CONF-860210--1

LA-UR--85-3342

DE86 000812

TITLE A FEASIBLE UTILITY SCALE SUPERCONDUCTING MAGNETIC ENERGY STORAGE SYSTEM

AUTHOR(S) R. J. Loyd, Bechtel, S. M. Schoenung, Bechtel, T. Nakamura, Bechtel, D. W. Lieurance, General Dynamics, M. A. Hilal, General Dynamics, J. D. Rogers, CTR-9, J. R. Purcell, GA Technologies, W. V. Hassenzahl, Berkeley Laboratory

SUBMITTED TO IEEE Power Engineering Society Winter Meeting
New York, NY
February, 1986

MASTER

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

FORM NO 836 R4
ST NO 2629 5/81

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

SUMMARY

A FEASIBLE UTILITY SCALE SUPERCONDUCTING MAGNETIC ENERGY STORAGE SYSTEM

R. J. Loyd
S. M. Schoenung
T. Nakamura
Bechtel, Inc.
San Francisco, California

D. W. Lieurance
M. A. Hilal
General Dynamics
San Diego, California

J. D. Rogers
Los Alamos National Laboratory
Los Alamos, New Mexico

J. R. Purcell
G. A. Technologies, Inc.
San Diego, California

W. V. Hassenzahl
Lawrence Berkeley Laboratory
Berkeley, California

This paper presents the latest design features and estimated costs of a 5000 MWh/1000 MW Superconducting Magnetic Energy Storage (SMES) plant. SMES is proposed as a commercially viable technology for electric utility load leveling. The primary advantage of SMES over other electrical energy storage technologies is its high net roundtrip efficiency. Other features include rapid availability and low maintenance and operating costs. Economic comparisons are made with other energy storage options and with gas turbines.

In a diurnal load leveling application, a superconducting coil can be charged from the utility grid during off-peak hours. The ac grid is connected to the dc magnetic coil through a power conversion system that includes an inverter / rectifier. Once charged, the superconducting coil conducts current, which supports an electromagnetic field, with virtually no losses. During hours of peak load, the stored energy is discharged to the grid by reversing the charging process. The principle of operation of a SMES unit is shown in Fig. 1. For operation in the superconducting mode, the coil is maintained at extremely low temperature by immersion in a bath of liquid helium.

DESCRIPTION

The 5000 MWh/1000 MW SMES plant consists of a 556 turn, 4 radial layer series-wound solenoidal coil and all necessary support systems. The coil has an aspect ratio of 0.019 (19 meters high and 1000 meters in diameter) and is housed in a circular bedrock trench, which provides support for the coil structure against radial magnetic forces. Fig. 2 is a cut-away view showing the coil and related components.

The coil employs a 200 kA conductor made of copper/niobium-titanium superconductor imbedded in a high purity aluminum stabilizer. The conductor is positioned in an alloy aluminum structure which supports the conductor against magnetic loads. The coil operates in a superfluid helium bath at 1.8 K and one atmosphere. The helium is maintained at 1.8 K by a refrigeration system. To minimize convective and radiative heat transfer the helium vessel is enclosed in a vacuum vessel fitted with radiation shields. Design of the SMES plant includes a system for protection of the coil in the event of an emergency shut-down while the coil is charged. The liquid helium is removed and the stored energy is dissipated in the coil materials, warming the coil safely to ambient temperature.

Operation of the plant is relatively simple. The charge and discharge rates are controlled remotely by the utility, while the refrigeration system requires local control. Dispatch efficiency is 94%. Therefore, a SMES plant is economical to dispatch when the cost of peaking power exceeds the cost of base-load power by only 6 percent, as compared to a 30 to 50 percent differential required for other energy storage technologies. Total energy efficiency is about 91%. Construction of a 5000 MWh plant is estimated to take two years and cost approximately $961 million in 1984 dollars. This cost is competitive with other energy storage technologies.

Work to date has identified no unresolvable technical issues, although detailed engineering work remains prior to demonstration and commercial application of this technology. Future efforts will focus on establishing definitively the cost of SMES as function of stored energy, design and construction of an engineering prototype, and materials research and development that may result in additional cost reductions.

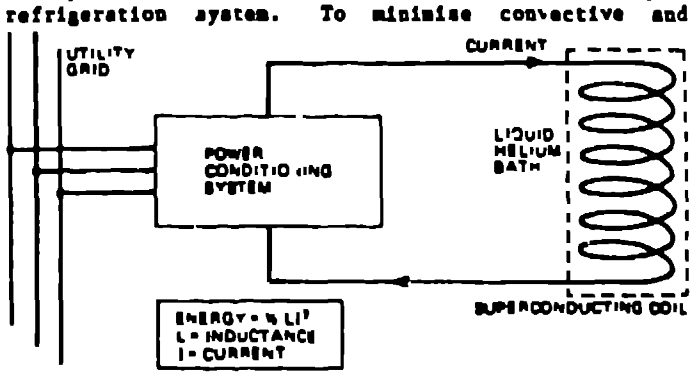

Figure 1 SMES – PRINCIPLE OF OPERATION

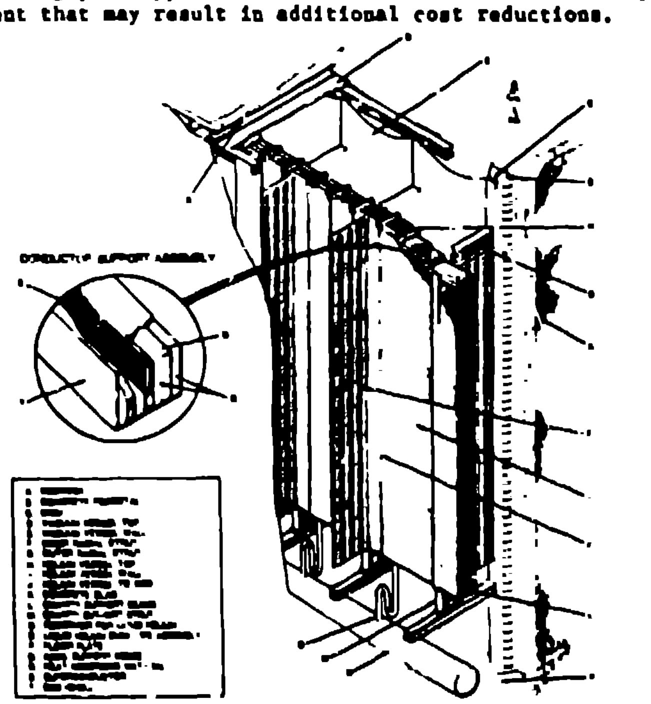

Figure 2 SUPERCONDUCTING MAGNETIC ENERGY STORAGE PLANT

A FEASIBLE UTILITY SCALE SUPERCONDUCTING MAGNETIC ENERGY STORAGE SYSTEM

R. J. Loyd
S. M. Schoenung
T. Nakamura
Bechtel, Inc.
San Francisco, California

D. W. Lieurance
M. A. Hilal
General Dynamics
San Diego, California

J. D. Rogers
Los Alamos National Laboratory
Los Alamos, New Mexico

J. R. Purcell
G. A. Technologies, Inc.
San Diego, California

W. V. Hassenzahl
Lawrence Berkeley Laboratory
Berkeley, California

Abstract - This paper presents the latest design features and estimated costs of a 5000 MWh/1000 MW Superconducting Magnetic Energy Storage (SMES) plant. SMES is proposed as a commercially viable technology for electric utility load leveling. The primary advantage of SMES over other electrical energy storage technologies is its high net roundtrip efficiency. Other features include rapid availability and low maintenance and operating costs. Economic comparisons are made with other energy storage options and with combustion turbines.

INTRODUCTION

In a diurnal load leveling application, a superconducting coil can be charged from the utility grid during off-peak hours. The ac grid is connected to the dc magnetic coil through a power conversion system (PCS) that includes an inverter/rectifier. Once charged, the superconducting coil conducts current, which supports an electromagnetic field, with virtually no losses. During hours of peak load, the stored energy is discharged to the grid through the PCS by reversing the charging process. The principle of operation of a SMES unit is shown in Fig. 1. For operation in the superconducting mode, the coil is maintained at extremely low temperature by immersion in a bath of liquid helium.

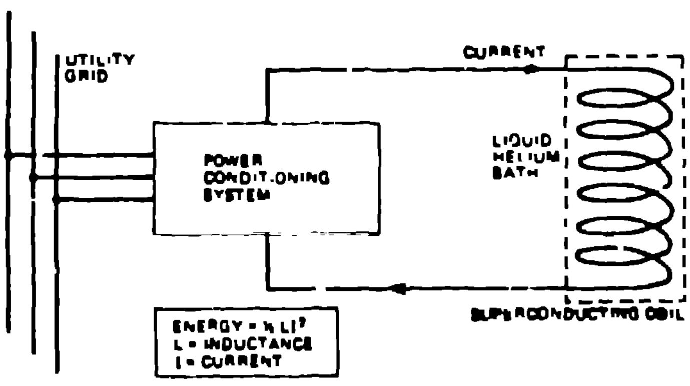

Fig. 1 SMES Principle of Operation

To be feasible, a utility scale SMES plant should have a low aspect ratio (coil height/coil diameter) so that it can be constructed in an open trench [1,2]. This paper briefly reports a SMES design concept resulting from two DOE-funded studies having the goal of identifying, developing and quantifying a low aspect ratio system configuration that is technically feasible and would have a commercially viable capital cost [3,4].

DESCRIPTION

The 5000 MWh, 1000 MW SMES plant design consists of a 556 turn, four radial layer, superconducting solenoidal coil plus all necessary support systems. Figure 2 shows a "bird's eye" view of the plant and Fig. 3 is a cut-away view showing the coil and related components.

The coil employs a 200 kA conductor made of copper/niobium-titanium superconductor stabilized by high purity aluminum. The conductor is positioned in an alloy aluminum structure (conductor support assembly) which supports the conductor against magnetic loads. The coil operates in a superfluid helium bath at a nominal temperature of 1.8 K and a nominal pressure of one atmosphere. The helium, contained by a vessel surrounding the coil, is maintained at 1.8 K by a refrigeration system. To eliminate convective heat transfer the helium vessel is surrounded by a vacuum. To minimize radiative heat transfer, two

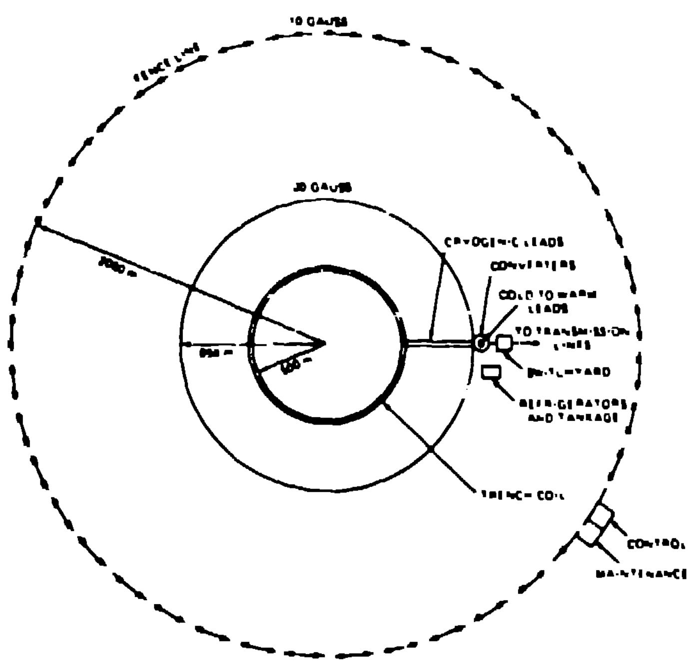

Fig. 2 Overall Plan View of the 5000 MWh SMES Plant

fixed temperature shields are located between the cold helium vessel wall and the ambient temperature vacuum enclose. To minimize conduction heat transfer, the struts are also fitted with fixed temperature heat intercepts. The shield and strut intercept temperatures are maintained by active cooling. Over 24 hours the refrigerators consume energy equivalent to 2 percent of the usable coil charge.

COIL

The coil is a series-wound solenoid, with an aspect ratio of 0.019, and an inductance of 945 Henries. Stored energy of the coil at full and minimum charge is 5250 MWh and 250 MWh, respectively. The coil, wound at a diameter of 1000 m is housed in a circular bedrock trench, which provides ultimate support for the coil structure against radial loads. The coil is supported over its full height from both the inner and outer trench walls by radial struts, the spacing of these struts is determined by allowable stresses in the conductor support assembly. When charged, the magnetically induced outward radial force is transmitted to the outer trench wall. When fully discharged, the radial load is directed inward and is transmitted to the inner trench wall. The inward load is the result of thermal hoop stresses from cooling the stationary coil. Axial loads are borne internally by the coil winding structure. A plan view showing a coil segment, helium vessel, struts, and vacuum enclosure is given in Fig. 4.

Each winding consists of a conductor and a conductor support assembly. The coil turns are electrically isolated from one another by vertical and horizontal insulator sheets. Figure 5 shows the coil winding pattern and series connections between radial layers. This parallel helix winding pattern was selected in preference to a pancake pattern primarily because it simplifies design of the conductor support assembly and permits radial grading of the superconductor content in the conductor; however, other benefits accrue.

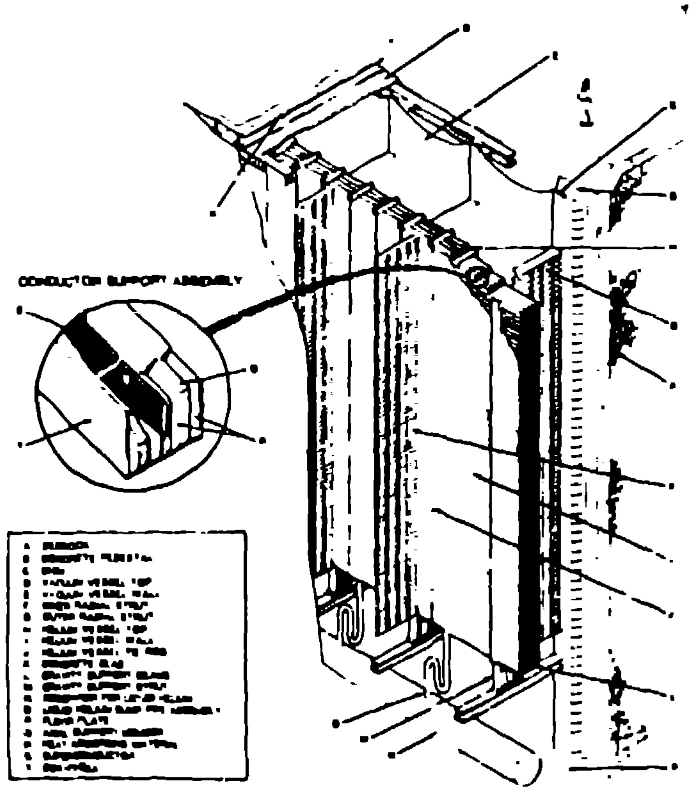

Fig.3 Superconducting Magnetic Energy Storage Plant

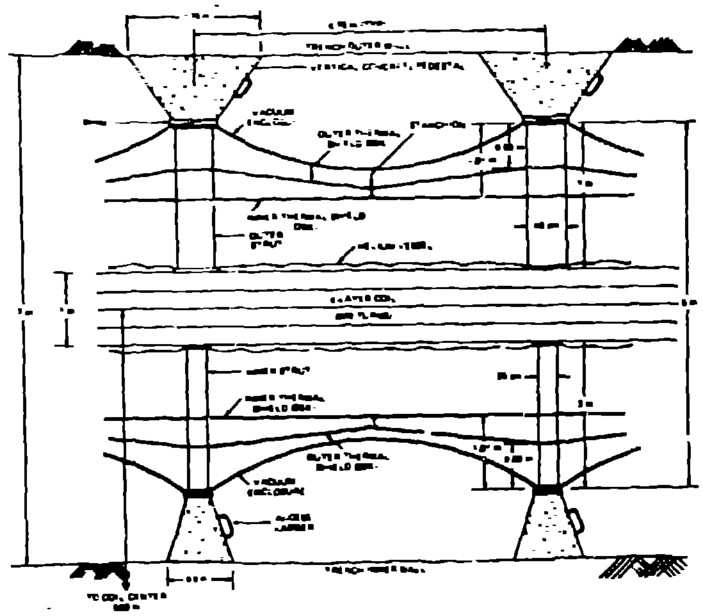

Fig. 4 Plan View of the Coil

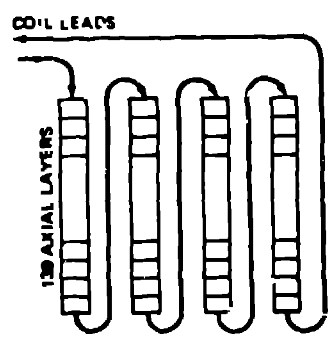

Fig. 5 Radial Layer Connection Pattern

A schematic diagram of the conductor configuration is shown in Fig. 6. It consists of about one hundred - 1 mm superconductor strands imbedded in the surface of a rectangular, high-purity aluminum stabilizer. For ruggedness, the conductor is 90% covered with thin, high strength aluminum overwrap. The aspect ratio of the conductor varies with location in the coil to accommodate bearing loads and to minimize AC losses. Maximum average AC losses expected for this conductor is expected to be 2.6 kW, and are dominated by coupling losses.

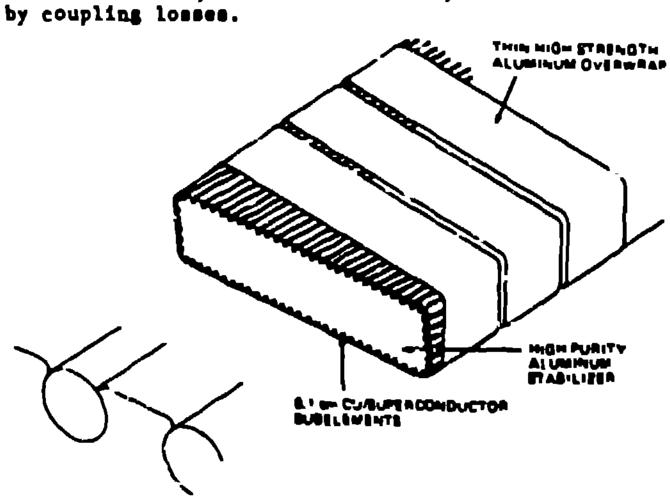

Fig. 6 Conductor Configuration

CONDUCTOR SUPPORT ASSEMBLY

The conductor support assembly, detailed in Fig. 7, consists of a box shell and axial support members within the box shell. All enclosed voids are filled with heat absorbing material, probably tar. The box shell is subject to tensile stress due to cooldown, bending stresses, and radial compressive stress. The axial support members inside of the box shell are not mechanically continuous in the circumferential direction and are therefore stressed only by radial bending and cumulative axial compressive loads. This decoupling of cooldown stress from axial stress is a key feature of the design.

Figure 8 shows the coil winding insulator detail. Each winding is insulated radially by vertical insulators and axially by horizontal insulators spanning the width of the coil. Recesses are machined or molded in the horizontal insulators so that the axial compressive forces will be borne only by the axial support components of the conductor support assembly. During operation, compression-induced static friction between the insulators and the conductor support assemblies transfers the shear force between adjacent windings due to bending. Accordingly, no slip between components occurs and the four-layer assemblage restrains radial magnetic loads as a composite beam. The horizontal insulators are constructed of G-10CR glass reinforced epoxy, while the vertical insulators can be made from less expensive material.

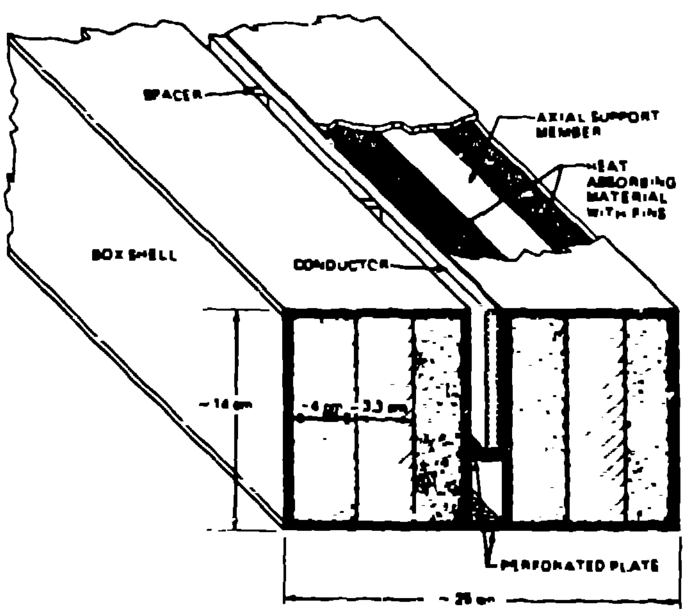

Fig. 7 Conductor and Support Assembly

COIL PROTECTION

If, for any reason, part of or all of the conductor should begin to lose its superconducting capacity, a coil protection system is activated to shut down the coil. This system simultaneously dumps the 3 million liters of liquid helium coolant into a storage reservoir located below the coil and drives superconductor into a "normal" resistive state with cold helium gas [5]. Once the superconductor is normal, current is shared between the conductor and the coil winding structure in inverse proportion to their resistances at their respective temperatures. The current is resistively converted to heat, which is absorbed by the conductor, the conductor support assembly, and the heat absorbing material contained in the enclosed voids of the conductor support assembly. The thermal capacity of the structure is designed to absorb the thermal energy without causing thermal or mechanical damage to the coil. Because the conductor is in good thermal contact with the structure, its temperature rises only slightly ahead of the temperature of the conductor support assembly. Hot spots and excessive voltages do not occur.

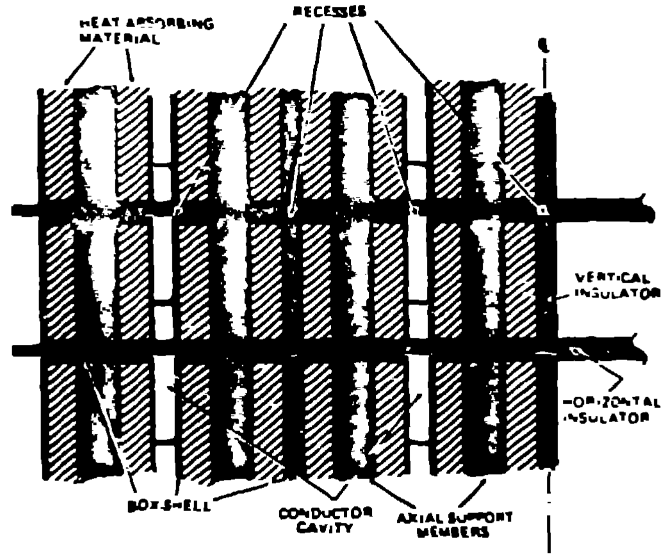

Fig. 8 Coil Cross Section Showing Vertical and Horizontal Insulator Detail

OTHER PLANT COMPONENTS

The helium vessel walls consist of aluminum attached to the horizontal G-10CR insulators. The top of the helium vessel is restrained against internal pressure by tie rods extending the height of the coil.

Figures 3 and 4 illustrate the arrangement of the struts relative to the coil. Because the radial magnetic force is directed outward while the thermal cool-down force is directed inward, the resultant can be either inward or outward depending on the level of stored energy. Regardless of the direction of the net radial force, both inner and outer struts are always under compression, assured by appropriate prestressing with the shims. The struts are composed of G-10CR glass-reinforced epoxy panels.

The atmospheric pressure load on the vacuum enclosure is transferred to the coil winding structure by the radial struts. No tensile loads are transmitted to the trench wall. Figure 4 shows the arrangement of the vacuum enclosure walls. The floor of the vacuum enclosure consists of stainless steel plate. The top, also flat, consists of steel sheet welded to the underside of beams supported by the concrete pedestals.

The SMES coil is located below grade to make use of the earth as structure for resisting the net radial loads generated by the coil. The depth of the trench from grade is about 25 m and assumes a level site. This allows adequate height for the helium reservoir, the coil and other hardware. The width of the trench is 7 m, which allows for the coil, struts, thermal shields, vacuum enclosure, and vertical concrete pedestals.

The inner and outer trench walls are subject only to compressive loads. The forces applied by the radial struts are transferred to the trench wall via vertical concrete pedestals designed to load the rock to a maximum pressure of 1.92 MPa (20 ton/ft^2). This limit allows the plant to be sited in igneous, volcanic or sedimentary rock of moderate strength.

OPERATION AND PERFORMANCE

Normal operation and maintenance for a SMES plant should be relatively simple. The charge and discharge rates would be controlled remotely by the utility dispatcher. The refrigeration system would require local control. About 40 equivalent full-time personnel would be required for 24-hour operation of the plant; maintenance of the refrigeration, vacuum, power conditioning, and other plant systems; and administration of the facility.

In a SMES plant, the major energy loss takes place at the PCS during coil charge and discharge. Assuming a 97 percent one-way PCS efficiency, the plant could be economically dispatched when the cost of adding generation exceeds the cost of base-load charging power by about 6 percent. This compares to a required 30 to 50 percent differential for other modes of energy storage. The magnitude and direction of power through the PCS can be changed rapidly (i.e., in tens of milliseconds). As a consequence, a SMES plant would benefit power system operators by being used not only for load leveling, but for load following, as a swing generator, for spinning reserve, for transient stability augmentation, and for subsynchronous resonance damping.

COSTS

Table 1 presents the estimated total capital requirement at startup including allowance for funds during construction (AFDC), in 1984 dollars. The estimated cost of a SMES plant capable of delivering nominal 5000 MWh daily at a nominal power of 1000 MW is $961 million. This includes 25 percent contingency on the coil and other energy related components and 15 percent contingency on power related components. A 1982 EPRI-funded study [6] states that there would be at least a small market for a nominal 5000 MWh, 1000 MW SMES plant costing $1000/kW (computed as power-related costs, $/kW + energy-related costs, $/kWh x hours of discharge at full power) in 1981 dollars. When computed on the same basis, the design reported herein is estimated to cost $988/kW in 1984 dollars. Neglecting licensing and land, the overnight construction costs are 157 $/kWh for energy related components and 140 $/kW for power related components, in 1985 dollars.

Figure 9 compares current dollar revenue requirements (¢/kWh discharged) for SMES with other near-term energy storage options: lead acid batteries, salt-based compressed air energy storage (CAES), underground pumped hydro (UPH), and with combustion turbines (CT). Because of its high energy efficiency, the value of SMES relative to other energy storage technologies and combustion turbines increases with the cost of charging electricity and premium fuels. This is demonstrated by the curves in Fig. 10 which are based on increased rates for charging electricity (6 ¢/kWh vs. 3 ¢/kWh) and natural gas ($12/million BTU vs. $6/million BTU), both in 1985 dollars. Considering the time frame during which SMES will be available (1990's) and the 30-year projected plant life, even these prices for charging electricity and natural gas are probably low. Table 2 delineates the capital cost inputs, O&M cost inputs, and efficiencies used to derive the economic screening curves in Figs. 9 and 10.

Table 1 Capital Requirement (Millions of Dollars*)

Cost Item	Storage Related Costs	Power Related Costs	Totals
Direct Process Capital			
Materials and Offsite Fabrication	407.6	79.0	486.6
Construction	93.7	24.4	118.1
Total Direct Process Capital	501.3	103.4	604.7
Indirect Process Capital	21.2	7.8	29.0
Total Process Capital	522.5	111.2	633.7
General Facilities	2.4	—	2.4
Engineering and Home Office	26.2	5.6	31.8
Geotechnical	2.1	—	2.1
Licensing	2.5	—	2.5
	555.7	116.8	672.5
Contingency	138.9(25%)	17.5(15%)	156.4
Total Plant Investment	694.6	134.3	828.9
AFDC	83.0	5.0	88.0
Total Plant Investment at Startup	777.6	139.3	916.9
Preproduction	7.9	1.4	9.3
Inventory and Refrigerants	26.5	—	26.5
Land	7.9	—	7.9
Total Capital Requirement	819.9	140.7	960.6

* 1984 Dollars

COMMERCIALIZATION POTENTIAL

The work to date has identified no unresolvable technical issues, but a significant amount of detailed engineering work remains prior to commercial application of this technology. The focus of future efforts should be directed towards establishing the cost of SMES as a function of stored energy, establishing an appropriate plant size that would serve as an engineering prototype and, materials research and development that may result in additional cost reductions.

Other than a small (30 MJ) SMES coil installed and successfully operated for line stabilization [7], no SMES plants have been built to date. However, due to the high energy efficiency and immediate load following capability of the SMES technology, and due to the favorable capital costs now being projected, commercial interest in SMES should grow over the next few years.

ACKNOWLEDGEMENT

This work was funded by Los Alamos National Laboratory under contracts 9-X44-J8666-1 and 9-X5-J8709-1.

REFERENCES

1. R. J. Loyd, G. F. Moyer, J. R. Purcell, and J. Alcorn, Conceptual Design and Cost of a Superconducting Magnetic Energy Storage Plant, EPRI EM-3457, April 1984.

2. R. J. Loyd, J. R. Purcell, and R. B. Schainker, "A Cost Study of Superconducting Magnetic Energy Storage for Large Scale Electric utility Load Leveling," Proc. of the 19th IECEC, Vol. 2, (1984), p. 1144-1149.

3. R. J. Loyd, T. Nakamura, and J. R. Purcell, Design Improvements and Cost Reductions for a 5000 MWh Superconducting Magnetic Energy Storage Plant, Los Alamos National Laboratory Report LA-10320-MS, (1985).

4. R. J. Loyd, et al., Design Improvements and Cost Reductions for a 5000 MWh Superconducting Magnetic Energy Storage Plant - Part II, Los Alamos National Laboratory Report, to be published, (1986).

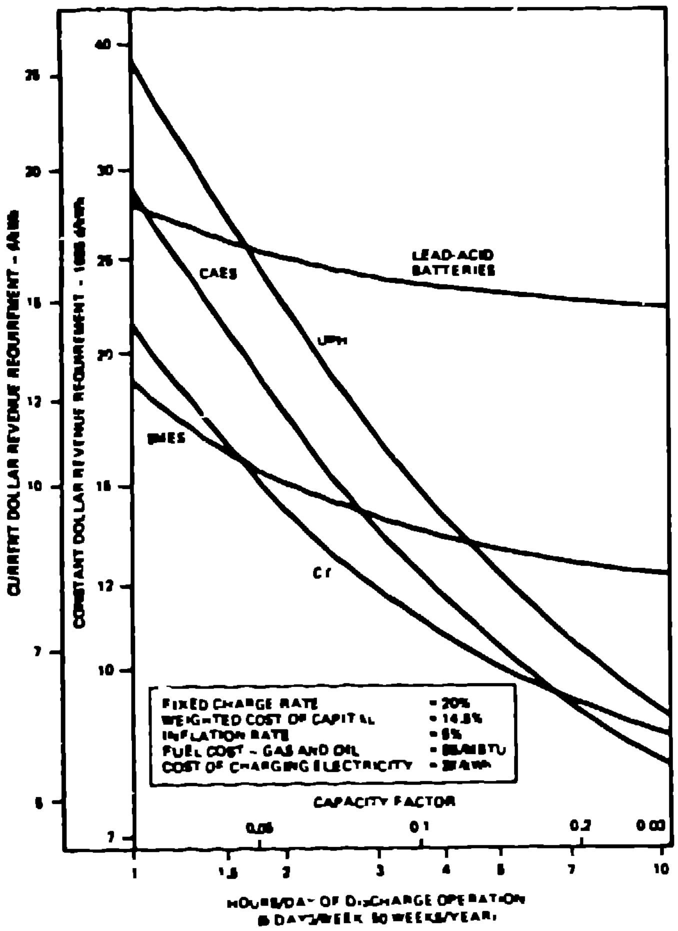

Fig. 9 Revenue Requirement Screening Curves for Various Energy Storage Technologies - Based on Current Fuel and Electricity Costs

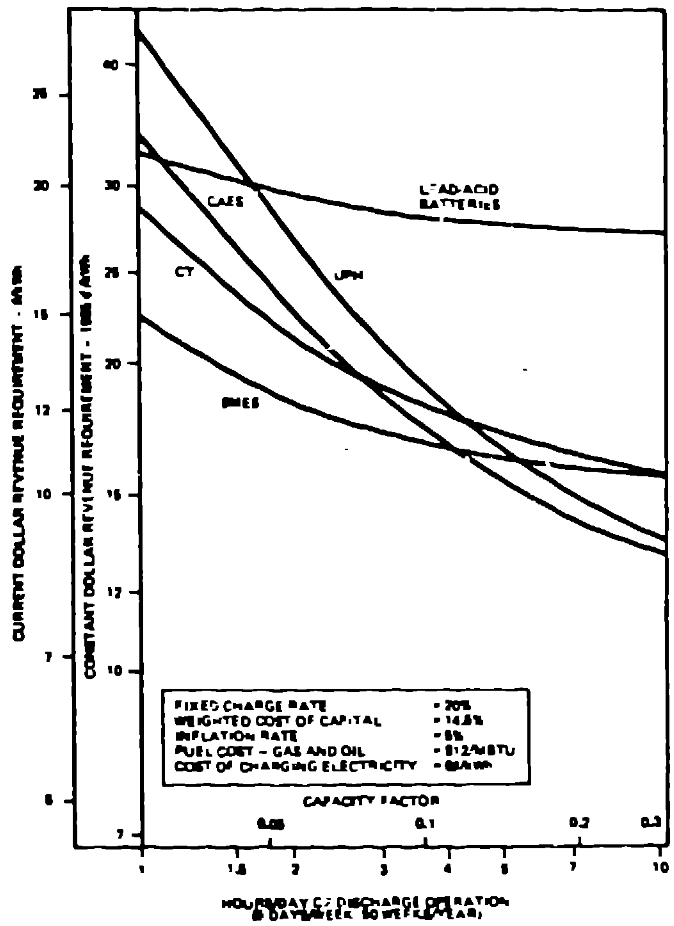

Fig. 10 Revenue Requirement Screening Curves for Various Energy Storage Technologies - Based on Increased Fuel and Electricity Costs

Table 2 Capital and O&M Costs and Efficiencies Used to Generate Screening Curves

Technology	Capital Cost*		Operation and Maintenance			Efficiency	
	Power Related ($/kW)	Energy Related ($/kWh)	Fixed ($/kW-Yr)	Variable ($/kWh-Yr)	Variable (¢/kWh)	Electric Energy (Out/In)	Fuel (Btu/kWh)
Lead Acid Batteries	113	201	0.62	17.12	N/A	0.66	N/A
Compressed Air Energy Storage (Salt-based)	412	10	4.74	N/A	0.82	1.25	4020
Underground Pumped Hydro	807	31	2.78	N/A	0.86	0.72	N/A
Combustion Turbines	268	N/A	0.62	N/A	0.40	N/A	11500
SMES	140	137	0.68	N/A	N/A	0.93	N/A

*Costs are in 1985 dollars, are for overnight construction and do not include owner's costs, allowance for funds during construction, licensing or land

REFERENCES

5. S. M. Schoenung, R. J. Loyd, J. D. Rogers and J. R. Purcell, Liquid Helium Dump Concept for a Large Scale Superconducting Magnetic Energy Storage Plant, "Advances in Cryogenic Engineering," Vol. 31, Plenum Press, New York (1986).

6. S. T. Lee, R. S. Albert and D. T. Imamura, Evaluation of Superconducting Magnetic Energy Storage Systems, EPRI EM-2861 (1983).

7. J. D. Rogers and H. J. Boenig, "30 MJ Superconducting Magnetic Energy Storage Performance on the Bonneville Power Administration Utility Transmission System," Proc. of the 19th IECEC, Vol. 2, (1984), p. 1138-1143.