of the conductor, $L_0$is the Lorentz ratio, and f(T) is a function of the heat removal capability associated with a cooling bath such as helium or nitrogen. Both electrical resistivity and thermal conductivity in metals are determined by the number of electrons that are free to move (electrons in the conduction band). The Lorentz ratio is a constant that relates these two parameters via the following relationship.

$$\rho\kappa = L_0 T \qquad \textbf{Eq. 3-2}$$

The transition also propagates from turn to turn and from layer to layer within the magnet. The theoretical basis for Eq. 3-1 is well founded, but the analysis does not predict these transverse velocities. An estimate of the these velocities relative to that along the conductor can be made by assuming that the relative thermal conductivity, the $\sqrt{\kappa}$ term in Eq. 3-1 provides this relationship. Estimates of the relative thermal conductivity in the different directions (including the effects of the insulation) yield transverse velocities that are 5 to 20 time less than the velocity along the conductor.

Quench velocities along the conductor for typical LTS conductors range from 1 to 100 m/s. Since magnets typically have dimensions of a few centimeters to a few meters, a quench will propagate within the magnet in periods measured in seconds. Experiments have shown that the calculation of propagation velocity is accurate enough to predict overall magnet performance during a transition.

The major protection issue for HTS magnets is to achieve a rapid quench velocity in spite of the fact that the specific heat is considerably larger, e.g., 80 times as large at 30 K than at 4 K. This can be achieved by decreasing the temperature margin ΔT and by minimizing the excess material that is in intimate contact with the superconductor.

4
COSTS OF HTS CONDUCTORS AND OTHER SMES SYSTEM COMPONENTS

4.1 Overview

A SMES system is composed of several components, as shown in Figure 4-1. The components that form the basis for the comparisons in this study are the superconducting coil, the cryostat and the refrigerator. In addition there are a series of incidental costs that are included as a miscellaneous category. The various cost components are summarized below and are described later in this section.

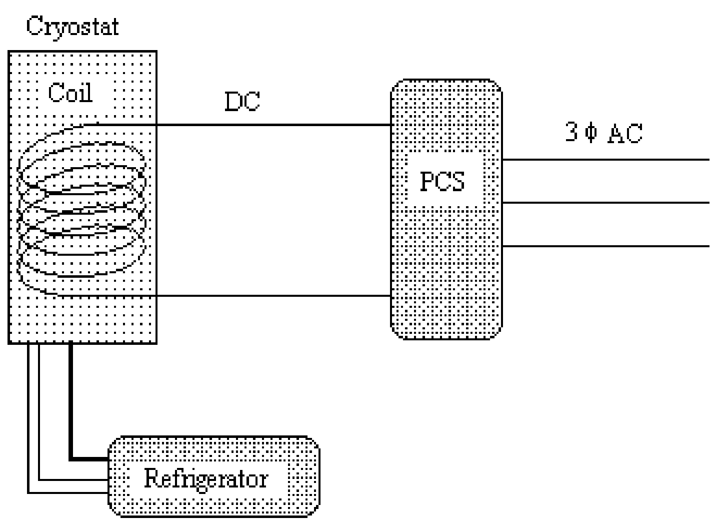

Figure 4-1
Block diagram of the principal components of a SMES system

1. Superconducting coil
    - Superconductor
    - Normal conductor (Cu)
    - Structure (to support the magnetic forces)
    - Conductor fabrication
    - Coil assembly

2. Refrigerator
   - A central refrigeration unit (which maintains the operating temperature of the coil)
   - Piping that carries cryogens to and from the cryostat
   - Installation
3. Cryostat
   - Supports for the superconducting coil
   - Inner vessel
   - Outer vessel
   - Superinsulation
   - Vacuum System
4. Miscellaneous
   - System installation
   - Power leads
   - Control and Instrumentation
   - Engineering

The PCS, which converts the power in the AC grid into direct current for the superconducting coil is not included in the system comparison in this study. The design and cost of the PCS are driven by the power requirements of the application and the combination of voltage and current for the superconducting coil. Since these parameters are held constant for each of the applications, the addition of the constant of the PCS would not be instructive.

4.2 Cost of the Superconducting Coil

4.2.1 Superconductor

Many of the previous studies of HTS SMES (see Appendix C) made assumptions regarding HTS current carrying capacity or simply proposed that very high currents could be achieved at 77 K, the temperature of liquid nitrogen. The present evaluation uses the measured current densities of superconducting materials presented in the previous section. As a result, because: a) HTS materials do not perform well when both the temperature and the magnetic field are elevated, and b) high fields are needed to assure a compact SMES device, only the temperature regime 30 K and below is explored here.

The projected cost of the various conductors in each SMES system are based on four components.

1. The measured current density of the fabricated superconductor, which was described in Section 3 above.
2. The cost of the materials used to make the superconductor.
3. The fabrication costs the superconductor.
4. A margin for profit by the manufacturer.

Gen I and Gen II high temperature superconducting materials use different base elements and compounds and require different fabrication processes. As a result, separate estimates of the costs must be made. Also, the time frame for commercial availability of Gen I and Gen II materials are different. Gen I materials are available and are being used to fabricate small coils today. However, some processing improvements are needed to achieve consistent, long (>1 km) lengths of conductor with a uniform current carrying capability. To date, only small laboratory samples of Gen II materials have been fabricated. Commercial Gen II conductors needed for magnet fabrication are not likely to become available for 3 to 5 years.

The developmental difference of Gen I and Gen II materials lends a different level of uncertainty to the estimates of their costs. As a result, an additional contingency is added to the cost of the Gen II materials.

Two approaches were considered for determining the cost of conductor in a SMES magnet system. One is to calculate the volume of conductor in cubic meters, based on the current carrying capacity of the material at the operational current and field, and then multiply this volume by the cost per cubic meter. The second method is to determine the quantity of conductor in kAm required to produce the required stored energy and then multiply by the cost in $/kAm at the operational field.

The first of theses approaches was chosen for the calculations because different conductor costs can be included in the estimates by changing a single program entry. This provides some flexibility today, but allows the future capability of obtaining rapid up-to-date system costs by making simple changes when material and labor costs need to be revised.

There is, however, considerable value in determining the cost of the superconductor in $/kAm to gain additional insight into the relative value of the materials at different fields and temperatures. These data are included below for each material in the appropriate sub-section.

4.2.1.1 Cost of Generation I Materials

Generation I conductors contain two material components. The superconductor, BSCCO, and the supporting matrix, silver. The costs of these materials are reasonably well known from a variety of sources.[21] The cost of the BSCCO starting material used for this study is $2 per kg. This cost is a very small portion of the total conductor cost and it is not expected to change significantly in the future. The cost of silver used for this study is $5.00 per Troy ounce, which is near the traditional average (14 Troy ounces make a U. S. pound). Unfortunately, the cost of silver is controlled by the commodity market. It has changed upward by factors of two or three in the past and there are some projections that this could occur again. Since silver is a major cost component of the Gen I materials fabricated today, an increase in cost will have a detrimental effect on their commercial viability.

The Bi2223 tapes fabricated today have an aspect ratio between 10 and 20 and have typical dimensions of 3 mm by 0.2 mm. The fabrication costs used in this study for Gen I materials are for tapes having these dimensions and are based on discussions with manufacturers. Though specific costs are proprietary are not generally given out, an estimate of equipment costs and labor requirements provide an estimate of the cost per meter of conductor. The average fabrication cost per meter of Gen I conductor today is estimated to be about $2. Two factors will contribute to a reduction in fabrication cost over the next two years. The first is the increase in material uniformity and longer piece lengths. The second is the anticipated increase in total production. For example, the BSCCO tapes undergo many passes through a pair of rollers as the cross section is changed from a circular wire to a flat tape. This process is labor intensive at present as the tapes are individually processed and there is a modest shape change during each pass. Labor costs for Nb-Ti superconductors decreased when larger quantities were produced. A similar effect is anticipated for the Gen I materials. Though making a clear estimate of the reduction of fabrication cost is not possible, a factor of 5, including the likely change to larger conductors, is in keeping with the reduced labor costs seen in Nb-Ti conductors. Thus, a projected fabrication cost of $0.4 per meter used in this study for Gen I materials.

The costs of a cubic meter of Gen I conductor are shown in Table 4-1. This cost includes an 11% profit for the manufacturer, which of course depend on the market at the time the materials are purchased. The resulting total cost of conductor is thus 1.64 M$ per cubic meter and for the calculations of SMES system costs in this report. This unit cost and the current densities given in Section 3 provide the cost in $/kAm of the Gen I conductors as given in Table 4-2.

The Gen I conductor BSCCO 2212 was found to be more attractive at 4.2 K than BSCCO 2223 and it requires less processing. However, the same fabrication costs are used for both Gen I materials because less of it is produced today.

Table 4-1
Costs Components of Generation I Conductors

Material	Ag	BSCCO	Total/Average
Conductor Fraction	**0.5**	**0.5**	**—**
Specific Gravity	**10.5**	**6.2**	**8.35 Avg.**
Cost ($/kg)	**154**	**2**	**78**
Weight kg/m^3 of Conductor	**5250**	**3100**	**8350 Total**
Cost $/m^3 of Conductor	**808500**	**6200**	**815000**
Fabrication Cost @0.4 $/m	**—**	**—**	**667000**
Profit at 11%			**158000**
Total Cost $/m^3 of Conductor			1640000

Table 4-2
Unit cost ($/kAm) of Generation I conductors as a function of magnetic field and temperature

Field/Temperature	4 K ($/kAm)	20 K ($/kAm)	30 K ($/kAm)
3 T	**1.75**	**4.32**	**4.90**
5 T	**2.09**	**4.56**	**6.07**
7 T	**2.38**	**5.21**	**8.63**
10 T	**2.67**	**6.31**	**23.35**
15 T	**2.98**	**8.20**	**164.00**

4.2.1.2 Cost of Generation II Materials

The cost of the Gen II material is based on an analysis similar to that carried out for the Gen I materials above. There is however, no large scale production of Gen II materials. Thus, a bottoms-up approach is used to develop a conductor cost in this case. The Gen II conductor is assumed to be in the form of a 1 cm wide tape, which may formed by any one of several processes under development today. The tape consists of layers of four different materials. Because the goal is to increase the overall, or engineering, current density, the Gen II superconductor is applied on both sides of the tape. The materials used and the process assumptions are discussed below.

1. The starting material for Gen II conductor fabrication is a metal backing that supports the other components and provides a backbone for the conductor over its entire length—which must be on the order of kilometers to be effective in practical devices. Nickel is the most frequently used backing material today. However, other materials are being explored for a variety of technical reasons. A nickel backing thickness of 50 μm is used for this cost estimate.

2. The second material is a substrate, which forms the crystalline pattern. Materials such as yttria stabilized zirconia (YSZ) and magnesium oxide are used for the substrates. The substrate also establishes a long range order, i.e., it maintains the superconductor lattice characteristics over large distances. This characteristic is necessary to maintain consistently high current density in long lengths of conductor. In addition, some of the Gen II conductors have a thin layer (< 0.3 μm) of a second substrate material, such as cerium oxide. This material provides a chemical barrier between the YBCO and the YSZ during the superconductor formation process. The total thickness of the substrate and buffer is 10 μm on each side of the backing.

3. The YBCO superconductor is formed on the substrate. Today the critical current of the superconductor depends on the thickness of the YBCO layer. Layers thicker than 1 μm usually have lower performance than thinner layers. However, layers thicker than 2 μm can be fabricated with techniques available today. It is assumed that 5 μm of high quality YBCO can be deposited because manufacturing capabilities will improve.

4. A 5 μm layer of silver is applied on the surface of both sides of the tape. It provides a path for current should the superconductor become normal and provides a contact layer for electrical connections.

Because Gen II superconductors are still in the developmental process, there is no specific manufacturing process that can be described and used to estimate the conductor costs. It is possible, however, to calculate material costs and to estimate the fabrication cost per meter of length of conductor. The material percentages and costs are given in Table 4-3.

Table 4-3
Materials and material costs for Generation II Superconductors

Material	Ni	Substrate	YBCO	Silver	Total/Average
Thickness (μm)	50	2 x 15	2 x 5	2 x 5	100.0
Specific gravity	7	2.5	6	10.5	6.7
Cost ($/kg)	10	10	10	152.72	54.7
kg/m^3 conductor	2800	750	600	1050	5400
Wastage	280	1500	1800	10	N/A
Cost ($/m^3)*	30800	22500	24000	162000	239000

* Includes wastage

The fabrication of Gen II materials typically referred to as coated conductors is being developed by many institutions both in the United States and overseas. Several documents describe the different procedures that can be used. It appears that the general form of the conductor described above is independent of the actual fabrication procedure for the backing, the type of substrate, and the procedure for applying the YBCO. As a result a general set of steps for fabrication is used here to establish a unit cost required to fabricate a meter of conductor. Critical to the cost estimate are the following assumptions.

- Either a single line or two nearly sequential lines can be used to fabricate the conductor (including the addition of silver to the surface).
- One piece of apparatus is adequate for deposition of both the substrate(s) and the YBCO.
- The line(s) accept the backing material in a roll that is the proper length for the fabrication of the conductor at one end and accumulate and safeguard the completed conductor in the final length at the other end.
- The conductor backing material begins as a 5 cm wide strip, which is split after conductor fabrication. Thus, five, 1 km long conductors are fabricated simultaneously. This procedure was used at one time the fabrication of Nb_3Sn.
- The conductor moves through the line at 1.25 m/minute, which will allow the production of a 1 km piece of 5 cm wide material per day.
- The YBCO deposition rate is 0.1 μm per second, which has been observed on samples.

Since the deposition rate is 0.1 μm per second and 5 μm are to be deposited, the system must expose the conductor to YBCO deposition for a period of 50 seconds, thus, the deposition zone needs to be about 1 m long. Since the deposition for the substrate must be of the same length, the line will be on the order of 5 m including the silver deposition system and the supply and take-up reels. Because the improvements in Gen I conductor performance has come from improvements in temperature and process control, it is possible that slow deposition will be required. Thus, as a contingency, we assume that the length of the fabrication facility will be 10 m long which is twice the estimate.

The line is assumed to operate 200 days per year with a 20 percent down time. Thus it will produce about 800,000 meters or 0.8 m^3 of conductor in a year.

The facilities used today for Gen II wire production in meter lengths are about 2 meters long and cost about $200,000. Since the mass production line is 10 m long, its capital cost can be scaled to $1,000,000. The annualized cost is $250,000, based on 4 years operation with limited maintenance, exclusive of the labor costs included below. The cost of the space to install the line in a factory is $200,000, which is annualized to $40,000. Power to operate the line is estimated to be 100 kW during operation and 40 kW during idle periods. If the average power cost is 0.03 $/kWh, the total annual power bill for 200,000 kWh will be $6000.

Labor to produce the wire will depend on the number of individuals directly involved in the process, the oversight, and extent of quality control and assurance required. Here we assume that there will be two lines operating simultaneously and that 3 full time technicians will be required for a pair of lines and that 0.5 engineers, 0.5 quality assurance staff and 1 miscellaneous staff will also be required. In addition there are overhead functions for the facility, purchasing, etc. It is estimated that the pair of lines will require 6 full time equivalents and that the average salary including benefits is $70,000. The annual labor cost is $420,000. As a contingency this cost for labor is assigned to each single line.

Since the conductor is 10 mm wide and 0.1 mm thick, a cubic meter is the equivalent of 1000 km of conductor. As shown in Table 4-4, the cost of fabrication is 0.90 $/m, exclusive of material, and 1.25 $/m total, including a profit of 10% and a contingency of 0.42 $/m. A recent estimate by IGC [22] suggested that the cost would be about 4 $/m in a few years, but did not assume large-scale production.

The cost per cubic meter and the current densities given in Section 3 provide the cost in $/kAm of the Gen II conductors shown in Table 4-5.

Table 4-4
Cost components of Generation II conductors

Item	Cost ($/m)	Cost ($/m3)
Labor*	0.525	525,000
Facility	0.050	50,000
Production Line*	0.313	312,500
Power	0.008	8000
Fabrication Cost Subtotal	0.896	895,500
Material	0.239	239,000
Subtotal	1.134	1,134,500
Profit (10%)	0.115	115,500
Total	1.250	1,250,000

* Contingency included in these two items is $.42 per meter, or 33%.

Table 4-5
Unit cost ($/kAm) of Generation II conductors as a function of magnetic field and temperature

Field/Temperature	4 K ($/kAm)	20 K ($/kAm)	30 K ($/kAm)
3 T	0.49	0.62	0.74
5 T	0.62	0.78	0.94
7 T	0.72	0.91	1.10
10 T	0.86	1.09	1.32
15 T	1.20	1.53	1.86

4.2.1.3 Niobium Titanium

The cost of Nb-Ti conductors are determined by the cost to fabricate the materials for magnetic resonance imaging and particle accelerator magnets. These two applications use, on the average, well over than 100,000 kg (100 tones) of copper stabilized Nb-Ti material per year. The Large Hadron Collider under construction at CERN, which is near Geneva, Switzerland, will use about 1000 tones over the next 5 years for accelerator dipoles.

The homogeneous Nb-Ti material used as a precursor for the conductor costs about $130 per kg. It is combined with copper and formed into wires that are approximately 1 mm in diameter. The ratio of copper to Nb-Ti and the exact dimensions of the wires are determined by the application. The wires may be used directly or they can be formed into cable or braided composite conductors. The LHC uses several conductors, one of which is the cable for the outermost of two layers that form the dipole magnets. This conductor consists of 36 wires (strands) that are

0.825 mm in diameter. Copper occupies 66% of the cross section. These strands are assembled as a tubular structure and then flattened into a “Rutherford” cable, which has a cross section of about 1.5 mm by 16 mm. The delivered cable costs about 80 $/lb. or 176 $/kg. Because smaller quantities will be used for the SMES applications considered here, the cost for copper stabilized Nb-Ti wire with 62% copper (Cu/SC ratio=1.6) is estimated to be 100 $/lb. or 220 $/kg. Table 4-6 shows the resulting unit cost of Nb-Ti conductor in $/kAm.

Table 4-6
Unit cost ($/kAm) of Nb-Ti conductors at 4.2 K as a function of magnetic field

Magnetic Field	Cost ($/kAm)
3 T	1.31
5 T	1.49
7 T	1.84
9 T	2.84

4.2.2 Normal Conductor

The operating temperature and magnetic field determine the quantity of each class of superconductor needed for a given application. These parameters also set the minimum quantity of normal conductor because the superconductors have some normal conductor added during fabrication.

Independent of the type of superconductor and the operating temperature and field, there must be adequate normal conductor to carry the current for a period long enough to assure the safety of the magnet. Copper is added to achieve magnet protection. The quantity of Cu is based on the need to limit the initial heating of the conductor while still allowing a large fraction of the coil to transition from the superconducting to the normal state. These two goals are somewhat contradictory. However, a compromise solution is achieved by assigning a maximum operating current density of 450 A/cm^2 to both silver and copper. Once the current carrying capacity of the silver in the HTS conductors and the copper in the Nb-Ti conductors has been determined, additional copper is added to reach the 450 A/cm^2 criterion.

4.2.3 Structure

The structure required to support the superconducting coil is based on the need to restrain the Lorentz forces associated with the magnetic field produced by the coil. A general relationship between the stored energy and the constraining structure is used to estimate the material requirement. This relationship has been checked on other magnet systems and has been found to provide and adequate measure of the structural requirements. An alternative approach would have been to carry out a detailed design of the magnet and then similarly detailed design of the structure based on the local forces within the magnet. This will be required prior to building a SMES system. However, it would have required a great deal of time and effort and the resulting costs would not have been significantly different from those estimated here.

The approach uses the virial theorem, which relates the stored energy in a mechanical system to the volume of structural material under stress that is required for containment. This can be expressed as:

$$Vol = \kappa \frac{Energy}{Stress_{Working}}, \qquad \textbf{Eq. 4-1}$$

where κ is a geometrical constant that describes how effectively the structure is used in the design. One cubic meter of a material having a working stress of 276 MPa (40 ksi) and used in the best possible design can support the load created by 276 MJ of stored energy. Note that this result is independent of the density of the material. The same volume of a heavy material (steel, e.g.) would be required as of a light material (aluminum (e.g.). Neither the solenoidal or toroidal geometries considered here allow the structural materials to operate at their highest efficiencies. About 2.5 times the ideal amount of material is needed for both magnet configurations.

Since many of the magnet components contribute to the constraint of the magnetic forces, the first step in determining the required quantity of aluminum structure is to calculate the fraction of the magnetic load that these components—mainly the conductor—can carry. The copper and silver in the conductor are assigned a working stress level of 69 MPa, (10 ksi) and the nickel backing a stress level of 276 MPa (40 ksi) for the analysis. Sufficient aluminum structure is then added to support the remaining load.

The conductor materials support a great deal of the load in the small SMES unit at 30 K. However, large volumes of structural material (up to 13 cubic meters of aluminum) are needed for the 1500 MJ systems.

The approach mentioned above was used for all the toroidal calculations. The cost of structural aluminum was observed to be a small fraction of the cost of other components. Because this contribution was low and the solenoid calculations were long, it was decided to use include 2.5 times the virial volume of aluminum for all the solenoidal cases. The effect is to increase the solenoidal costs slightly, which is considered to be a conservative approach.

4.3 Cost of the Cryostat

The cost of the cryostat is a simple estimate based on the dimensions of outside of the superconducting coil plus an increment for the vacuum and superinsulation, etc. The assumed cost is $1000 for each square meter of this calculated surface. This unit cost is used for all temperatures and is independent of the quantity of stored energy. It is based on limited information on cryostat costs for existing and proposed superconducting magnets. It is low for the two smaller units (4 and 100 MJ) and is approximately correct for the 1500 MJ system. Nevertheless it provides a good estimate for making comparisons for the different temperatures and fields for each of the 3 sizes.

4.4 Refrigeration

The heat load that must be removed by the refrigerator is produced by several different processes. Not all of the heat input occurs at the operating temperature. Thus, the refrigerator must be designed to provide cooling at both the operating temperature and at intermediate temperatures for heat shields and conduction intercepts. For the purpose of this study, each of these heat inputs is converted to an effective load at the operating temperature. The following heat inputs are used in this study and the total refrigeration load is a sum of these terms.

1. Heat conduction along the supports for the mass of the coil and cryostat is based on the weight of the cold mass. A value of 7 watts per 1000 kg is used for the value at 4 K. The conduction at 20 K (30 K) is assumed to be 95% (90%) of the value at 4 K.

2. Radiation from ambient to the cold mass is estimated to be 0.03 W/m^2 for the entire surface of the cryostat. Since most of this load occurs at an intermediate temperature, and is driven by the ambient temperature outside the cryostat, it is held constant independent of operating temperature.

3. Thermal conduction associated with the power leads is assumed to be 4.0, 2.8, and 2.0 W/kA at 4, 20, and 30 K respectively.

4. AC losses in the coil associated with operation are assumed to be a constant input of 30, 25, and 20 W respectively at 4, 20, and 30 K for the two 1500 MJ cases. Lower losses are used for the smaller units. Note that the heat input is assumed to be continuous, rather than pulsed, which it would be in real operation.

5. Thermal losses in the helium transfer system are assumed to be 40% of the calculated load.

The refrigeration load for 4 different cases are given in Table 4-7.

The costs for the 4 K refrigeration used in this report are based on a continuing assessment in this area that was initiated by Strobridge, Mann, and Shelton in 1966. [23] That effort included a survey of many different helium refrigerators available at the time. Several updates to that information have been made by the original authors, by subsequent users of refrigeration, and by magnet builders. The early data prepared by Strobridge et al. is still relevant to cost estimates today when a factor is included for inflation. Updated refrigerator costs were included in a paper by Green, Burns, and St. Lorant in 1991. [24] Their estimates are used in this report with a 20% across-the-board cost increase. This increase has been confirmed by contacting two helium refrigerator manufacturers.

Table 4-7
Refrigeration loads in watts for sample SMES systems

Configuration	Torus	Torus	Solenoid	Solenoid
Size	**1500 MJ**	**1500 MJ**	**1500 MJ**	**100 MJ**
Operating Temperature (K)	30	4	4	30
Conduction (W)	870	960	541	49
Radiation (W)	15	15	4	1
Power Leads (W)	80	160	320	40
AC Losses (W)	20	30	30	3
Transfer (W)	395	460	354	196
Total	1380	1625	1253	317

The results of the two papers mentioned above are relevant at temperatures well above 4 K if the costs are based on the room temperature power requirements rather than the heat load. This is seen to be very reasonable when it is observed that gaseous helium is the working fluid in nearly all refrigerators for temperatures below 100 K. Thus the general characteristics of the refrigeration units considered in this study are similar for all the SMES systems and all temperatures. Only the minimum operating temperature and the room temperature power requirements are different.

The refrigeration requirements for temperatures at 20 and 30 K are scaled from the 4.5 K values by two factors. The first factor is the Carnot efficiency. Less room temperature power, and thus less machinery is required for a 20 or 30 K refrigerator than is required for a 4 K refrigerator. To first approximation the relation is simply the ratio of the operating temperatures. Thus, ideally, a 1 kW refrigerator at 4.5 K would require 5 times the power—and be about 5 times the size—of a 1 kW refrigerator at 22.5 K. However, the room-temperature power required for refrigeration at temperatures above 4 K is even smaller than this theoretical estimate. There are two reasons for this additional reduction. First, refrigerators are not 100% efficient in terms of reaching the Carnot ideal. Second, the heat load at elevated temperatures can be smaller because radiation, conduction, and convection within the refrigerator itself decrease as the temperature increases.

The approach used in this study to estimate room temperature power is to assign a cost based on Figure 4-2 to each of the refrigeration cases. This is most easily accomplished by using the following formula.

$$C_{refr} = P_{refr}^{0.7} \cdot f(T),$$

where C(T) is the cost of the refrigerator at a temperature T, P is the calculated power in kilowatts at the operating temperature, and f(T) is a value from Figure 4- 2, namely: f(4)=$1,800,000, f(20)=$650,000, and f(30)=$500,000.

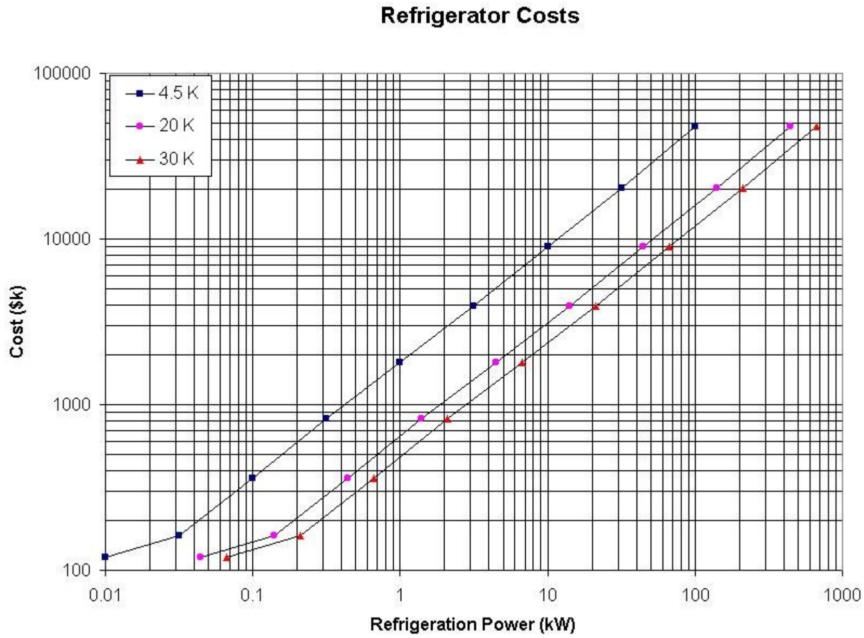

Figure 4-2
Cryogenic refrigeration costs

4.5 Construction

The cost of the construction of the SMES systems is based on estimates that were made in previous analyses of SMES systems. To simplify the calculations, the cost of construction of the 1500 MJ toroidal SMES was set at $2M. This value was set to give a total cost for the Nb-Ti System including refrigerator of about $10M. The cost of construction for other systems was based on the length of conductor and the total weight of the coil and cryostat.

4.6 Miscellaneous

The various miscellaneous items are often called the balance of plant. They include the following.

- Installation of components other than the coil, cryostat and refrigerator
- The control and instrumentation system
- Power leads
- System engineering

These items are expected to be approximately the same independent of operating temperature. As a result, a single value has been chosen for each specific coil configuration as summarized in Table 4-8.

Table 4-8
Miscellaneous costs for the different SMES systems.

System	1500 MJ Torus	1500 MJ Solenoid	200 MJ Solenoid	4 MJ Solenoid
Cost ($)	500,000	375,000	88,000	7,600

5 SMES SYSTEM EVALUATION AND SYSTEM COSTS

5.1 Design Approach and Cost Breakdown

The procedure for determining dimensions and costs for each of the different SMES cases required several *a priori* design assumptions. Previous assessments of SMES and other superconducting magnets provided ample input to simplify the analysis and to provide starting points for the optimization processes used in the analysis. The basic configuration aspects of the coils were the initial inputs to the calculations that were carried out by a computer code Mathcad®. This code had been used by one of the authors for previous analyses of HTS SMES systems.

5.1.1 Solenoid

Solenoidal magnets, Figure 5-1, are frequently described by their aspect ratio (β), which is simply the height divided by the diameter. Previous studies of the quantities of materials for solenoids [25] indicated that the conductor requirements are a minimum when the aspect ratio is about 0.3. This optimum became the starting point for the analysis, and was verified, as shown in Figure 5-2. Though this value minimizes the total amount of superconductor, it does not necessarily minimize the total system cost. As a result the aspect ratio was left as a design parameter throughout the analysis. As can be seen from the figures, the only restriction on the aspect ratio for a solenoid is $\beta > 0.0$.

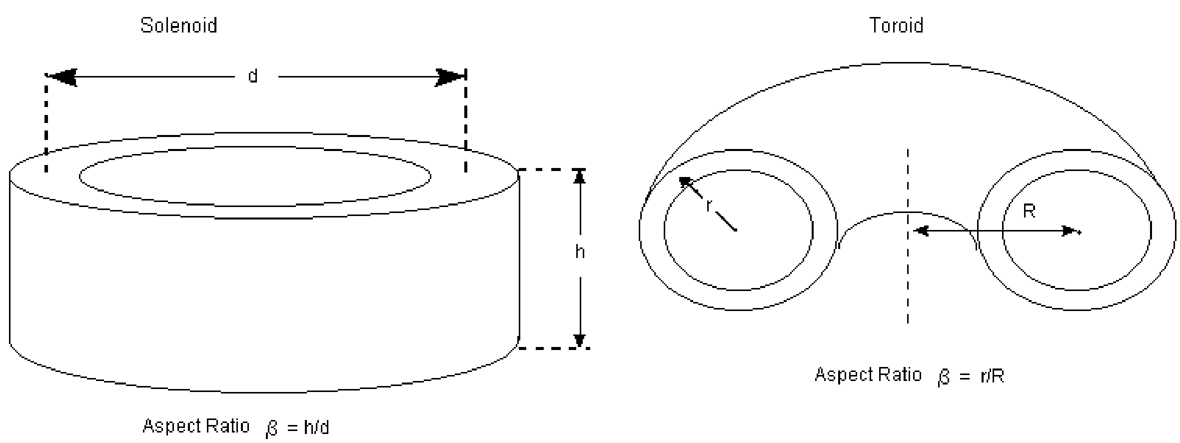

Figure 5-1
Sketches of solenoidal and toroidal coils showing aspect ratios

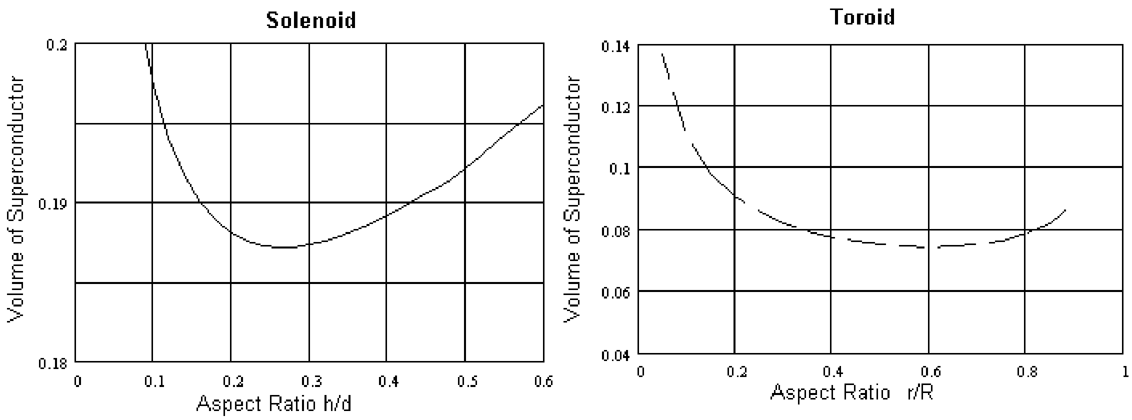

Figure 5-2
Effect of aspect ratio on quantity of superconductor required for a SMES coil

Assumptions for the analysis of the solenoidal SMES system included:

- The conductor is made up of ceramic based HTS superconductor combined with silver, and adequate normal conductor (copper) to provide quench protection.
- The coil is continuously wound in the axial direction, adding radial layers as needed. (This is in contrast to a pancake-wound approach.) The choice was made to simplify calculations and does not affect the results.
- Conductor spacing is maintained by the use of insulating materials, which decreases the average current density in the windings.
- Aluminum bands positioned outside the coil windings provide the structure to support the radial Lorentz force. (The conductor itself provides minimal hoop resistance.) A virial theorem approach was used to calculate the total amount of aluminum structure.
- The coil is contained within an aluminum cryostat. Either immersion cooling, cable-in conduit, or indirect (conduction) cooling is suitable. (This design detail was not addressed.)
- A single set of power leads carries current in and out of the coil to ambient temperature power electronics.
- Refrigeration is sized to meet all heat loads: conduction, leads, ac losses, radiation, and internal thermal inefficiencies.

5.1.2 Toroid

Toroidal magnets, Figure 5-1, are also described by their aspect ratio (β), which is the ratio of the minor and major radii. Previous studies of the quantities of materials for toroids [25] indicated that the conductor requirements are a minimum when the aspect ratio is about 0.5. This optimum became the starting point for the analysis, and was verified, as shown in Figure 5-2. Though $\beta = 0.5$ minimizes the total amount of superconductor, it does not necessarily minimize the total system cost. As a result, the aspect ratio was left as a design parameter throughout the analysis. As can be seen from the figures, the only restriction on the aspect ratio for a toroid is $\beta < 1.0$.

The assumptions for the toroidal SMES systems are generally the same as those for the solenoid. The two major differences are:

- A direct, closed form, calculation gives the conductor requirements for a toroidal coil. Thus, no assumptions were required for the winding geometries and the procedure for fabrication.
- More conductor is required for the torus than for the solenoid and some components of the conductor have structural capability. Part of the Lorentz load can be carried by this structural material. The Lorentz load for the torus is also carried in tension in an aluminum structure, however, the quantity of aluminum was reduced to reflect the structural contributions of the conductor components.

As described in Section 4, the total SMES system storage-related costs are made up from a number of components and were calculated based on material capabilities. The following sub-elements were used to develop total system costs.

a. Superconducting material

b. Normal conductor and superconductor support

c. Coil fabrication

d. Structure

e. Cryostat

f. Fabrication and assembly

g. Refrigerator

h. Miscellaneous components

5.2 Sensitivity Studies

The evaluation of HTS SMES systems provided a set of cost projections for different systems and system components. In particular it determined the cost sensitivities of the four base cases and several components to a number of design choices that are indicated in Table 5-1. The sections below describe the total system storage-related cost for a number of these parameters. However, exploring all the details of the sensitivity of individual components to the items in Table 5-1 is beyond the scope of this report.

5.2.1 Cost sensitivity to operating temperature and magnetic field

Plots of the sensitivity of the system storage-related cost of a 1500 MJ Gen I toroid to operating temperature and field are shown in Figure 5-3. The 4 K system has the lowest cost. This is mainly a result of the high current density of the Bi-2212 material at 4 K and the fact that it alone—among the materials evaluated here—is not sensitive to field orientation. A contrasting result is shown in Figure 5-4 for the 1500 MJ Gen II solenoid, where the 30 K case is least expensive. Cost breakdowns for these two cases are shown in Figures 5-5 and 5-6.

Table 5-1
Parameters used in the sensitivity study

Parameter	Values
Delivered Energy	4 MJ*, 100 MJ, 1500 MJ
Configuration	Solenoid Torus (1500 MJ only)
Temperature	4K, 20K, 30K
Superconductor	Gen I, Gen II, NbTi *(4K only)*
Aspect ratio Solenoid Torus	 0.2 to 0.5 0.3 to 0.7
Magnetic Field	2 to 15 tesla

* 3600 MJ = 1 MWh

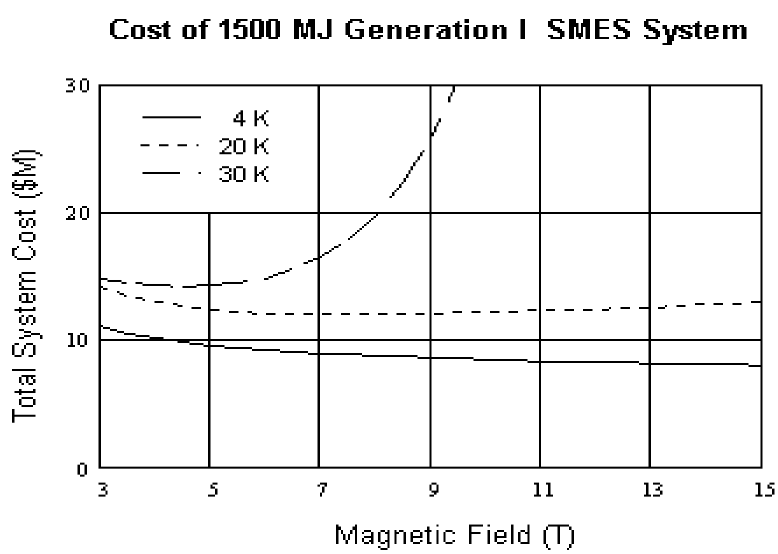

Figure 5-3
Total SMES system storage-related costs as a function of magnetic field for a 1500 MJ, β = .25 toroid, made with Generation I HTS materials

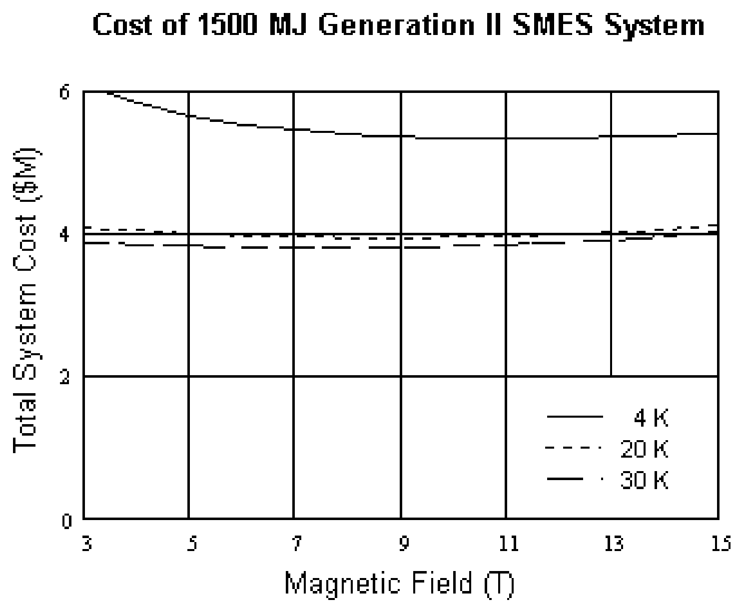

Figure 5-4
Total SMES system storage-related cost as a function of magnetic field for a 1500 MJ, β = .25 solenoid, made with Generation II HTS materials

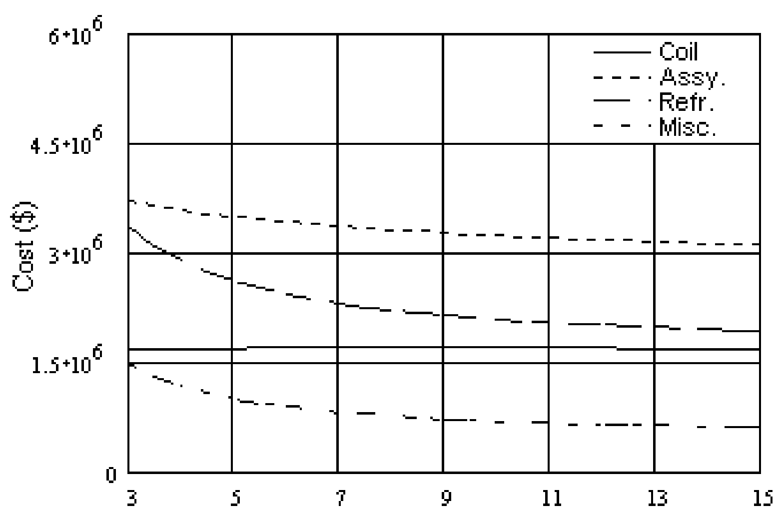

Figure 5-5
Cost breakdown for the 4 K, Gen I, 1500 MJ, β = .25, toroidal SMES

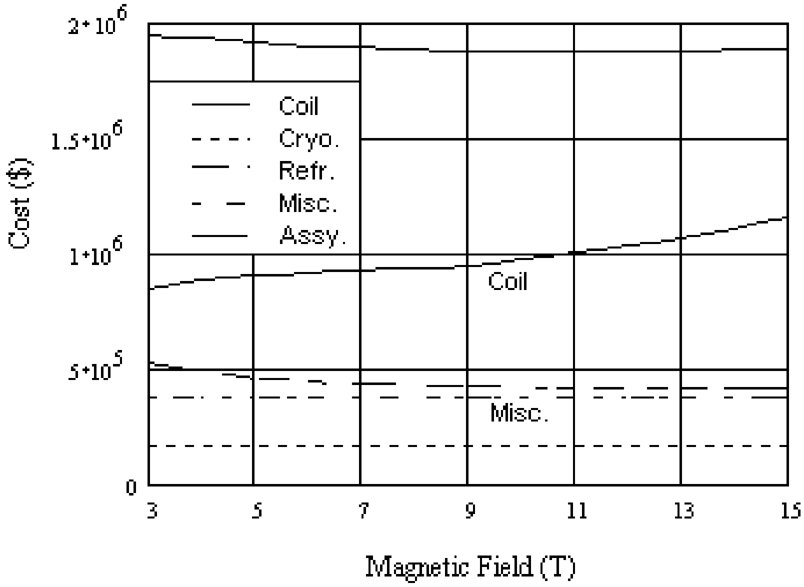

Figure 5-6
Cost breakdown for the 30 K Gen II, 1500 MJ, β = .25 solenoid SMES

5.3 Minimum Cost Results

The dimensions and costs of the least-expensive magnet system for each of the four cases are shown in Tables 5-2 and 5-3. The total costs are compared in Section 6, Figure 6-1 for the 1500 MJ case and in Figure 6-2 for the 100 MJ and 4 MJ cases.

Table 5-2
Overall coil dimensions for the four minimum cost cases

	SOLENOID			TORUS
	Case 1 (E = 4 MJ)	Case 2 (E = 100 MJ)	Case 3 (E = 1500 MJ)	Case 4 (E = 1500 MJ)
h (m) or 2r(m)	0.4	1.0	2.5	5.0
d (m) or 2R*(m)	1.5	4.0	10.0	9.7*

* Major diameter of toroid

Table 5-3
Costs and other parameters for the optimized systems

Type/Energy	Characteristic	Gen I	Gen II	NbTi
Solenoid	Cost ($M)	0.16	0.08	0.20
E=4 MJ	Aspect Ratio	0.25	0.3	0.25
Case 1	B (T)	15 (6)	9	6
	Temperature (K)	4 (20)	30	4
Solenoid	Cost ($M)	1.36	0.71	1.54
E=100 MJ	Aspect Ratio	0.25	0.25	0.25
Case 2	B (T)	15 (6)	9	5.5
	Temperature (K)	4 (20)	30	4
Solenoid	Cost ($M)	5.67	3.81	6.50
E=1500 MJ	Aspect Ratio	0.25	0.25	0.25
Case 3	B (T)	15	9	5
	Temperature (K)	4	30	4
Toroid	Cost ($M)	8.02	6.02	9.59
E=1500 MJ	Aspect Ratio	0.52	0.56	0.45
Case 4	B (T)	15	9.5	6
	Temperature (K)	4	30	4

From these results, it is clear that, if the manufacturing costs approach the estimates developed in section 5, SMES systems based on Generation II HTS materials will be extremely attractive. Gen I at 4K (i.e. Bi-2212) will also be able to compete with NbTi if labor costs can be reduced as total conductor output is increased.

6
CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Figures 6-1 and 6-2 provide a great deal of insight into the relative costs of different SMES systems. They support the following conclusions.

1. The cost of SMES systems made of Gen II conductors is predicted to eventually reach 50 to 70% of the cost of LTS based SMES systems.

2. As a result, if practical conductors can be made of the Generation II materials, it will be an ideal material for HTS SMES as well as a variety of other applications.

3. The results indicated that the lowest priced SMES systems will be made of Generation II materials and will operate at temperatures of 30 K (or higher).

4. Because of their higher operating temperature these systems will also have the lowest operating costs. (Operating costs were beyond the scope of this study.)

5. SMES systems made of Generation I materials can become competitive with LTS based SMES systems if fabrication costs can be reduced or silver content reduced.

6.2 Recommendations for Further Work

As a result of this study, the following suggestions are made for additional effort to develop HTS based systems. These recommendations relate to either system parameters or to HTS technology improvements.

Programmatic—system or application related

1. Develop SMES system costs as a function of temperature to determine the minimum capital cost system.

2. Develop SMES system costs for fields higher than 15 T, where applicable.

3. Explore cost details of Generation I and Generation II conductor fabrication.

4. Estimate operating costs of the SMES systems at different temperatures and develop a total life-cycle cost based on expected lifetime and performance. This should include operation of the refrigerator, PCS, maintenance, etc.

5. Assess the impact of device size and footprint—depends on allowable magnetic field—on value and potential market.

6. Carry out a sensitivity study of the cost of HTS SMES systems should some of the improvements listed below come to pass. This effort will establish priorities for further developmental work.

7. Carry out a complete evaluation of existing data on the effects of strain on HTS conductor performance. The effort should include both axial tension and transverse compression.

HTS Technology Advances

1. Evaluate existing approaches for conductor production and superconducting device requirements to determine the optimum form for HTS based conductors, e.g., cable in conduit conductors or multistrand tapes.

2. LTS wires are internally subdivided into thousands of filaments, which reduces hysteretic losses. In addition, independent current paths add stability and robustness to the system design. Various concepts should be explored to determine approaches that may provide similar subdivision in HTS materials.

3. Establish methods for sharing current among the different wires in the conductor and the different current paths in individual wires.

4. Develop conductor designs that incorporate a sufficient number of individually produced HTS conductors to carry 10,000 to 40,000 A.

5. The most expensive part of the Generation I material is the silver sheath. Alternative materials and methods for lowering the fraction of silver needs to be investigated.

6. Develop approaches for increasing the thickness of the YBCO layers in the Generation II conductors. Thicknesses of 1 μm are common today, but this needs to be increased by a factor of 5 or more to achieve the economics predicted in Figures 6-1 and 6-2.

7. There is little data on the performance of HTS materials at temperatures other than 4 and 77 K, and in self field. An effort to provide data at intermediate temperatures and at fields up to 20 T, and to have a facility available for the measurement of new materials would be a useful contribution to the development of future HTS conductors.

8. Carry out a sensitivity study of the cost of HTS SMES systems should some of the improvements listed above come to pass. This effort will establish priorities for further developmental work.

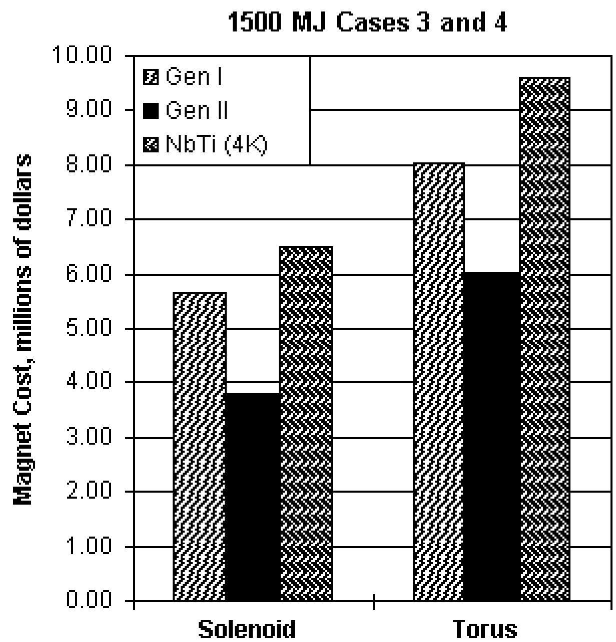

Figure 6-1
Cost comparison for 1500 MJ SMES systems—Cases 3 and 4 in this study

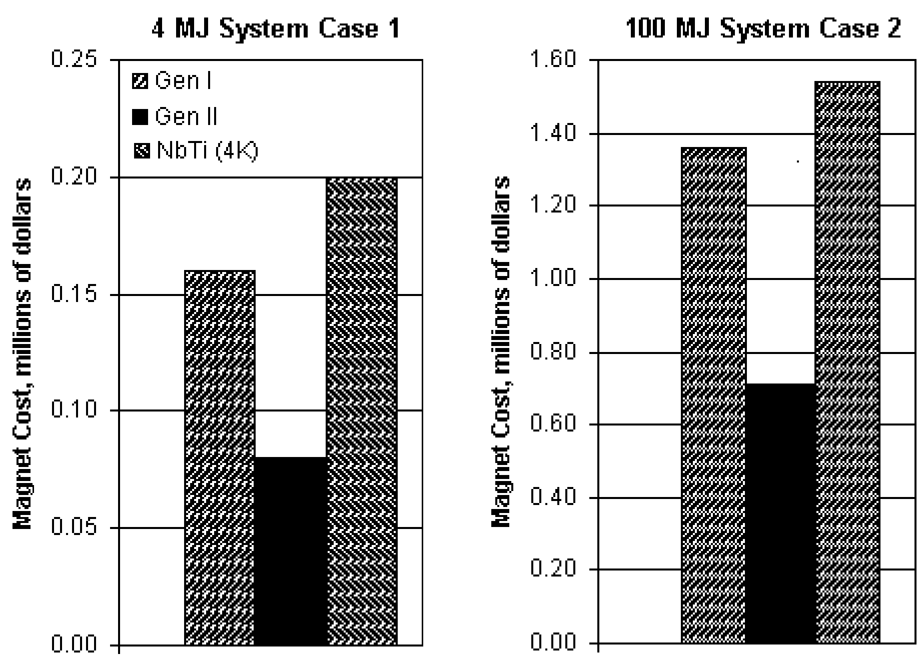

Figure 6-2
Cost comparison for 4 and 100 MJ SMES systems—Cases 1 and 2

A
REFERENCES

1. H. K. Onnes, *Leiden Comm*. 120b, 122b, 124c (1911).

2. The Applied Superconductivity Conferences are held in North America every even year. The proceedings of recent conferences are published in the IEEE Transactions on Applied Superconductivity.

3. S. Foner, E. J. NcNiff, Jr., B. T. Matthias, T. H. Geballe, R. H. Willens, and E. Corenzwit, "Upper Critical Fields of High-temperature superconducting $Nb_{1-y}(Al_{1-x}Ge_x)_y$ and Nb Al: Measurements of H_{c2} 400 kG at 4.2 K" Physics Letters, 31A 3490350, 1970.

4. J. G. Bednorz and K. Mueller, *Z. Phyzik* **B64**, 189 (1986).

5. M. K. Wu, *et al.*, Physics Review Letters, **58**, 908 (1987).

6. C. W. Chu, et al., *Science* **235**, 567 (1987).

7. Z. Z. Sheng, and A. Herman, Nature **332,** 55 (1989).

8. H. Maeda, *et al.*, Japanese Journal of Applied Physics **27**, L209 (1988).

9. Descriptions of the advances in HTS material performance can be found in several publications. One significant Meeting each year is the Material Research Society. Proceedings of the conferences are available in most University Libraries.

10. The American Physical Society (APS) has several U.S. and regional meetings that include sessions on HTS materials. In addition, there are several journals published by the American Institute of Physics, of which the APS is a member, that include HTS materials.

11. S. X. Dou *et al.*, Superconductivity Science Technology, 3, 138 (1990) and S. Jin *et al.*, U.S. Patent #4,952,554 (filed April 1987, issued August 1990).

12. M. Ferrier, "Stockage d'energie dans un enroulement supraconducteur", in Low Temperature and Electric Power. London, England: 1970, Pergamon, pp. 425-432.

13. H. A. Peterson, N. Mohan, and R. W. Boom, "Superconductive Energy Storage Inductor-Convertor Units for Power Systems", IEEE Trans. Power Systems", IEEE Trans. Power App. Syst., Vol. PAS-94, No. 4, July-August 1975.

14. W. V. Hassenzahl, Private Communications. Warm support was selected at LANL for SMES development and was reported in a paper on the possibility of warm support for fusion

magnets by J. R. Powell and P. Bezler, “A Comparison of Warm- and Cold-Reinforcement Magnet Systems for Tokamak Fusion Reactors”, in Proc. Technology of Controlled Thermonuclear Fusion Experiments and the Engineering Aspects of Fusion Reactors (Austin, TX, 1973), pp. 358-383.

15. R. L. Cresap, W. A. Mittelstadt, D. N. Scott, and C. W. Taylor, “Operating Experience with Modulation of the Pacific HVDC Intertie”, IEEE PAS Summer Meeting, Mexico City 1977.

16. *Facts with Energy Storage: Conceptual Design Study*, EPRI, Palo Alto, CA: 1999. TR-111093.

17. J. T. Steiger, G. Fuchs, P. Verges, K. Fischer, L. Schultz, and A. Gladun, “Critical current in silver sheathed Bi-2223 tapes”, IEEE Trans. Appl. Supercon. **7**, 1347, (1997).

18. Several approaches can be used to extrapolate from short sample to working values. Since there is little experience with the use of HTS materials in magnet design, a conservative design value of 0.55 to 0.6 is used. Private analysis W. V. Hassenzahl, based on experience with LTS magnet design.

19. M. S. Lubell, IEEE Trans. On Magnetics MAG-19, 754 (1988).

20. Martin N. Wilson, Superconducting Magnets Oxford Science Publications, Oxford, UK, 1983.

21. Private communications HTS wire manufacturers.

22. Private Communication form M. Walker of IGC *vis-à-vis* data from 1998 DOE Peer Review of the Superconductivity Program for Electric Systems.

23. T. R. Strowbridge, IEEE Transactions on Nuclear Science, NS-16, No.2, P1104 (1969).

24. M. A. Green, R. A. Byrns, and S. J. St. Lorant, “Estimating the Cost of Superconducting Magnets and the Refrigerators Needed to Keep Them Cold”. Advances In Cryogenic Engineering, Vol 37, Feb, 1992 Plenum Press, New York.

25. W. V. Hassenzahl, “A Comparison of the Conductor Requirements for Energy Storage Devices Made with Ideal Coil Geometries”, IEEE Transactions on Magnetics, VOL. 25, No.2 March 1989. 1998 ASC.

B
CRITICAL CURRENT DENSITIES OF HIGH TEMPERATURE SUPERCONDUCTORS

This Section Prepared by Dr. Nina Heinig

B.1 Introduction

For large-scale applications of superconductivity, such as magnets, generators, and power-transmission lines, the parameter controlling performance is the amount of electrical current that can be carried in the wires that make up the device. Thus, the critical current density, J_C, is the important materials parameter for these applications. For superconducting magnet energy storage (SMES) devices made from high temperature superconductors (HTS), a feasible product can be expected to run in Tesla magnetic fields, and at temperatures between 15 and 77 K.

Typically, transport Jc is found by measuring the current-voltage characteristic of the material, and selecting an arbitrary level of dissipation (either voltage, or electric field) to define J_{CT}. A HTS J_C criterion of 1 or even 10 μV/cm is common in the literature, but a better comparison of properties can be made at a lower dissipation level of 0.1 μV/cm. This lower criterion is commonly used in low-temperature superconductors, and more accurately reflects the low levels of dissipation needed for applications.

Another useful parameter for determining performance is the “n-value”. The relationship between the current through and the voltage across a superconducting wire can be approximated by a power-law.

$$V \propto I^n$$

The power n defines the sharpness of the transition from the superconducting to the normal state, and is related to both intrinsic superconducting properties, and the Jc variation in the conductor. Since SMES magnets must run at high currents and have low internal power dissipation, a high n value is desired. The low-temperature superconductors NbTi and Nb_3Sn have $n \approx 40$ and $n \approx 25$-30 respectively. The values of n for each of the HTS materials are included in the discussion.

There are other considerations when comparing J_{CT} made from different materials and processes for magnet fabrication. The engineering critical current density, J_E, which is the critical current divided by the entire composite cross-section, not just by the superconducting cross-section, is more relevant when designing a magnet. Different HTS will require different amounts of normal material to create viable, long-length superconducting cables. The quantity of normal stabilizer and structure will depend on the requirements for tensile strength, fabrication, and quench protection. For serious comparison of state-of-the-art Jc values it is also important to consider the length of material measured. It is possible to fabricate short segments of HTS with very high J_{CT}. Applications, however, require kilometer lengths of homogeneous material.

The high temperature superconductors discussed in this report include:

1. $Bi_2Sr_2Ca_2CuO_X$ (Bi-2212)

2. $(Bi,Pb)_2Sr_2Ca_2Cu_3O_X$ (Bi-2223)

3. $YBa_2Cu_3O_{7-X}$ (Y-123)

The structure of the report shall be to discuss the critical current densities of these materials individually. General discussions of the feasibility of HTS power applications can be found in references [A B C] at the end of this appendix. Comparisons of high field J_C of HTS with Nb_3Sn and Nb_3Al have been done recently by R. Flükiger [D].

B.2 Bi-2212

Bi-2212 materials are made by either a powder-in-tube (PIT) technique, or by a dip-coating method. In both cases a silver component is included in the conductor to promote grain alignment. The present (1997) world record Jc for this material is held by Hitachi Research Labs in Japan, with a J_C(4.2K, 0T) = 0.49 MA/cm^2, and J_C(4.2K, 23T, H||c) = 0.107 MA/cm^2 [A]. Field dependence at 4.2 K in both parallel and perpendicular orientations can be found in the work of Okada et al. (1995){E]. The field dependence of Jc at various temperatures was studied by several groups for Bi-2212/Ag PIT tape [F,G]. Intermagnetics General [H], Oxford Instruments, and American Superconductor Corp. are the main commercial suppliers of Bi-2212 conductor. Material made using dip-coating by Showa Wire and Cable Co. showed J_C(4.2 K, 21 T) = 0.1 MA/cm^2, and was used to fabricate a small test coil [I].

At 4.2 K, Bi-2212 performs better than Bi-2223 and Y-123, and at high magnetic fields already has an advantage over conventional superconductors [D]. Long lengths have been fabricated and used to make “pancake-coil” design magnet inserts. At higher temperatures, J_C(H) starts to decrease rapidly above about 25-30 K, because of the relatively low transition temperature ($T_C \approx 85$ K) and low irreversibility field. The main problems facing Bi-2212 conductor development are non-uniform Jc along the length of the conductor (i.e. better process control), and improving the strength of the Bi-2212/Ag composite.

Bi-2212 fabrication techniques are well developed, and long lengths can be made at the present time. The relatively low T_C and low irreversibility field constrain future improvements in J_C. Some improvements in J_C(H) can be expected by introducing pinning centers, either by introducing impurities (e.g. MgO grains) or by proton irradiation of the finished coil. In the near future (5 years), it is reasonable to expect that high field insert magnets made from Bi-2212 to be commercially available.

B.3 Bi-2223

While all the Bismuth-based HTS material have low irreversibility fields, Bi-2223 has a much higher transition temperature than Bi-2212 ($T_C \approx 110$ K), making it attractive for 77 K, self-field operation. Bi-2223 is made by a PIT technique with a silver sheath, with phase purity more difficult to obtain than in Bi-2212. From ref. [A], the record J_C(77 K, 0 T) = 0.055 MA/cm^2 over a 5 cm length is from American Superconductor (ASC), but over kilometer lengths this value drops to 0.012 MA/cm2. Sumitomo Electric in Japan has slightly higher J_C values over kilometer lengths, with J_C(77 K, 0 T) = 0.0177 MA/cm^2. Other leading manufacturers of Bi-2223 conductor include Vacuumschmelze/Siemens and FZK (Karlsruhe) in Germany, and Intermagnetics General.

The Bi-2223 field dependence of J_C at different temperatures have been investigated by various groups [J,K,L,M,N]. In the paper by Dhallé et al. [N], J_C(H) between 0 and 2 T is measured between 40 K and 80 K, with strong field dependence observed for all temperatures. They also observed that the n-value had a strong dependence on temperature and field, finding at 10 K and 4 T that n=14, while at 6 T the n-value dropped to 10. At 60 K and only 1 Tesla, the n-value was only 3.

Moderate lengths of Bi-2223 are presently available. Most research appears to focus on ac and dc applications in self field at 77 K, i.e. for power transmission lines. Presently, Bi-2223 has not achieved the J_c(77 K, 0 T) needed for these applications, widely believed to be 0.10 MA/cm^2. However, improvements in powder uniformity and density, better grain alignment and better thermomechanical process control can lead to improved J_C. For the next 5 to 10 years, Bi-2223 will be the HTS material of choice for power applications. Efforts now are starting to focus on bringing production costs down, which will impact the competitiveness of HTS products.

B.4 YBCO or Y-123

It is only in the past several years that research efforts have re-focused on Y-123 based coated conductors for bulk-scale applications. Y-123 was one of the earliest HTS discovered, and most electronic device applications work is done on this material. With a critical temperature of 90 K, and a very high irreversibility field, progress in bulk applications was delayed by the problem of weak coupling across high angle grain boundaries (>10°). Unlike Bi-2212 and Bi-2223, Y-123 does not self-align. By biaxially texturing a substrate material, and then depositing the Y-123 by pulsed laser ablation or other technique, high-angle grain boundaries can be avoided. Excellent J_C(77K, 0T) values on the order of 1 MA/cm^2 have been achieved by a number of groups (LANL, LBNL, ORNL, Fujikura, Sumitomo, Univ. Göttingen). The transition in the current-voltage curve is also sharper than in Bi-2223, having a typical n=4 at 5 T and 77 K [O]. The caveat is that these values are on very short lengths of conductor, usually one cm or less. The principle challenge will be to maintain high Jc values as processes are scaled up to longer lengths. In Japan, Sumitomo Electric has succeeded in fabricating up to half a meter of Y-123 coated conductor with J_C(77 K, 0 T) = 0.20 MA/cm^2 [A,P].

In-field J_C(75K) transport data on Y-123 coated conductors have been taken at LANL[Q,R], as well as additional magnetization J_C data at various temperatures [S]. Iijima et al. has also published in-field J_C(77K) for various orientations [T]

Y-123 is a highly desirable material for power applications because of its high J_C values at 77 K and good in-field behavior. Obstacles include increasing the length of material, increasing fabrication speeds, particularly of the aligned substrate material, and finding alternative non-magnetic metallic substrates to replace the currently used textured Ni and Hastalloy material. These significant problems are certainly not insurmountable, and steady progress is currently being made. Y-123 coated conductors are a “second-generation” HTS, and may be the material of choice for bulk scale applications within the next 10-15 years.

B.5 Appendix B References

a. WTEC Panel Report on “Power Applications of Superconductivity in Japan and Germany”, International Technology Research Institute, Loyola College in Maryland, September 1997.

b. Grant P. M., “Superconductivity and Electric Power: Promises, Promises, Past, Present and Future”, IEEE Trans. Appl. Supercon., **7**, pp 112-132, (June 1997).

c. U. S. DOE 1995 Annual Peer Review, August 1995, Alexandria VA: Superconductivity Program for Electric Systems.

d. Flükiger, R., “Materials for classical and high-T_c superconducting tapes and wires at 4.2 K”, Supercond. Sci. Techn. **10**, 872-875, (1997).

e. Okada M., Tanaka K., Sata J., Awaji S., and Watanabe K., “Transport properties of $Bi_2Sr_2Ca_1Cu_2O_x$/Ag multifilament tape”, Jpn. J. Appl. Phys. **34**:4770-4773 (1995).

f. Kusevic I., Simundic P., Babic E., Ivkov, J., Marohnic Z., Ionescu M., Liu H. K., and Dou S. X., “J_c-B-T surface of high-J_c $Bi_2Sr_2CaCu_2O_{8+x}$/Ag tape”, Supercon. Sci. Techn. **9**, 1060-1065, (1996).

g. J. Tenbrink and H. Krauth in “Bismuth Based High Temperature Superconductors”, p 369, eds. H. Maeda and K. Togano, Marcel Dekker Inc., New York 1996.

h. L. R. Motowidlo, G. Galinski, G. Ozeryansky, W. Zhang, and E. E. Hellstrom, “Dependence of critical current density on filament diameter in round multifilament Ag-sheathed $Bi_2Sr_2CaCu_2O_x$ wires processed in O_2”, Appl. Phys. Lett., **65**, 2731, (1994); Motowidlo et al, MRS/ISTEC Meeting 1995.

i. T. Hasegawa, Y. Hikichi, T. Koizumi, A. Imai, H. Kumakura, H. Kitaguchi, and K. Togano, “Fabrication and Properties of Bi-2212 Multilayer Superconducting Tapes and Coils”, IEEE Trans Appl. Supercond., **7**, 1703, (June 1997).

j. T. Staiger, G. Fuchs, P. Verges, K. Fischer, L. Schultz, and A. Gladun, “Critical current in silver sheathed Bi-2223 tapes”, IEEE Trans. Appl. Supercon. **7**, 1347, (1997).

k. J. A. Parrell, D. C. Larbalestier, G. N. Riley, Jr., Q. Li, W. L. Carter, R. D. Parrella, and M. Teplitsky, “Connectivity and flux pinning improvements in Ag-clad BSCCO-2223 tapes produced by changes in the cooling rate”, J. Mater. Res. **12**, 2997, (1997).

l. C. M. Friend, L. Le Lay, and T. P. Beales, “Current connectivity in Bi-2223 Silver-sheathed tapes for power cables”, IEEE Trans. Appl. Supercon., **7**, 1821, (1997).

m. Q. Li, H. J. Wiesmann, M. Suenaga, L. Motowidlo, P. Haldar, “Vortex phase diagram and J_c limiting factor in high Tc Bi-2223/Ag superconducting tapes”, Appl. Phys. Lett. **66**, 637, (1995).

n. M. Dhallé. M. Cuthbert, M. D. Johnston, J. Everett, R. Flükiger, S. X. Dou, W. Goldacker, T. Beales, and A. D. Caplin, “Experimental assessment of the current-limiting mechanisms in BSCCO/Ag high temperature superconducting tapes”, Supercon. Sci. Tech. **10**, 21-31, (1997).

o. N. Heinig, measurements on LANL IBAD samples.

p. K. N. Hasegawa, N. Yoshida, K. Fujino, H. Mukai, K. Hayashi, K. Sato, T. Ohkuma, S. Honjyo, H. Ishii, and T. Hara, “In-plane aligned YBCO thin film tape fabricated by pulsed laser ablation”, in Proc. 16th Int. Cryogenic Engineering Conf./ Int. Cryogenic Materials Conf., p 1413-1416, ed T. Haruyama, T. Mitsui, and K. Yamafuji, 1997. Oxford, UK: Elsevier Science.

q. X. D. Wu, S. R. Foltyn, P. N. Arendt, W. R. Blumenthal, I. H. Campbell, J. D. Cotton, J. Y. Coulter, W. L. Hults, M. P. Maley, H. F. Safar, J. L. Smith, “Properties of YBaCuO thick films on flexible buffered metallic substrates”, Appl. Phys. Lett. **67**, 2397-2399, (1995).

r. H. Safar, J. Y. Coulter, M. P. Maley, S. Foltyn, P. Arendt, X. D. Wu, and J. O. Willis, “Anisotropy and Lorentz-force dependence of the critical currents in YBaCuO thick films deposited on nickel alloy substrates,” Phys. Rev. B, vol **52**, R9875-R9878, (1995).

s. M. P. Maley, private communication (1998).

t. Y. Iijima, M. Hosaka, N. Tanabe, N. Sadakata, T. Saitoh, O. Kohno, and J. Yoshitomi, “Fabrication of high-J_c tapes using continuously deposited YSZ buffer layers by IBAD method.”, in Adv. of Superconductivity 8, pp 659-662, eds. H. Hayakawa and Y. Enomoto, Tokyo: Springer-Verlag (1996).

C
SUMMARIES OF PREVIOUS HTS STUDIES

C.1 Superconducting Magnetic Energy Storage Technical Considerations and Relative Capital Cost With High-Temperature Superconductor Material, R. J. Loyd, A. M. Bulc, D. Majumdar (Bechtel National Inc.), 1991, Final Report to EPRI October 1991, Research Project 2988-2

Report Objectives

- To evaluate the present and long-term prospects and potential impacts of high temperature superconductor (HTS) materials on SMES technology.
- To outline several design approaches for SMES coils to accommodate HTS-based conductors.
- To propose a set of minimum technical requirements that HTS materials must meet to be considered for use as primary conductor in SMES.
- To quantify the reduction in capital cost that could result from the deployment of HTS materials as primary conductor in SMES.

Report Conclusions

Threshold HTS Materials Requirement for Use in Conventional SMES Conductors	
Item	**Requirement**
Operating maximum magnetic field	3 Tesla (30,000 gauss)
Operating superconductor critical current density	120 A/mm^2 (12,000 A/cm^2)
Mechanical properties	Appropriate for making a coil

C.2 Prospects for the Use of High T_c Materials for Superconducting Magnetic Energy Storage, William V. Hassenzahl, Proceedings of EPRI Workshop on High-Temperature Superconductivity, April 1988, EPRI EL/ER-5894P-SR

Abstract

Energy Storage is often used by the electric utilities to accommodate changing electric power demands. The most familiar type of storage is the 65% efficient pumped hydro in which the low cost energy available from efficient base load plants is used at night and sometimes on weekends to pump water form a lower source up to a higher reservoir. As the water flows out of the reservoir it is used to produce electrical energy. Superconducting Magnetic Energy Storage (SMES) is another method of storing energy on a scale that is appropriate for the electrical utilities. Projections for SMES systems using conventional Nb-Ti superconductors show an efficiency greater than 92% and other advantages such as rapid power reversal capability--contributing to the systems spinning reserve, ease of siting, and potential long life--there are few moving mechanical components. A design for a 5000 MWh SMES plant is described and then used as the basis for a set of technical and cost comparisons for the potential use of the recently discovered high critical temperature superconductors for SMES. Construction and operating costs suggest the need for large plants if SMES is to be competitive. The impact of the new materials on the various SMES components and the overall system for a range of sizes is presented. This analysis suggests that, should the new superconductors achieve their potential, SMES will be competitive at smaller plant sizes.

Report Conclusions

There are many uncertainties as to the eventual evolution of the physical characteristics of the new superconductors. However, based on several reasonable assumptions it has been possible to estimate the potential impact of these materials on SMES. The cost effectiveness is seen to range from somewhat positive to very negative, depending on these assumptions. The likely effect, based on a direct, equal cost substitution for conventional superconductors is about an 8% saving at 5000 MWh. This is not a sufficient increase to make SMES an immediate choice by utilities, but would certainly improve its chances for use. The effect on cost is greater at smaller sizes so that it may be possible that the size of a unit at breakeven cost, *vis-a-vis* other types of storage, would drop below 1000 MWh. This effect would be most significant for the eventual penetration of SMES into the utility market.

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

C.3 Conceptual Design Study of Superconducting Magnetic Energy Storage Using High Temperature Superconductors, S. M. Schoenung (W. J. Schafer Associates), R. L. Fagaly, M. Heiberger, R. B. Stephens, J. A. Leuer, R. A. Guzman, E. R. Johnson (General Atomics), J. Purcell, L. Creedon, J. R. Hull (Advanced CryoMagnetics), Final Report to DOE February 1993, DOE/CE/34019-1

Abstract

A conceptual design for superconducting magnetic energy storage (SMES) using oxide superconductors with higher critical temperatures than metallic superconductors has been analyzed for design features, refrigeration requirements, and estimated costs of major components. The study covered the energy storage range from 2 to 200 MWh at power levels from 4 to 400 MW. A SMES that uses high temperature superconductors (HTS) and operates at high magnetic field (e. g., 10 tesla) can be more compact than a comparable, conventional low-temperature device at a lower field. The present state of the art high T_c superconductors was projected to the kilometer long wires needed for a cycling SMES device. Silver-clad, bismuth-based superconductor is the only form which is likely to be available in the near future. This wire should have a cross section of approximately 1 cm^2 and carry 10 kA in fields up to 10 tesla (T). For satisfactory performance it must be made on the form of twisted multifilaments. The refrigeration power required for a higher temperature unit (20 to 77 K) will be less by 60 to 90 percent. The improvement in energy efficiency is significant for small units but less important for large ones. The material cost for HTS units is dominated by the cost of superconductor, so that the total cost of an HTS system will be comparable to a low temperature system only if the superconductor price in $/Ampere-meter is made comparable by increasing current density or decreasing wire cost.

Report Conclusions

A conceptual design of a modular SMES device based on projected properties of high temperature superconductors has been analyzed for design and performance features, and major component costs have been estimated. More compact configurations are possible for HTS-SMES if operated at a magnetic field greater than that possible for conventional low temperature superconductors. This leads to some savings. Refrigeration power and energy requirements are reduced significantly at higher operating temperatures. However, since coil costs are dominated by superconductor cost, an HTS-SMES unit will be of comparable cost to an LTS system only if the superconductor material is of comparable cost (no more a factor of 2 greater) on a $/A-m basis.

In summary, conductor needs for HTS-SMES are:

- Long lengths of uniform, multifilamentary twisted wire
- J_c of at least 10^4 A/cm^2 at 20 K; 10^5 A/cm^2 would be better
- Operation at fields greater than 2 T; 5 to 10 T would be better

- Improved allowable strain
- Higher superconductor fraction (greater than 10%, ideally 50%)
- Reduced cost; reduced silver requirements
- Detailed data on J_c as a function of T and B for long lengths of wire
- HTS power leads

As conductor developments proceed, HTS-SMES could be advanced through additional studies. In particular, it would be useful to extend the size range of design concepts to smaller units, which are more suitable for cold structure. It would also be valuable to determine optimum energy and power ratings for specific applications, to investigate HTS conductor design challenges at higher discharge rates, and to characterize benefits and cost relative to alternative technologies.

C.4 Superconducting Magnetic Energy Storage (SMES) Using High-Temperature Superconductors (HTS), Susan M. Schoenung, Robert L. Bieri (W. J. Schafer Associates), Final Report for Sandia National Laboratory May 1994, Subcontract AG-5265

Abstract

Utility and industry interest in superconducting magnetic energy storage (SMES) for power quality and end-use applications is growing. These applications are served by SMES units in the capacity range form 1 to 30 MJ with power ratings from 1 to 10 MW. Although today's system costs are high, there is potential for cost savings in the refrigeration system if high temperature superconductors (HTS) could be used. This is especially true for high-duty-cycle applications, such as transient and frequency stabilization, where eddy-current losses are large. Another potential obstacle to widespread use of small SMES systems is the magnetic field produced by a solenoid coil. A toroidal coil has almost no external field, but is generally more expensive than a solenoid. A system of two coils with opposite currents (a shielded solenoid) limits the extent of the external field, but also has a cost penalty. In this report we present results of a configuration and cost analysis of HTS SMES in solenoidal, toroidal, and shielded solenoidal configurations and an analysis of refrigeration requirements vs. duty cycle over the energy range of 1 to 10 MJ and duty cycles up to 1 Hz. Costs and designs for low-temperature (LTS) SMES systems are presented for comparison. A brief review of cooling approaches is also included.

Report Conclusions

This study has investigated the features of small SMES systems in two sizes (1 MJ and 10 MJ) and three configurations using high-temperature and low-temperature superconductors. Alternatives to a single solenoid having reduced magnetic field are the torus and the shielded solenoid. For HTS systems, the shielded solenoid is more expensive by a factor of 1.23 to 1.27, and the torus is more expensive by a factor of 2 to 3. (Because the coil is a smaller fraction of the system costs for LTS systems, the relative cost penalty for advanced Geometries is lower; an LTS is only 1.02 to 1.10 times as expensive as a solenoid over this energy range.) The footprint area to the 10 gauss line is nearly the same for the shielded solenoid for both 1 MJ and 10 MJ coils. The torus has by far the smallest footprint, as determined by external magnetic field. In high duty cycle applications, an HTS system has good potential for significantly reduced refrigeration if a modest twist pitch is achievable. Progress in wire design and fabrication is essential if HTS SMES is to be feasible for high duty cycle applications. Reasonable HTS conductor cost will require reducing HTS unit costs and improving J_c.

C.5 HTS SMES Magnet Design and Test Results, S. S. Kalsi, D. Aided, B. Connor, G. Snitchler, J. Campbell, R. E. Schwall (American Superconductor Corporation), J. Kellers (American Superconductor Europe), Th. Stephanblome, A. Tromm (Gesellschaft für Innovative Energieumwandlung und Speicherung GmbH), P. Winn (Applied Engineering Technologies), IEEE Transactions on Applied Superconductivity, Vol. 7, No. 2, June 1997.

Abstract

This paper describes design, construction, and testing of a 5 kJ Superconducting Magnetic Energy Storage (SMES) magnet. This magnet was built by American Superconductor Corporation (ASC) for Gesellschaft für Innovative Energieumwandlung und Speicherung (EUS) of Germany. The magnet consists of a solenoidal coil constructed from a silver-sheathed $BiPb_2Sr_2Ca_2Cu_2O$ (Bi-2223) conductor which was reacted before winding. The coil is epoxy impregnated and cooled with single stage Gifford McMahon (G-M) cryocoolers for operation at 100 A (DC) with substantial AC components due to the frequent variation of current (ramp-up and ramp-down.) The dominant heat load in the magnet is eddy-current heating caused by the current ramping operation. To accommodate this heat load, a separate cryocooler is employed for the cooling the main coil. A smaller capacity cryocooler is used for intercepting the heat load of the conduction cooled current leads. Specialized thermal interfaces were developed for operation in AC fields and at high voltages. The magnet can be ramped from zero to 100 A in 2 s and back to zero current in 2 s. One hundred sequential ramp-up/ramp-down cycles can be accommodated before the magnet temperature exceeds the allowable maximum.

The magnet was tested in early spring of 1996 and was shipped to EUS in mid June. The successful operation of this magnet illustrates that the technology of cooling HTS magnets with G-M type cryocooler is now fully established. The long term operation of this magnet at EUS will verify the reliability of HTS magnet system in critical applications and will open future applications for HTS in the area of SMES and other magnets.

Report Conclusions

This paper describes the first significant HTS SMES magnet. It was built and integrated by American Superconductor corporation. It uses flexible composite Bi-2223 HTS wire. It was delivered to the Gesellschaft für Innovative Energieumwandlung und -Speicherung GmbH, Germany in late June and is currently integrated to a novel power conditioning system. This system will be used in a scaled grid to improve local power quality. Experimental results will be communicated at future conferences. The successful design and testing of this magnet shows that HTS technology can be utilized for commercial products in the electrical power industry at the 2 kW level.

C.6 Design Considerations of a HTS m-SMES, R. Mikkonen, M. Lahitnen, J. Lehtonen, and J. Paasi (Tampere University of Technology), B. Conner, S. S. Kalsi (American Superconductor), European Conference on Applied SC, July 1997

Abstract

A 5 kJ HTS SMES system has been designed at Tampere University of Technology with a coil manufactured by American Superconductor (ASC). The outer diameter of the pancake type coil is 317 mm and the axial length is 66 mm. The operating current is 160 A. The magnet will be cooled to the operating temperature of 20 K with a two stage Gifford-McMahon type cryocooler with a refrigeration capacity of 60 W at 77 K and 8 W at 20 K. The cryogenic design is determined by the application of the system and its specific AC requirements. The system will be demonstrated in the event of a short term loss of power. This paper overviews the main design principles of the present SMES system.

Report Conclusion

A prototype HTS μ-SMES system has been designed and constructed in order to compensate a loss of power of a micro computer. The coil was manufactured at ASC from multifilamentary composite BSCCO-2223 conductor in a react and wind fashion. The optimum operation temperature of the cryogen free magnet is 20-30 K. With the aid of a proper cryogenic integration and thermal analysis it is possible to determine a safe level for the operating current and magnet ramping rate before an irreversible thermal runway. Test results will be reported in forthcoming conferences.

C.7 UW Table IV-HTS Magnet Development—Performed for USAF PCCIE Office, 1995, Mostafa Abdelsalam

Abstract

No specific abstract exists, however, the goal of this project was to manufacture and test small coils wound from HTS (Bi-2212) samples.

Report Conclusions

During this project, a total of 16 small coils were produced-some fabricated by the wind and react process and some by the react and wind process. The tests showed great variability in performance due to bubbling in the conductors. Typical currents were around 100 A and Jc of 68-230 kA/cm^2. A proposed follow-on was not funded.

C.8 Technical Evaluation of the Impact of High Temperature Superconductors on SMES Applications, Phil Sanger (Westinghouse), Report to EPRI

Abstract

Ten years ago the discovery of superconductors with critical temperatures above the boiling point of liquid nitrogen was made. This discovery has been followed by an intense period of development improving our understanding of the characteristics of these materials and identifying production methods leading to full scale manufacturing. Most recently, Los Alamos National Laboratory and Oak Ridge National Laboratory have announced two different methods suitable for large scale implementation with encouraging mechanical and superconducting properties. In this report we will assess the unique design problems presented by these new superconductors, determine the cost impact of the less demanding cryogenic environment and investigate the sensitivity of the MicroSMES costs to HTS conductor cost and properties.

This study concludes that intrinsic stability of these superconductors will probably not require the micron size multifilamentary structures, that thick films (up to 100 microns) are necessary for useable conductors, that current densities in the conductor composite should be greater than 100 kA/cm2 to be interesting and that new techniques in both conductor fabrication and field shaping are necessary for the rapid ramping needed for power quality SMES magnets. In addition these superconductors must be available at less than $70/kiloampere meter to be considered at all and can result in 30% reductions in net present value cost if they are available at present day superconductor cost of less than $10/kiloampere meter. Finally the benefit of high temperature superconductors diminishes rapidly as the stored energy increases and the refrigeration becomes a smaller element of the cost.

Report Conclusions

The conclusions of this study are divided into two areas: 1) guidance for conductor development and 2) conductor cost benchmark where impacts to the SMES market could be made.

- Guidance for Conductor Development

1. The properties of the new superconductors suggests that the multifilament structure of the present superconductors is not necessary to maintain stability in this new class of superconductors.

2. The present adoption of silver as the stabilizer in unnecessary and not cost effective.

3. Films with a thickness up to a hundred microns will be necessary to construct a conductor with a width of less than several centimeters carrying kiloampere currents which is needed for reasonable magnet designs.

4. Current densities greater than 100 kA/cm2 must be available in the thick films to allow for reasonable coil designs to implemented.

5. Methods of film construction and conductor assembly techniques must be developed that minimize parasitic circulating currents due to rapid ramping of the magnet.

- Conductor Cost Benchmarks.

1. The threshold high temperature superconductor cost level for SMES applications is roughly $70 per kiloampere meter.

2. Significant improvements in operation simplicity and a 20% reduction in operating costs can be offered with a conductor cost of less than $30 per kiloampere meter.

3. High temperature conductor costs of less than $10 kiloampere meter offers capital cost reduction of 15% and greater than a 30% reduction in the net present value cost of MicroSMES.

C.9 HTS Wires (Incomplete title), K. Sato, K. Haya (Basic High-Technology Laboratories), Proceedings of MT-15

Abstract

Since the discovery of HTS materials, long and high-Jc HTS wires have been developed using BSCCO material. The critical current density was over 10,000 A/cm^2 at each application condition, and close to 10,000 A/cm^2. Two breakthroughs, i. e. multifilamentary technique and thermomechanical processing could make it possible. Towards actual application of HTS wires, many prototypes were developed. Among these prototypes, 2,000 A current leads and 3 Tesla magnet have been put for daily operation at present, and 3-phase transmission cable prototype was evaluated successfully. Further developments up to 14,500 A current leads, 7 Tesla magnet cooled at 20 K and 30 m long power cable prototype were achieved. These application fields are peculiar to novel properties of HTS wires, i. e. wide range of critical surfaces and high temperature operation.

Report Conclusions

The HTS wire and application development are described. Long, high-Jc BSCCO wire is already used in current leads and developmental magnets. A power cable prototype was successfully evaluated. Near future application to industrial magnets are very promising. For all applications, it is important to consider novel features peculiar to high-Tc superconductors, i. e. wide temperature and magnetic field range capabilities.

C.10 Advantages and perspectives of SMES, J. F. Picard, C. Levillain, P. G. Therond (Electricité de France, R&D division), SCENET 2nd Workshop on Power Applications of Superconductivity, November 1997

Abstract

SMES is the only commercial application of superconductivity into electrical equipment. This technology of energy storage is particularly suited for pulsed discharges, taking advantage of the high power density available with SMES. In this domain, power quality, whose impact and importance are increasing nowadays, represents most of potential application for SMES operation.

EDF, among other utilities and customers, considers carefully present application cases. Perspectives of cost and technologies evolution are also addressed; both smoothing of voltage sags and mitigation of flicker are relevant application cases for SMES.

We present in this contribution, on the one hand, different structures and sizing to be used and smoothing for voltage sags. Secure the energy supply of loads ranging from 1 MVA to a few 10 MVA represents the main part of application cases. On the other hand, the possibility to mitigate flicker is a promising way we are investigating. Innovative structures are considered for this purpose.

Finally, we address development for new SMES generation, using High T_c Superconductor (HTS), operating at intermediate temperature between liquid Helium and liquid Nitrogen under high magnetic field. Very exciting objectives in terms of technical and economical performances of HTS SMES are expected to bring new competing solutions for power quality.

Report Conclusions

Only abstract available at this time.

C.11 Minimal Performances of High Tc Wires for Cost Effective SMES Compared with Low Tc's, C. Levillain, P. G. Thérond (Electricité de France), IEEE Transactions on Magnetics, Vol. 32, No. 4, July 1996

Abstract

On the basis of a 22 MJ/10 MVA unit without stray field, we determine minimal performances for High T_c Superconducting (HTS) wires, in order to obtain HTS Superconducting Magnetic Energy Storage (SMES) competitive compared with Low T_c Superconducting (LTS) ones. The cost equation mainly considers the wire volume, the fabrication process and losses. We then recommend HTS critical current densities and operating magnetic fields close to the present state of the art for short samples. A 30% gain for HTS SMES compared with LTS one could be expected.

Report Conclusions

This detailed analysis based on performance close to the present state of the art on short HTS samples, provides costs for HTS SMES operating around 30K. The HTS devices are competitive compared with LTS at 4 K. For equal HTS and LTS wire costs per unit volume, a 30% reduction for HTS SMES cost compared with similar LTS device could be expected with J_{CWHTS} around 400 A/mm2 and B_{MHTS} around 10 T.

The main contributions to the improvement for HTS SMES are:

- higher ratio of the operating to critical current (α_{HTS}=0.8 and α_{LTS}=0.65) and $J_C x B_M > 1$;
- reduced storage dimensions and consequently wire volume (especially on the wire length) due to larger operating magnetic fields for HTS around 20-30K;
- reduced refrigeration requirements with potential further improvements by using cryocoolers.

C.12 The SSD: A Commercial Application of Magnetic Energy Storage, W. E. Buckles, M. A. Daugherty, B. R. Weber, and E. L. Kostecki (Superconducting, Inc.), IEEE Transactions on Applied Superconductivity, Vol. 3, No. 1, March 1993

Abstract

A magnetic energy storage system (SSD™) has been developed by Superconductivity, Inc. to provide power to industrial electrical loads subjected to short term voltage disturbances. This paper provides an overview of the SSD system as presently installed at customer sites including magnet, cryostat, refrigeration and power conditioning equipment. Electric power interruptions are unpredictable in time but are typically of short duration. The SSD system provides rapid response backup power by means of a superconducting magnet connected to the load through a current to voltage converter and a dc to ac inverter. Power flows from the magnet to the load when the line voltage drops below a preset value. The magnet is designed with terminal characteristics matched to the inverter dc voltage, connected load and required carryover time. Cryogen inventory is maintained through use of a Collins cycle liquifier. All system components are designed for long term unattended operation and can be mounted in a semi-trailer. Remote monitoring provides information on system performance and status.

Report Conclusions

Superconductivity, Inc. has developed a commercial application of superconducting magnetic energy storage. The SSD is a self contained standby power system with a compact footprint operating at bus-level power. Units presently installed and under construction utilize a 1 MJ magnet connected to the power grid by a current-to -voltage regulator (chopper) and a 12 pulse inverter. Cryogenic and support systems incorporate redundancy or significant zero-capacity hold up time. Units at field sites are monitored in real time after extensive testing at the factory.

C.13 Micro Superconducting Magnetic Energy Storage (SMES) System For Protection of Critical Industrial and Military Loads, A. K. Kalafala, J. Bascuñan, D. D. Bell, L. Blecher, F. S. Murray, M. B. Parizh, M. W. Sampson, and R. E. Wicox (Intermagnetics General Corporation), IEEE Transactions on Magnetics, Vol. 32, No. 4, July 1996

Abstract

A 6 MJ, 750 kVA Micro SMES system has been designed to protect critical loads against voltage sags and interruptions, as well as to provide continuous power conditioning. Life-cycle costs have been minimized through the use of simplified through the use of energy efficient refrigeration units. Maintenance is simplified through the use of Line Replaceable Units (LRU). Availability is maximized through a design approach which allows the magnet to continue protecting the load even in the case of refrigeration degradation or total failure. Reliability is maximized by the use of proven commercial-off-the-shelf (COTS) items. The system provides ride-through capability for ~ 9 seconds at a power level of 454 kW. The system comprises a niobium titanium superconducting magnet, permanent conduction cooled hybrid current leads, a low loss cryostat, a closed-loop refrigeration subsystem, an off-the-shelf uninterruptible power supply (UPS), a magnet interface unit to connect the magnet to the UPS, and an off-the-shelf monitoring unit providing both local and remote monitoring capability of system parameters.

Report Conclusions

A Micro SMES System is under construction by Intermagnetics General Corporation for the US Air Force PCCCIE Material Group. System delivery was initially planned for May 1996. Actually installation occurred in late 1997 and testing is in progress in early 1998. The system is part of an overall effort by the USAF to evaluate SMES technology and its potential for improving the performance of critical processes. The system configuration was selected on the basis of increased availability, reduced maintenance requirements, and ease of set-up at the intended time.

C.14 Memo from John Ziegler, Houston Advanced Research Center/Technology Development Laboratory

Summary

The HARC/TDL SMES Consortium program has two primary objectives: (1) the development of second generation MicroSMES technologies and (2) high-level studies of transmission enhancement opportunities around the state of Texas

The first objective, development of second generation MicroSMES technologies, has absorbed a higher percentage of HARC/TDC effort over the last year than originally anticipated. The results from this effort are extremely encouraging, however, and hold great promise for meeting increasingly stringent industrial power quality requirements for loads in the 1-10 MW power range. We have successfully developed a fast persistent switch that allows an energy storage coil to operate in persistent mode, containing the circulating current entirely within superconducting elements. This eliminates steady-state energy losses in the external components and dramatically reduces the refrigeration requirements and the total system operating costs. When a disturbance is sensed on the incoming utility lines, however, the fast persistent switch opens in less than two milliseconds (1/8 of a power line cycle) and allows the external power conditioning system to extract energy from the storage coil to supply the protected load. The MicroSMES unit can protect loads against short duration transients in a standalone configuration, or it can be integrated with a standby generator to also provide continuous, uninterrupted power during extended outages. HARC/TDC is currently fabricating a pre-prototype unit that will demonstrate the key features of a second generation MicroSMES energy storage system:

- fast persistent switch to permit persistent mode operation,
- modular energy storage subsystem suitable for a wide range of power and energy requirements,
- zero fringe field design to eliminate stray magnetic field problems, and
- low capital and operating costs

C.15 Operation of a Small SMES Power Compensator, K. P. Juengst , H. Salbert (Forschungszentrum Karlsruhe, Institut für Technische Physik), O. Simon (Elektrotechnisches Institut (ETI), Universität Karlsruhe), Proceedings from European Conference on Applied SC, July 1997, Eindoven.

Abstract

A system for compensation of fluctuating loads has been designed, constructed, and laboratory operated. It consists of an IGBT based current converter and a NbTi mixed matrix conductor superconducting magnet system. Power and energy ratings are 80 kVA and 200 kJ, respectively, The dynamic converter has a very short response time and the magnet can withstand high rates of current/field change. Operation on the laboratory grid was successful in compensating the varying power demand of a periodically stressed induction machine. For a field demonstration, the mobile system has been shipped to a saw-mill near Karlsruhe.

Report Conclusions

The next step is a test period in an industrial environment. Given the power and energy capabilities of the SMES power compensator, a saw-mill has been chosen as the industrial test site. Measured data from the mill were used for lab tests. Successful smoothing of power variations has been achieved. The system has been shipped to the mill for tests in July/August 1997.

C.16 Development of 1 kWh/1 MW Module Type SMES, Katsuya Tsutsumi, Fujio Irie (Research Laboratory, Kyushu Electric Power Co., Inc.), Tsutomu Tokunaga (Central Electric Power Council), Hidehiko Okada (Oita University), Tadao Ezaki, Masakatsu Takeo (Kyushu University), The Proceedings of the IEA Symposium on Use of Superconductivity in Energy Storage, October 1994

Abstract

The ultimate goal of the research and development of SMES is introduction of large scale SMES intended for load leveling purposes. In development of large scale SMES, there are diverse technical problems to be solved such as the development of large capacity superconductive coil and a supporting method of electromagnetic force generated by the coils.

However, for SMES in system control use such as for load fluctuation compensation and system stabilization, the SMES can be of small storage capacity and their early and practical application may be realized sooner.

This paper is to make a description on planned demonstration tests with use of a 1 kWh/1 MW test device which will be produced as part of studies. It will also refer to the module structure of SMES, adopted as one possible method to expand capacity. Basic experiments conducted with use of the module structure SMES test device proved itself capable of electric power control or control at quenching, just as a single SMES does.

Report Conclusions

This paper has described 1 kWh/1 MW module Type SMES development plan to be implemented under a five year plan starting in 1994. This project envisions practical application of a Module Type SMES in actual power systems.

At present, detailed design of superconductive magnets and related equipment is being carried out. We intend to make another presentation, given an opportunity, on the results of the design of this equipment.

C.17 Development and Test Results of a Double 0.5 MJ Coil SMES System, V. E. Keilin, V. P. Agalakov, O. P. Anashkin, N. N. Britousov, A. V. Dudarev, A. V. Krivykh, A. S. Kilikov, V. V. Lysenko, S. M. Miklyaev, S. A. Shevchenko, and M. I. Surin (RRC "Kurchatov Institute"), IEEE Transactions on Magnetics, Vol. 32, No. 4, July 1996.

Abstract

The design and test results of a SMES system built for Korea Electrical Power Company are described. The system consists mainly of two superconductors (SC) coils, two cryostats, primary power supply and DC-AC-DC converter to transfer the stored energy from one coil to another and vice versa. Each of two almost identical coils can store more than 0.5 MJ at about 1.55 kA. Minimum energy transfer time is about 2 s. The conductor is made by cabling several SC, copper and stainless steel. Their eddy current losses at liquid helium temperatures are lower than at AC losses in the coils. After preliminary testiness in Moscow the system was delivered to Republic of Korea and successfully tested at Korea Electrotechnology Research Institute.

Report Conclusions

The energy transfer between two coils was determined. The current decay is determined mainly by Ohmic losses in the converter and the connecting cables. During the tests both in Moscow and in Korea, all components of the SMES proved their reliability. It seems that many technical decisions and approaches implemented in 0.5 MJ project can be extended to SMES of larger energy range (at least up to 1-10 MJ range)

C.18 Small, High-Power 1 MJ SMES, H. W. Lorenzen, U. Brammer, F. Rosenbauer, R. M. Schöttler (Lehrstuhl für Elektrische Maschinen und Geräte, Technische Universität München, Germany), IEEE Transactions on Magnetics, Vol. 32, No. 4, July 1996.

Abstract

A small pilot energy storage plant will be installed at Technische Universität München. The center of the facility is a small fast-acting SMES. It consists of six coils forming a torus with a storage capacity of about 1 MJ. The main requirements governing the design of the SMES are outlined in their realization is described. Emphasis is laid on the helium cooling circuit and the quench protection system with a coil bypass branch and a heating device. In case of a coil quench the bypass must be activated by IGBT modules working at cryogenic temperatures.

Report Conclusions

The six coils are finished and were assembled in a torus beginning in March 95. Currently the vacuum vessel and parts for the support construction and helium system are completed.

Preliminary test, such as vacuum tightness and the coil’s resistances and inductances, are scheduled for March to September 95. The testing phases will start after that with the device’s cooling-down and D. C. excitation.

Present status of this program is being determined.

D RECENT JAPANESE STUDIES: COPY TRANSLATION

A conference on HTS SMES was held in Japan in December, 1998. Several papers in the conference were reviewed and were partly translated by Ms. B. Cory. The following are excerpts of four of the papers. Limited modification have been made to Cory's translation to reflect proper use of English technical terms.

I Masahiro Yamamoto, Overview of ISTEC/SMES Project

Overall Plan

As you know, the SMES system can store energy as electricity, and thus has a highly efficient energy storage capability. Moreover, the fact that it allows high speed input and output of energy, means both real and reactive power can be controlled independently. Other features determine that it has high capabilities not only in energy storage capacity aspects (kWh) but also in aspects of instantaneous output of electric power. It is anticipated that the SMES system will fulfill a significant role in future electric power systems in terms of load-leveling of power, load change compensation, improving system stabilization, etc.

Due to these factors, the Japanese government, electric power companies, manufacturers, and research groups concerned with superconducting energy storage are engaged in investigation, research, and conceptual design work on its utility.

The Agency of Natural Resources and Energy, Ministry of International Trade and Industry, has taken the first step toward full-scale development of SMES in Japan. It is conducting a project 'Study of Factors and Technology Development for Superconducting Electric Power Storage System' during fiscal years 1991-1998 to establish the necessary technological basis for building a small-scale SMES pilot plant. As shown in Table D-1, ISTEC is consigned to implement this with the participation of electric power companies and manufacturers. In addition, in order to promote effective research, an advisory committee of experts in the field (Table D-2) has been set up to examine and review the content of the studies.

Table D-1
Implementation SMES Structure/Organization. The Agency of Natural Resources and Energy has consigned overall leadership of the program to ISTEC. Work on the program is carried out by power companies and contractors

Technical area	Responsible Entity
Superconducting coil	Chubu Electric Power
Quench protection	Tohoku Electric Power
AC to DC converter equipment	Dengen Kaihatsu (Electric Utility Development) Co.:
Persistent current switch and direct current circuit breaker	Dengen Kaihatsu (Electric Utility Development) Co.:
Optimal system research	Kyushu Electric Power
Utility system effects of SMES operation	Central Research Institute of the Electric Power Industry
Testing and evaluating HTS materials	Osaka Science and Technology Center—New Materials Center
Coil testing	Toshiba

Table D-2
Committee Organization

Central Committee	Chairman	Taiji Sekine (Tokyo Science Univ.)
	Secretariat	Eisuke Shôda (Tokyo Univ.)
Administrative organization ISTEC		
Superconducting Coil Subcommittee	Chairman	Takashi Satô (Fusion Research)
	Vice Chairman	Takumi Inosaka (Chubu Electric)
	Vice Chairman	Hiromichi Satô (Tohoku Electric)
Equipment Subcommittee	Chairman	Osami Tsukamoto (Yokohama National Univ.)
	Vice Chairman	Ryûichi Abe (Electric Utility Development)
	Vice Chairman	Hiromichi Satô (Tohoku Electric)
System Research Subcommittee	Chairman	Yoshishige Murakami (Fukui Technical Univ.)
	Vice Chairman	Akiyoshi Tsutsumi (Kyushu Electric Power)
	Vice Chairman	Naoyuki Uchida (Central Electric Research)
Testing and Evaluation Methods Working Group	Chairman	Mitsuzô Yoshimura (Kyoto Univ.)
	Vice Chairman	Akio Matsushita (Kyushu Technical Univ.)
	Vice Chairman	Takakazu Shintomi (High Energy Research)

II Tatsurô Koike, "SMES Research at Kansai Electric Power Company"

Introduction

At Kansai Electric Power Company, we have implemented feasibility studies of SMES for system stabilization and SMES for electric storage since the latter 1980's to study the possibilities of research and development and application of SMES. As a result, we have determined that in the near future the realization of medium- and large-scale SMES for electric power storage is difficult due to:

- the many technical problems faced in implementation,
- the fact that the energy density is low compared to other methods, and
- the extremely high cost.

Therefore, we have decided to pursue research of SMES for system stabilization due to the following reasons.

1. With its capability for rapid input and output of energy and simultaneous yet independent control of effective power and reactive power, SMES contains the potential for becoming a universal system stabilization device with a wide range of abilities.

2. SMES for system stabilization deals mainly with phenomena on the order of seconds. A small-scale energy storage capacity is sufficient for this purpose, making it a suitable subject for research.

The research was defined to demonstrate the feasibility of SMES for system stabilization. A team consisting of Kansai Electric Power and other entities with their respective technologies and experience in the field of superconductivity, Osaka University, Mitsubishi Electric, Mitsubishi Heavy Industries, Sumitomo Electric, has conducted research based on the aims and goals mentioned below.

- Develop a small-scale SMES demonstration system.
- Verify the system stabilization effect of SMES.
- Accumulate technologies related to SMES, such as cryogenic and superconducting technologies.

Resulting from this, we built a 1.2 MJ small scale SMES demonstration system consisting of three 400 kJ superconducting coils, and we were able to verify the effectiveness of the system stabilization feature of SMES on a simulated power transmission line system. This paper describes a summary of the research, an overview of the facility, and the results of the tests conducted.

III Hidemi Hayashi, "SMES Research at Kyushu Electric Power Company"

Introduction

Because SMES allows for the highly efficient storage of electric power and high speed and high level of control, expectations are great for commercialization in the near future as an electric power control facility that can respond to the various needs of electric power system load-leveling and system control. However, many issues remain regarding the increase of capacity, reliability, cost decrease, etc., which have prevented its commercial application. At Kyushu Electric Power Company we intend to engage in technical development and the collection and accumulation of various data necessary with the aim of commercialization of SMES. To this end, we have designed and built a small-scale, model device (nicknamed "ESK": An Experimental SMES of Kyushu Electric Power) of a module composition with excellent scalability and reliability. At present we are promoting a plan to verify and evaluate, through testing with existing systems and related systems, the effect of implementing SMES, its reliability, etc. This article discusses the development policy and design for ESK, and the prototype fabrication of constituent devices, and the results of the testing of their properties.

IV Masami Masuda, "Towards The Commercialization Of HTS SMES", Shônan Technical University

Abstract

The persistent current characteristic of superconductivity is the basis of SMES technology. I questioned whether HTS SMES is able to maintain a persistent current. To test this, small rings of material from YBCO and BSCCO were fabricated and the temperature dependence of the attenuation characteristic of the persistent current flowing through the rings was measured. The range of temperature measured was 4 to 90K. As a result, I found that it was not possible to maintain a persistent current near the critical temperature. The advantage of HTS SMES is that the temperature of the environment of the superconducting magnet can be that of liquid nitrogen or higher. The necessity of a lower environmental temperature would nullify the advantage of HTS SMES. From this perspective, along with the results of the above experiment, I attempted an evaluation of HTS SMES. As a result, I determined that the inherent thermal energy at temperatures above 77K is appreciably large. Thus, I wish to point out that, no matter how much progress is made in researching high temperature superconducting materials with high critical temperatures, their applicability to SMES will be problematical.

Introduction

Within two to three months after the discovery of high temperature superconductivity in late 1986, its critical temperature surpassed that of liquid nitrogen. The impact of this on the industry has not yet been forgotten. Those in the industry still have fresh memories of the sudden jump in stock prices of corporations involved in superconductivity, heavy electrical equipment, electric cables, construction, and other related materials. It is probable that this situation was due to people thinking that a solution had been found to all of the problems unavoidable in the existing cryogenic superconductivity methods: issues of cooling temperatures, the securing of a cooling medium, and the attendant issue of economic viability.

At present, the issues that arose concerning high temperature superconducting material have gradually been resolved, and performance has improved year by year. Thus the expectations placed on this material are gradually becoming fulfilled. In this article I will consider the application of HTS to SMES technology and discuss whether there are points which differ from applications to other fields.

The expectations of the industry immediately after the discovery of high temperature superconducting material were that, as its critical temperature surpassed the temperature of liquid nitrogen, liquid helium which had been needed, would no longer be necessary. At present, advances have allowed the critical temperature to go several tens of Kelvins above the temperature of liquid nitrogen. Some are of the opinion that this is sufficient. However, when the box of high temperature superconductivity was opened with anticipation, we were faced with the problem of the low level of usable current density. This problem appears to be gradually being solved. Other problems related to high temperature superconductivity also exist, but it is not within the scope of this paper to discuss them.

There is one other problem that must be solved in terms of SMES technology. This is whether high temperature superconductivity can maintain electric currents with no losses for such a long time that it can be called a persistent current. As SMES is a method to store energy using the magnetic field created by this persistent current, unless this problem is solved, there is no reason for applying superconductivity to energy storage.

Before starting this discussion, I will present a broad classification of SMES. There should be no objection to classifying SMES into three categories: large scale, medium scale, and small scale. Each of these SMES categories uses particular technologies. These characteristics are shown in Table D-3.

Table D-3
Characteristics of Each Category of SMES

Category:	Large	Medium	Small
Stored Energy	5000MWh	0.1-10MWh	1-300MJ
Power Capacity	1000MW	10-100MW	
Operation Cycle	2-10 h	1 min.-2 h	0.1 s-2min.
Examples	EPRI, NEDO, ENAA	ETM, ISTEC, RASMES	BPA, Alaska, µSMES
Problems	Unknown technology problem of environmental magnetic field	Discovery of new value-added to economy arguments	Shows economy in use other than for µSMES

Before presenting the suppositions of advantages of applying high temperature superconductivity to these three categories, I have made the following assumptions:

- Technical handling is the same as for LTS;
- A higher magnetic field can be attained compared to cryogenic superconductivity;
- The operating temperature is higher than 77K;
- Current density similar to that of LTS is attainable;
- The cost per kA-m is the same as LTS.

Under these assumptions, HTS SMES will be discussed. These requirements have not been met as of now, but this discussion will be conducted in the anticipation of these requirements being met in the near future. Even so, there is yet another problem with HTS. As stated before, this is the issue of whether a persistent current can be maintained. An experiment was performed to ascertain this.