- Fabrication of a 4kJ High-Tc Superconducting Pulse Coil Wound with a Bi2223 Wire for SMES, H. Hayashi, H. Kimura, Y. Hatabe, K. Tsutsumi, Kyushu Electric Power Co., Inc; M. Iwakuma, K. Funaki, Kyushu University; A. Tomioka, T. Bohno, Y. Yagi, Fuji Electric Co., Ltd.
- A 5 kJ HTS SMES Magnet System with Temperature Variation, X.H. Jiang, Y.C. Lai, Dept. of Electrical Engineering, Tsinghua University; J. Yang, N.Q. Jin, Institute of Electrical Engineering, Chinese Academy of Sciences; Z.G. Cheng, Baoding Tianwei Group Co. Ltd.
- HT-SMES Operating at Liquid Nitrogen Temperatures for Demonstrating Power Conditioning, A. Friedman, N. Shaked, E. Perel, F. Gartzman, M. Sinvani, Y. Wolfus, Y. Yeshurun, Center of Superconductivity, Bar-Ilan University.

Refrigeration Systems

The two articles below show the cost vs. size dependence of the refrigeration systems for superconducting magnets.

- 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.

Coil Geometries

Several different geometries have been considered for SMES. They are described in the report below. In general, the solenoid is simplest to build and is the lowest price. However, other designs might be more effective for specific applications, particularly those where the stray magnetic field is important.

- 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.

Other Reports on SMES Applications and Benefits

- W.V. Hassenzahl, B.L. Baker, and W.E. Keller, "The Economics of the Superconducting Magnetic Energy Storage Systems for Load levelling: a Comparison with Other Systems," Los Alamos Scientific Laboratory Report LA-5377-MS, September 1973.
- "Reassessment of Superconducting Magnetic Energy Storage (SMES) Transmission System Benefits", Power Systems Engineers, EPRI Report 1006795, March 2002.
- J. DeSteese, et al "Benefit/Cost Comparisons of SMES in System-Specific Application Scenarios," Proc. World Congress on Superconductivity, Munich, Germany, September, 1992.

years was based on a dual use concept. Several reports and papers related to this effort are given below.

- W. V. Hassenzahl, "Superconducting Magnetic Energy Storage", IEEE Trans. on Magnetics Vol. 24 No.2, March 1989, pp 750-758.
- Hassenzahl, W. V., R. B. Schainker, and T. M. Peterson, "The Superconducting Energy Storage ETM", Modern Power Systems Review, Vol. 11-3, pp 27-31, March 1991, London.

Other Articles In The Design And Use Of SMES

Other articles of interest in the design and use of SMES include:

- Facts with Energy Storage: Conceptual Design Study, EPRI, Palo Alto, CA: 1999. TR-111093
- W. V. Hassenzahl, "Considerations against force compensated coils", IEEE Trans. on Magnetics, Vol. 24 No.2, March 1989, pp 1854-1857.
- J. F. Picard, C. Levillain, P. G. Therond (Electricité de France, R&D division), SCENET, "Advantages and perspectives of SMES", 2nd Workshop on Power Applications of Superconductivity, November 1997.
- C. Levillain, P. G. Thérond (Electricité de France), 'Minimal Performances of High Tc Wires for Cost Effective SMES Compared with Low Tc's", IEEE Transactions on Magnetics, Vol. 32, No. 4, July 1996.
- 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.
- 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.

High Temperature Superconductors for SMES

Since their discovery in 1986, high temperature superconductors have been proposed for SMES applications. Some of the papers on the subject are listed here:

- 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

3. 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. Later

4. Private correspondence with Tom Abel, Projects and Services Manager, American Superconductor, October, 2003

5. J. D. Rogers, M. H. Barron, H. J. Boenig, A. L. Criscoulo, J. W. Dean, and R. I. Schermer, "Superconducting Magnetic Energy Storage", Proc. 1982 ASC, IEEE Trans. Magnetics, Vol. MAG-19, May 1983, pp. 1078-1080, and E. Hoffman, J. Alcorn, W. Chen, Y. H. Hsu, J. Purcell, and R. Schermer, "Design of the BPA Superconducting 30-MJ Energy Storage Coil", Proc. 1980 ASC, IEEE Trans. Magnetics, Vol: Mag-17, Jan. 1981.

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

7. George Ullrich, "Summary of the DNA SMES Development Program," IEEE Trans. Appl. Superconductivity, Vol. 5, No. 2, June 1995 pp 416-421.

SMES Bibliography

A series of conferences and journals contain innumerable articles on superconductivity and SMES technology, including:

- The Applied Superconductivity Conference is held in North America every even year. The proceedings of recent conferences are published in the IEEE Transactions on Applied Superconductivity. They contain considerable information on applicable superconducting materials and on SMES technology.
- The Material Research Society meets at least once per year and the proceedings of these meetings contain considerable information on the status of basic research in the area of superconductivity.
- The American Physical Society (APS) has several national and regional meetings each year that include sessions on LTS and HTS materials. In addition, there are several journals published by the American Institute of Physics, of which the APS is a member, that include articles on superconductivity.

Seminal Articles and Books

- The first paper on the phenomenon of superconductivity was:
  H. K. Onnes, Leiden Comm. 120b, 122b, 124c (1911)
- The first paper on high temperature superconductivity was:
  J. G. Bednorz and K. Mueller, Z. Phyzik B64, 189 (1986)

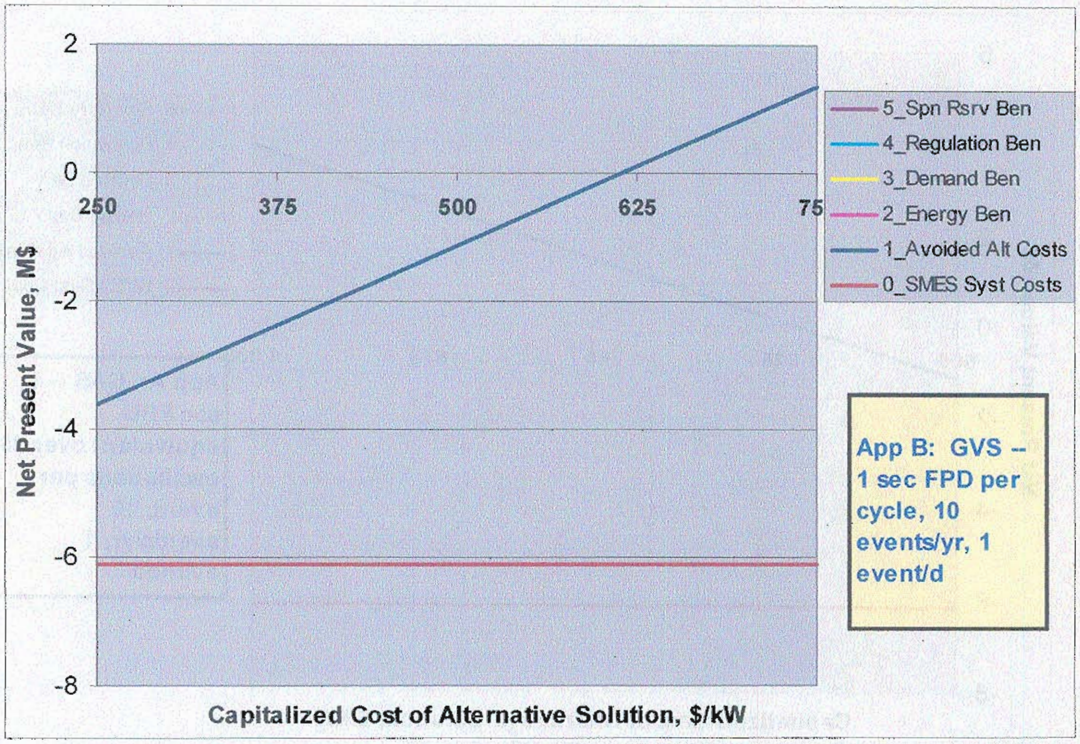

Figure 12-10
Application B: SMES System NPV vs Cost of Alternative Solution

- Application F: Short Duration Power Quality (SPQ) – This application was evaluated on the assumption that an alternative solution capable of mitigating SPQ events can be obtained for net capitalized costs of about $1000/kW, including acquisition, fixed and variable O&M, and property taxes and insurance costs. As shown in Table 12-8, this application yields a NPV of $1.4 million for an initial investment of about $5.1 million on this basis. As a measure of the sensitivity of NPV with respect to alternative solution costs, Figure 12-11 illustrates the change in NPV over a range of $500 to $1500/kW and shows that SMES systems will compete favorably against alternative solutions with net capitalized costs in excess of about $860/kW. As an additional indicator of NPV sensitivity with respect to the cost of energy storage, if the price of GAS SMES were increased from $3.03 to $4.16 million, the NPV would equal zero, i.e., costs and benefits would be equal.

Table 12-8
Summary of Benefit and Cost Analyses of SMES Battery Systems

Applications	Single Function		
	App A: GAS -- 1 sec FPD equivalent over 20 oscillations per event, 10 events/yr, 1 event/d	App B: GVS -- 1 sec FPD per cycle, 10 events/yr, 1 event/d	App F: SPQ -- 2 sec FPD per cycle, 100 events/yr, 5 events/d, 1 event/hr
Alt Solution Value, $/kW	750	500	1,000
Initial Installed Cost, M$	3.76	3.76	5.11
Total Costs, M$	(6.1)	(6.1)	(8.6)
Total Benefits, M$	7.50	5.0	10.0
Benefit to Cost Ratio	1.23	0.82	1.16
NPV, M$	1.4	(1.1)	1.4
SMES Module	DSMES-3KV	DSMES-3KV	DSMES-480V
SMES 2006 Price, ($K, FOB)	2,030	2,030	3,030
SMES Price for NPV=0, ($K, FOB)	3,180	1,100	4,160

- Application A: Grid Angular Stability (GAS) – This application was evaluated on the assumption that an alternative solution capable of mitigating GAS events can be obtained for net capitalized costs of about $750/kW, including acquisition, fixed and variable O&M, and property taxes and insurance costs. As shown in Table 12-8, this application yields a NPV of $1.4 million for an initial investment of about $3.8 million on this basis. As a measure of the sensitivity of NPV with respect to alternative solution costs, Figure 12-9 illustrates the change in NPV over a range of $500 to $1000/kW and shows that SMES systems will compete favorably against alternative solutions with net capitalized costs in excess of about $610/kW. As an additional indicator of NPV sensitivity with respect to the cost of energy storage, if the price of DSMES-3KV were increased from $2.03 to $3.18 million, the NPV would equal zero, i.e., costs and benefits would be equal.

Table 12-5
Capital and Operating Costs for SMES Systems

Applications	Single Function		
	App A: GAS -- 1 sec FPD equivalent over 20 oscillations per event, 10 events/yr, 1 event/d	**App B: GVS -- 1 sec FPD per cycle, 10 events/yr, 1 event/d**	**App F: SPQ -- 2 sec FPD per cycle, 100 events/yr, 5 events/d, 1 event/hr**
SMES Capacity, MWhac	0.003	0.003	0.006
PCS Initial Cost, $/kW	120	120	150
BOP Initial Cost, $/kW	50	50	50
SMES Initial Cost $/kW	207	207	309
SMES Initial Cost $/kWh	740,000	740,000	560,000
Total Capital Cost, M$	3.8	3.8	5.1
O&M Cost – Fixed, $/kW-year	14.5	14.5	22.2
O&M Cost– Variable, $/kW-year	8.7	8.7	12.4
NPV SMES Disposal Cost, $/kW	0.0	0.0	0.0

Note: The total initial cost may be calculated in two ways:
1. By mutiplying the sum of PCS, BOP and Battery initial costs expressed in $/kW by the reference power,
2. OR by mutiplying the sum of PCS and BOP expressed in $/kW by the reference power and then adding the product of Battery Initial cost expressed in $/kWh and the Battery Capacity

Benefit and Cost Analyses

SMES System Pricing and Integrated System Costs

American Superconductor has adapted product lines in response to market forces over the past few years, which saw a rapid rise in demand for power quality equipment in the late 1990's, and subsequent abrupt decline more recently. During this period, demand for utility grid support systems has been constrained to local congestion issues. In response to this market, American Superconductor has brought forth the D-VAR product line, which focuses on demand for reactive power products. D-SMES based products remain an important element of their product portfolio.

For the Handbook's reference deployment date of 2006 and rating of 10MW$_{ac}$, nominal unit prices supplied by American Superconductor [4] for 3 MW$_{ac}$, 3 MJ D-SMES products have been applied to the 10 MW$_{ac}$ GAS and GVS (10 MJ, DSMES-3KV) and SPQ (20 MJ, DSMES-480V) applications.[19] No replacement modules are projected over the 20-year project lifetimes. The resultant SMES prices for GAS, GVS and SPQ applications used in the benefit-cost assessments herein are:

SMES Unit	2006 Prices, K$
DSMES-3KV	**$2030**
DSMES-480V	**$3030**

The scope of supply corresponding to the above units includes refrigeration and refrigeration power supply, the magnet (coil) and magnet control system, and the DC-chopper (magnet interface to the inverter), plus technical support for system integration, installation and startup.

The cost of integrated systems is obtained by combining the cost of the SMES scope of supply with the appropriate PCS and BOP costs as described in Chapter 5. The PCS and BOP costs shown in Table 12-5 are based on the methodology described in Chapter 5. SMES systems for the GAS and GVS applications use Type I PCS as a result of relative high (3000 V$_{dc}$) DC-link voltage, while the system for SPQ uses a Type III "discontinuous" IGBT-based PCS. Since the cost of exterior enclosures is included in the SMES scope of supply, the cost of exterior space is included at $20 per square foot. SMES disposal costs are assumed to be negligible since no hazardous materials are involved. In accordance with the provisions of Chapter 5, BOP costs are assigned at $50/kW because SMES is commercially available as a fully integrated system.

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[19] The designations DSMES-3KV and DSMES-480V are used for the purposes of describing adaptations used in this Handbook and are not American Superconductor designations.

- Application B: Grid Voltage Stability (GVS) – This application requires that the system continuously detect and mitigate infrequent voltage instabilities and provide short duration real power, as well as continuous reactive power. D-SMES, adapted to 3000 V_{dc} chopper voltage, was equipped with a Type I PCS and configured for this application to be capable of real power discharges for up to 1 second, as well as to provide reactive power. The system will spend virtually its entire life in standby mode, for which standby SMES efficiency is calculated at 99.4%, attributed to continuous power for refrigeration and coil current losses at the PCS interface. The net system standby efficiency, including PCS losses, is 97.4%, and the projected life for this application is 20 years.
- Application F: Short Duration Power Quality (SPQ) – This application requires that the system continuously detect and mitigate infrequent PQ events lasting to up to 2 seconds. D-SMES, capable of full power discharges for up to 2 seconds, was equipped with a Type III PCS, based on 750Vdc chopper voltage (pulse factor of 5) suitable for discontinuous IGBT converters. This system will also spend virtually its entire life in standby mode, for which standby SMES efficiency is calculated at 98.3%, attributed to continuous power for refrigeration and coil current losses at the PCS interface. The net system standby efficiency, including PCS losses, is 96.3%, and the projected life for this application is 20 years.

costs for bulk storage, made smaller systems more attractive and that significantly reducing the storage time would increase the economic viability of the technology. Thus, there has also been considerable development on SMES for pulsed power systems. Though EPRI and government organizations have supported some of this effort, a great deal has been internally supported by industry. The total labor R&D in this area has been about 250 person years. In addition, several devices have been fabricated. We estimate that the combined international effort is on the order of $50M for SMES systems for pulsed power, system stability, and for other rapid discharge applications.

T&D System Energy Storage Applications

Select Applications for SMES Systems

This section presents the select applications for which the SMES is suited and describes the key features of the SMES systems when configured to meet the requirements of those applications. Screening economic analyses have shown that SMES systems are potentially competitive for three of the single function applications described in detail in Chapter 3. The following list briefly summarizes and reiterates key requirements for all applications. Those for which SMES is best suited are enclosed by borders.

Single Function Applications

Application A: Grid Angular Stability (GAS) – mitigation of power oscillations by injection and absorption of real power at periods of 1 to 2 seconds. The reference duty cycle for analysis is standby for infrequent events characterized by 20 oscillatory cycles, cumulatively equivalent to a full power discharge (FPD) of 1-second duration; 1 event per day; 10 events per year. Valued at the cost of alternative solutions.

Application B: Grid Voltage Stability (GVS) – mitigation of degraded voltage by additional reactive power plus injection of real power for durations up to 2 seconds. The reference duty cycle for analysis is standby for infrequent events characterized by 1 second FPD, 1 event per day, 10 events per year. Valued at the cost of alternative solutions.

Application C: Grid Frequency Excursion Suppression (GFS) – "prompt" spinning reserve (or load) for mitigating load-generation imbalance. Requires energy storage to discharge real power for durations up to 30 minutes. The reference duty cycle for analysis is standby for infrequent events characterized by 15-minute FPD, 1 event per day, 10 events per year. Valued at the cost of alternative solutions.

Application D: Regulation Control (RC) – system frequency regulation in concert with load following. The reference duty cycle for analysis is characterized by continuous cycles equivalent to 7.5-minute FPD and charge cycle (triangular waveform), 2 cycles per hour deployed with 10 minutes advance notice. Valued at market rates.

Application E: Spinning Reserve (SR) – reserve power for at least 2 hours with 10 minute notice. The reference duty cycle for analysis is standby for infrequent events characterized by 2-hour FPD, 1 event per day, 10 events per year. Valued at market rates.

Application F: Short Duration Power Quality (SPQ) – capability to mitigate voltage sags (e.g., recloser events). The reference duty cycle for analysis is standby for infrequent events characterized by 5 seconds

Table 12-2
Existing Installations of Micro-SMES

Start of Operation	Customer	Location	Application	Power (Voltage)	Energy, MJ
May 1992	Central Hudson G&E	Fishkill, NY	Semiconductor Testing Facility	500 kVA ($480 \ V_{ac}$)	1.0
December 1993	Tyndall AFB	Panama City, FL	Five General Military Buildings	500 kVA ($480 \ V_{ac}$)	1.0
March 1993	CYANCO	Winnemuca, NV	400 HP/4160V Motor at Chemical Plant	500 kVA ($4160 \ V_{ac}$)	1.0(+)
May 1995	Brookhaven National Laboratory	Upton, NY	Light Source Research Center Ultra-violet Light source, ring, and experiment station	1.4 MVA ($480 \ V_{ac}$)	2.8
May 1995	McClellan AFB	Sacramento, CA	Semiconductor Chip Mfg. Lab Fiber Optic Mfg. Facility Removed when Base Closed	750 kVA ($480 \ V_{ac}$)	2.8
July 1996	U.S. Air Force	Tinker AFB, OK	DC Link Support for two 800 kW/1000kVA Ups	1.0 MVA ($560 \ V_{ac}$)	2.8
June 1997	U.S. Air Force	Tinker AFB, OK	DC Link Support for two 800 kW/1000kVA UPS	1.0 MVA ($560 \ V_{ac}$)	2.8
April 1997	SAPPI - Stanger	Stanger, South Africa	1000 kVA Paper Machine	1.0 MVA ($400 \ V_{ac}$)	3.0
May 1997	AmeriMark Plastics	Fairbluff, NC	Plastic Extrusion Plant Removed when plant sold	1.4 MVA ($480 \ V_{ac}$)	3.0
May 1999	STEWEAG	Gleisdorf, Austria	Automotive Parts Foundry	1.4 MVA ($480 \ V_{ac}$)	3.0
June 2002	Edison/STM	Agrate, Italy	Semiconductor Processing Facility Voltage Sags - 2 Units	8.0 MVA ($480 \ V_{ac}$)	3.0
April 2002	EDF	Paris, France	Voltage Sag Protection	8.0 MVA ($400 \ V_{ac}$)	3.0

hand, the overall system efficiency is less. Fortunately, in these applications, efficiency is usually not a significant economic driver. The SMES coil stores energy with absolutely no loss while the current is constant. There are, however, some losses associated with changing current during charging and discharging, and the resulting change in magnetic field. In general, these losses, which are referred to as eddy current and hysteresis losses, are also small.

Unfortunately, other parts of the SMES system may not be as efficient as the coil itself. In particular, there are two potentially significant, continuous energy losses, which are application specific:

- The first is associated with the way SMES systems store the energy. The current in the coil must be flow continuously, and it circulates through the PCS. Both the interconnecting conductors and the silicon-based components of the PCS are resistive. Thus, there are continuous resistive losses in the PCS. This is different from batteries, for example, where there is current in the PCS only during charge and discharge.
- The second is the energy that is needed to operate the refrigerator that removes the heat that flows to the coil from room temperature via: a) conduction along the mechanical supports, b) radiation through the vacuum containment vessel, and c) along the current leads that extend from ambient temperature to the coil operating temperature.

The overall efficiency of a SMES plant depends on many factors. Diurnal (load-leveling) SMES plants designed 20 years ago were estimated to have efficiencies of 90 to 92%. Power quality and system stability applications do not require high efficiency because the cost of maintenance power is much less than the potential losses to the user due to a power outage. Developers rarely quote efficiencies for such systems, although refrigeration requirements are usually specified. A 3 MJ/3 MW_{ac} micro-SMES system, for example, requires about 13 kW of continuous refrigeration power.

Status of SMES Deployment

D-SMES

Today the only commercial SMES product is the D-SMES unit produced by American Superconductor. The individual, trailer-mounted D-SMES units consist of a magnet that contains 3 MJ of stored energy (see Figure 12-1). They can deliver 3 MW for about 1 second and 8 MVAR continuously at 480 V_{ac}. This is accomplished by a PCS that has full 4-quadrant control and uses IGBT based inverters. There is an instantaneous overload capability of 2.3 times continuous (2.3x) for reactive power in the inverter so that the dynamic reactive output can be as high as 18.4 MVAR for up to 1 second. Three networked systems with a total of 9 units have been installed, as indicated in Table 12-1. An additional unit has been ordered.

Figure 12-8
Large Liquid Helium Refrigerator (JAERI)

SMES manufacturers design their systems so that both the coil current and the allowable voltage include safety and performance margins. Thus, the PCS power capacity typically determines the rated capacity of the SMES unit. In particular, as energy is removed from the coil, the current decreases. As a result, the PCS must be designed to deliver rated power at the lowest operational coil current, which is about half of the maximum current. Equivalently, about a quarter of the stored energy remains in the coil at the end of a typical discharge.

The PCS provides an interface between the stored energy (related to the direct current in the coil) and the AC power grid. Several different designs have been suggested for the PCS, depending on the application and the design of the SMES coil. The power that can be delivered by the SMES plant depends on the charge status (the current I) and the voltage capability of the PCS, which must be compatible with the grid.

Control System

The control system establishes a link between power demands from the grid and power flow to and from the SMES coil. It receives dispatch signals from the power grid and status information from the SMES coil. The integration of the dispatch request and charge level determines the response of the SMES unit. The control system also measures the condition of the SMES coil, the refrigerator, and other equipment. It

Since only a few SMES coils have been constructed and installed, there is little experience with a generic design. This is true even for the small or micro-SMES units for power-quality applications, where several different coil designs have been used.

A primary consideration in the design of a SMES coil is the maximum allowable current in the conductor. It depends on: conductor size, the superconducting materials used, the resulting magnetic field, and the operating temperature. The magnetic forces can be significant in large coils and must be reacted by a containment structure within or around the coil. The coil shown in Figure 12-5 has stainless straps within the cabled conductor for this purpose. The baffle structure at the top of the coil limits gas circulation and maintains a temperature gradient from the liquid helium bath around the coil to the ambient-temperature top plate. Another factor in coil design is the withstand voltage, which can range from 10 kV to 100 kV.

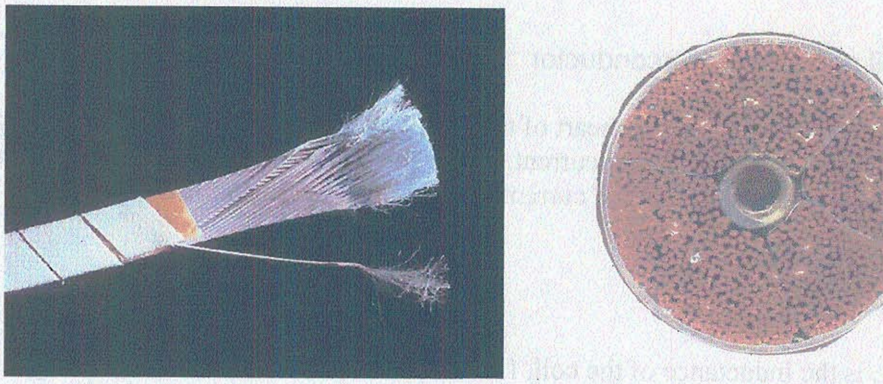
Cryogenic Refrigerator

The superconducting SMES coil must be maintained at a temperature sufficiently low to sustain a superconducting state in the wires. For commercial SMES today, this temperature is about 4.5 K (-269°C, or -452°F). This thermal operating regime is maintained by a special cryogenic refrigerator [6] that uses helium as the refrigerant. Helium must be used as the so-called "working fluid" in such a refrigerator because it is the only material that is not a solid at these temperatures. Just as a conventional refrigerator requires power to operate, electricity is used to power the cryogenic refrigerator. Thermodynamic analyses have shown that power required to remove heat from the coil increases with decreasing temperature. Including inefficiencies within the refrigerator itself, between 200 and 1000 watts of electric power are required for each watt that must be removed from the 4.5 K environment. As a result, design of SMES and other cryogenic systems places a high priority on reducing losses within the superconducting coils and minimizing the flow of heat into the cold environment.

Both the power requirements and the physical dimensions of the refrigerator depend on the amount of heat that must be removed from the superconducting coil. The refrigerator consists of one or more compressors for gaseous helium and a vacuum enclosure called a “cold-box”, which receives the compressed, ambient-temperature helium gas and produces liquid helium for cooling the coil. The 30 MJ coil shown in Figure 12-5 required a dedicated refrigerator that occupied two small trailers, one for the compressor and one for the “cold box”. The coil was tested at 4.5 K and then removed from the cryostat while still cold, which leads to the ice on the surface of the helium vessel. The coil is approximately the size of early power quality SMES coils, such as those fabricated by American Superconductor Inc. and Intermagnetics General Corporation.

Small SMES coils and modern MRI magnets are designed to have such low losses that very small refrigerators are adequate. Figure 12-7 and Figure 12-8 show cryogenic refrigerators of different capacities. In Figure 12-7, a small cryogenic refrigerator (the 30 cm section) and a cold-finger extension that would be appropriate for recondensing liquid

All practical SMES systems installed to date use a superconducting alloy of niobium and titanium (Nb-Ti), which requires operation at temperatures near the boiling point of liquid helium, about 4.2 K (-269C or -452°F) which is 4.2 degrees centigrade above absolute zero. Typical conductors made of this material are shown in Figure 12-4.



a b

Figure 12-4
Typical Conductors Made of the Superconductor Nb-Ti (LBNL & LLNL)

Figure 12-4a, on the left, is a flattened cable made of 30 composite strands wrapped in an insulator made of Kapton and epoxy-fiberglass. Each strand is 0.7 mm in diameter and contains several thousand, 6 μm diameter Nb-Ti filaments extruded in a copper matrix. Figure 12-4b, on the right, is a CICC cable made of several hundred of these strands in a stainless steel conduit. During operation, helium is in direct contact with the superconducting strands and, in the CICC shown, the helium flows through the central tube. Lawrence Berkeley National Lab (LBNL) and Lawrence Livermore National Lab (LLNL) supplied figures 4a and 4b, respectively.

Many tons of Nb-Ti alloy are fabricated worldwide each year for applications such as magnetic resonance imaging (MRI) magnets and accelerators for nuclear physics research. In addition, the aerospace industry uses considerably more of a slightly different Nb-Ti alloy each year for rivets that hold the aluminum skin in place on the bodies and wings of most commercial and military aircraft. Some "research grade" SMES coils use high-temperature superconductors (HTS). However, the state of development of these materials today is such that they are not cost effective for utility-application SMES. An evaluation HTS for SMES was made for EPRI in 1998 [4].

Since the superconductor is one of the major costs of a superconducting coil, one design goal is to store the maximum amount of energy per quantity of superconductor. Many factors contribute to achieving this goal. One fundamental aspect, however, is to select a coil design that most effectively uses the material. This is generally accomplished by a solenoidal configuration, as in the two SMES installations shown in Figure 12-5 and Figure 12-6. Figure 12-5 shows the 30 MJ [5] superconducting coil developed by the Los

Figure 12-1
A Trailer Mounted D-SMES Unit With 3MW and Up to 16 MVA Capacities (Picture Supplied by American Superconductor)

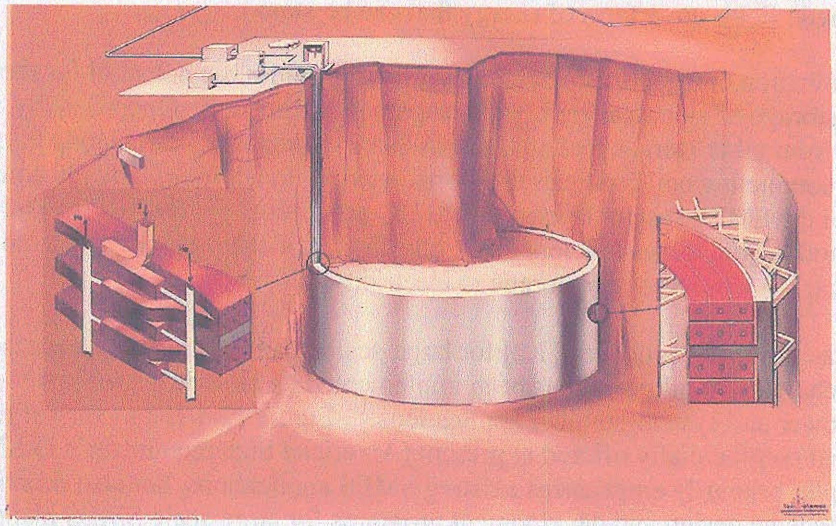


Figure 12-2
Artist Concept of a Large-Scale Diurnal SMES System Constructed Underground

Description

System Components

The power and stored energy in a SMES system are determined by application and site-specific requirements. Once these values are set, a system can be designed with adequate margin to provide the required energy on demand. As illustrated by the SMES systems