Received by OSTI OCT 09 1985

CONF-850814--26

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36.

LA-UR--85-3195

DE86 000777

TITLE: DESIGN AND COST OF A UTILITY SCALE SUPERCONDUCTING MAGNETIC ENERGY STORAGE PLANT

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SUBMITTED TO Cryogenic Engineering Conference
Boston, MA
August 12-16, 1985

MASTER

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Los Alamos
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Los Alamos, New Mexico 87545

FORM NO 836 R4
ST NO 2629 5/81

CEC '85 BD-22

DESIGN AND COST OF A UTILITY SCALE SUPERCONDUCTING MAGNETIC ENERGY STORAGE PLANT

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ABSTRACT

Superconducting Magnetic Energy Storage (SMES) has potential as a viable technology for use in electric utility load leveling. The advantage of SMES over other energy storage technologies is its high net roundtrip energy efficiency. This paper reports the major features and costs of a jointly developed 5000 MWh SMES plant design.

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.

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 a DOE-funded study[3] 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.

FUNCTIONAL 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 1 shows a "bird's eye" view of the plant and Fig. 2 is a cut-away view showing the coil and related components.

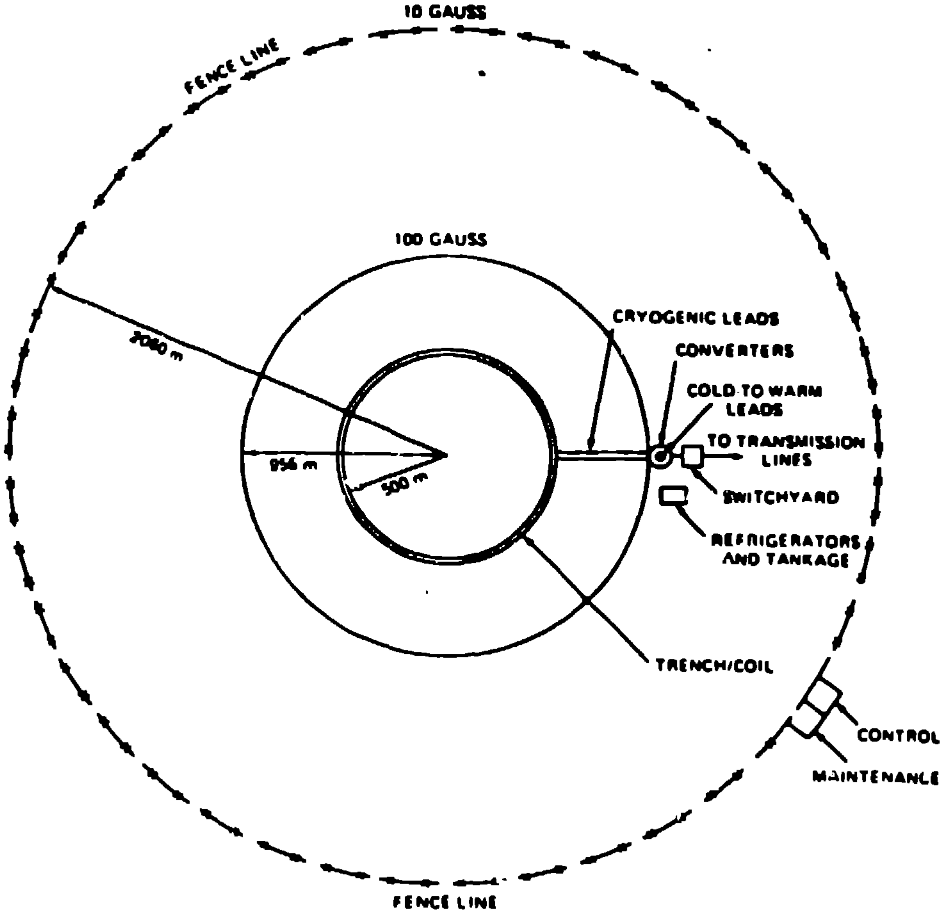

Figure 1 OVERALL PLAN VIEW OF THE 5000 MWH SMES PLANT

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 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

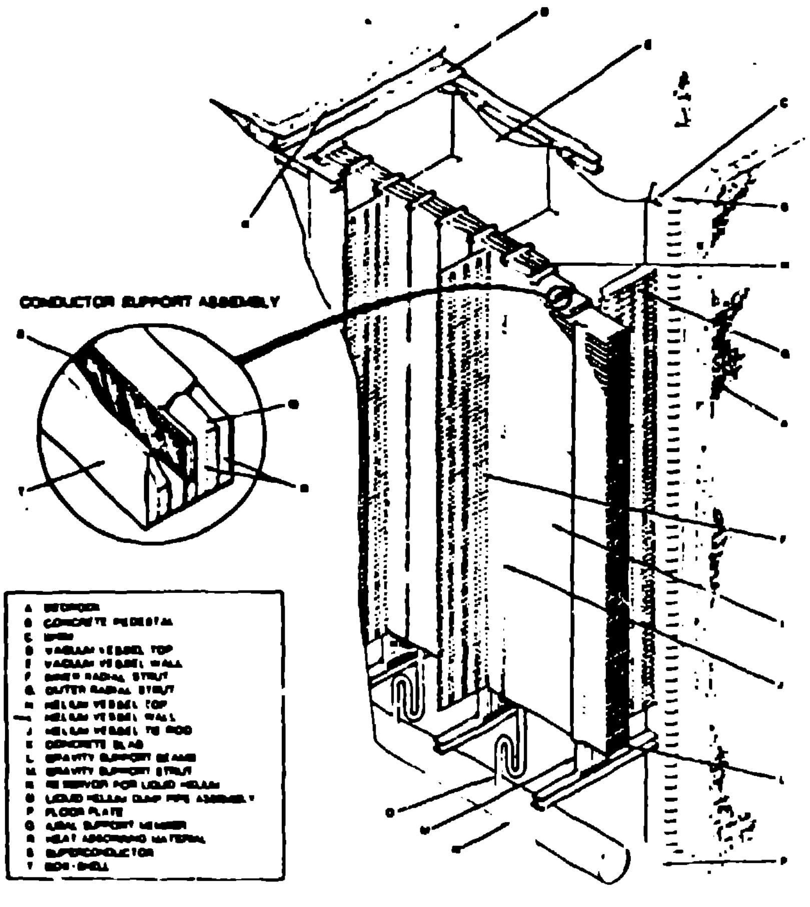

Figure 2 SUPERCONDUCTING MAGNETIC ENERGY STORAGE PLANT

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. 3.

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 4 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.

A schematic diagram of the conductor configuration is shown in Fig. 5. 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.

CONDUCTOR SUPPORT ASSEMBLY

The conductor support assembly, detailed in Fig. 6, 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-

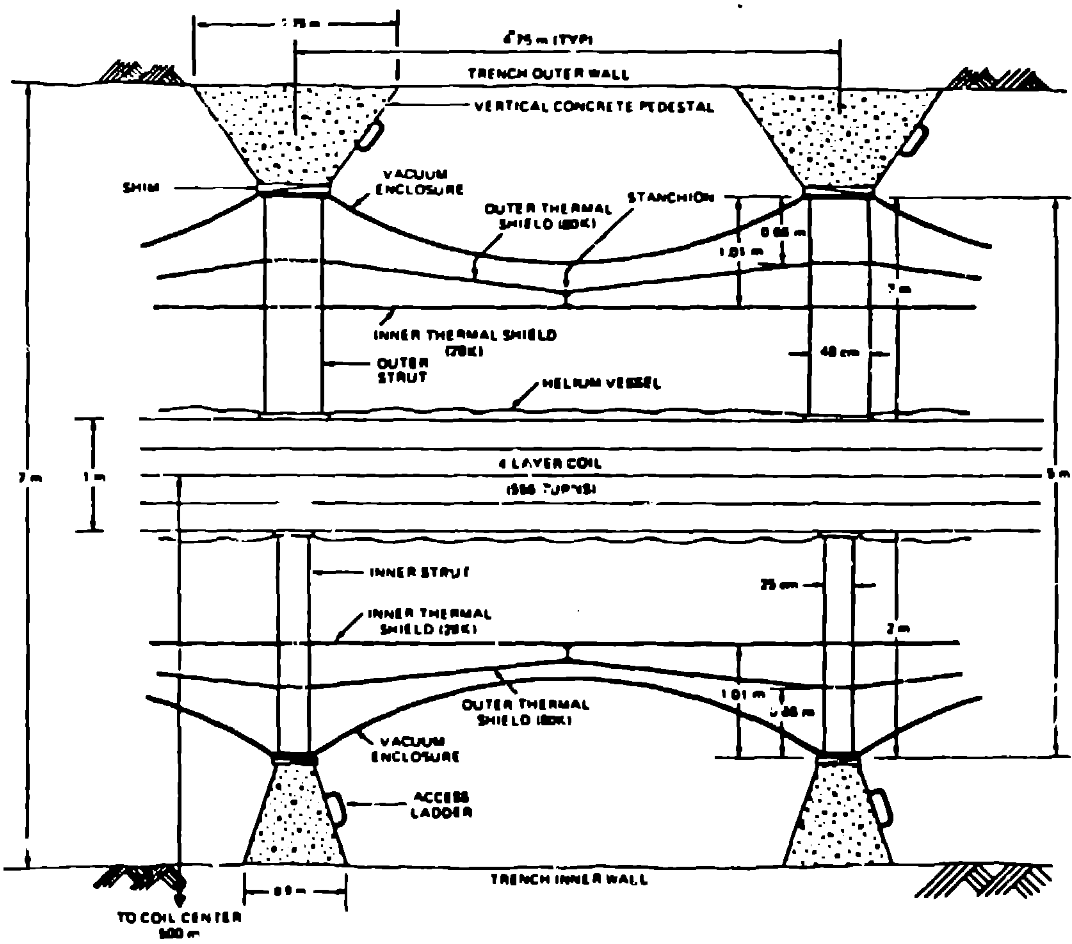

Figure 3 PLAN VIEW OF THE COIL

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.

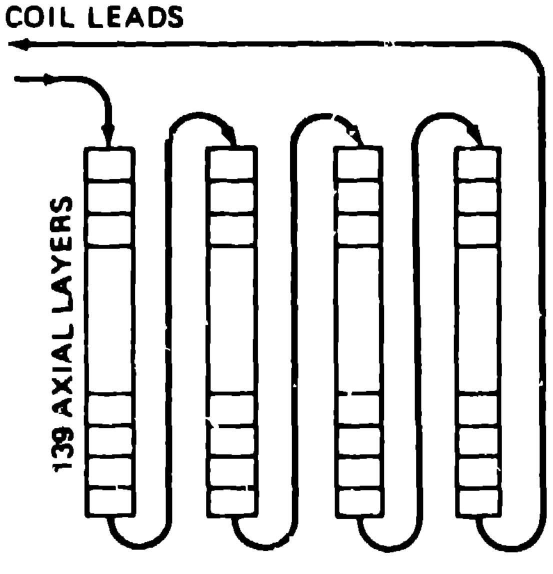

Figure 4. RADIAL LAYER CONNECTION PATTERN

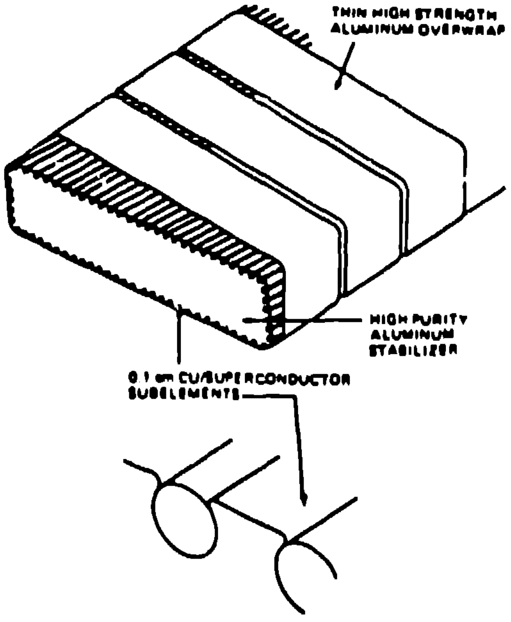

Figure 5. CONDUCTOR CONFIGURATION

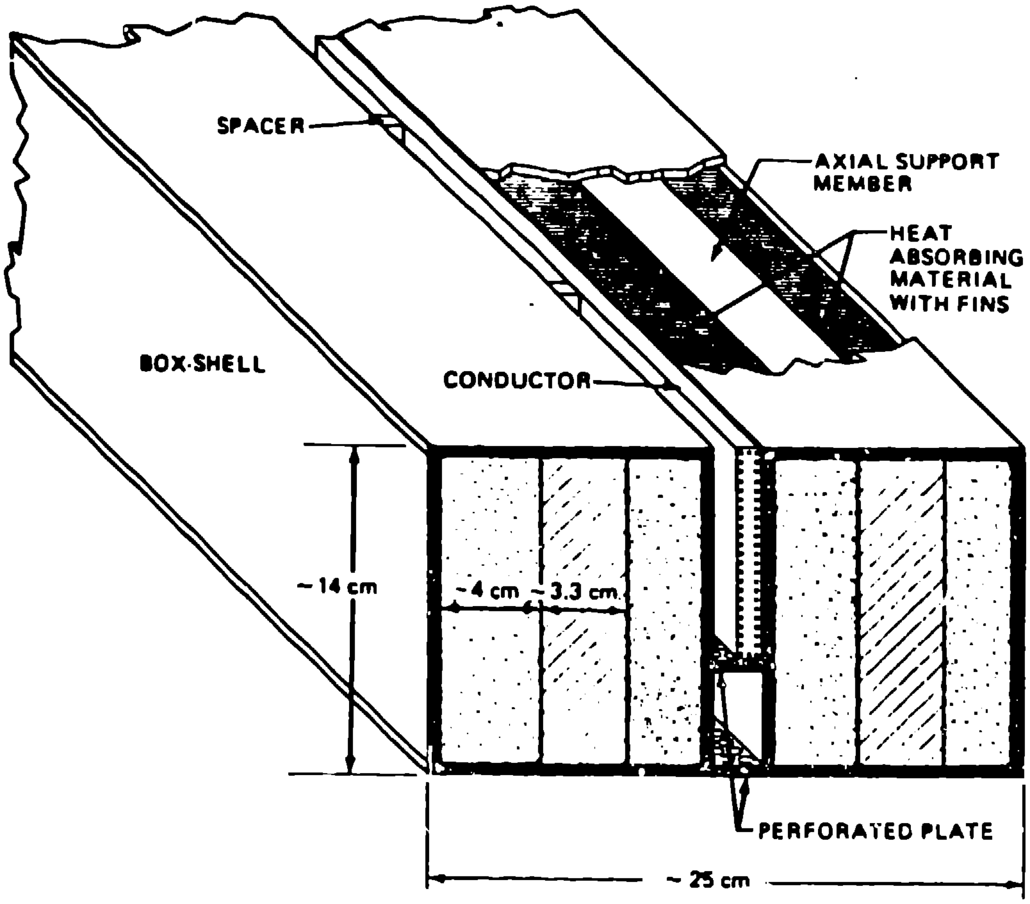

Figure 6. CONDUCTOR AND SUPPORT ASSEMBLY

Figure 7 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.

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

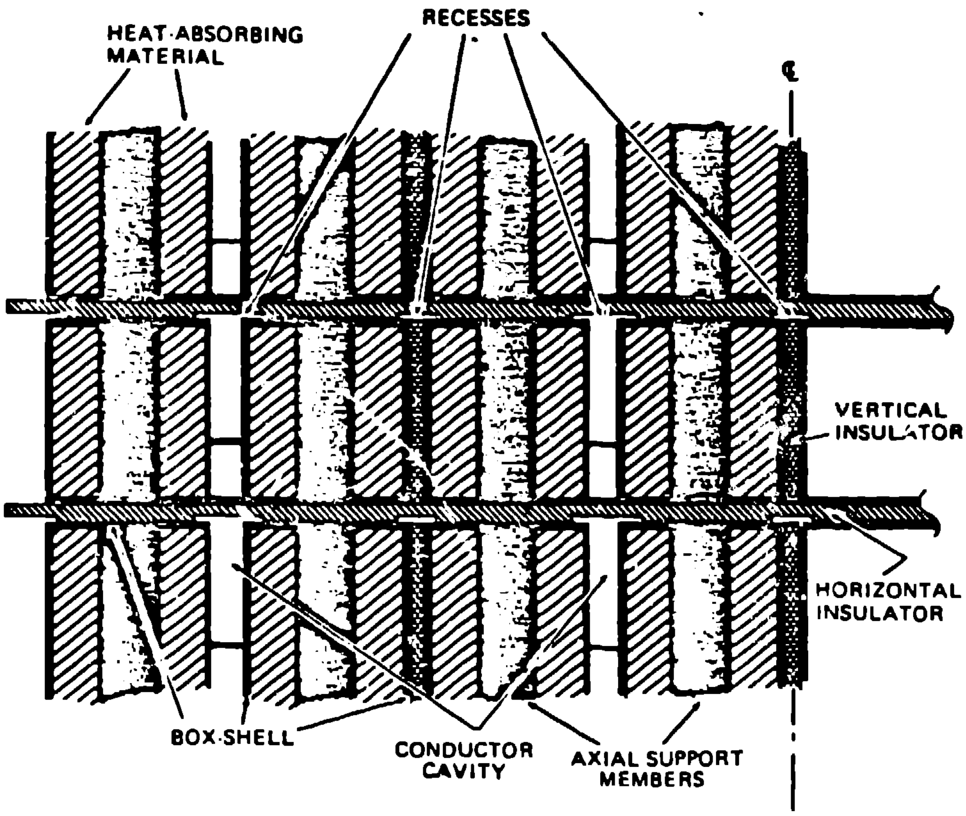

Figure 7 COIL CROSS SECTION SHOWING VERTICAL AND HORIZONTAL INSULATOR DETAIL

mechanical damage to the coil. The electrical resistivity of the high purity aluminum stabilizer in the conductor is substantially lower than that of the alloy aluminum coil winding structure at all temperatures up to melting. A direct result of these properties is that, once normal, the local conductor temperature will tend to be higher than the local structure temperature at all times during a protective energy dump. However, because the conductor is in good thermal contact with the structure, its temperature tracks only slightly ahead of the temperature of the conductor support assembly. Hot spots and excessive voltages do not occur.

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 2 and 3 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 pre-stressing 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 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.

A 1982 EPRI-funded study[4] 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. Furthermore, because of its high energy efficiency, the value of SMES relative to other energy storage technologies will increase with the cost of charging energy.

COMMERCIALIZATION POTENTIAL

The work to date has identified no unresolvable technical issues, but a significant amount of detailed engineering work remains prior to

Table 1 TOTAL CAPITAL REQUIREMENT (MILLIONS OF DOLLARS)

	1984 Dollars		
	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

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, 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.

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