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Superconducting Magnetic Energy Storage (SMES) Program

January 1—December 31, 1979

University of California

LOS ALAMOS SCIENTIFIC LABORATORY

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Superconducting Magnetic Energy Storage (SMES) Program

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Compiled by

John D. Rogers

SUPERCONDUCTING MAGNETIC ENERGY STORAGE (SMES) PROGRAM

January 1 - December 31, 1979

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ABSTRACT

Work is reported on the development of two superconducting magnetic energy storage units. One is a 30-MJ unit for use by the Bonneville Power Administration to stabilize power oscillations on their Pacific AC Intertie, and the second is a 1- to 10-GWh unit for use as a diurnal load-leveling device. Emphasis has been on the stabilizing system. A contract was placed for the fabrication design of the 30-MJ coil design. Orders have been placed for the stabilizing system converter and protective energy dump system, converter transformer, automation of the 4.5 K refrigerator and its installation into a trailer, and a trailer mounted heat-rejection system. A third compressor was added to the refrigeration system, and the refrigerator was tested and accepted. The superconductor for the 30-MJ coil has been received, tested, and found to be satisfactory. Development of the 5-kA superconducting cable is still under way. The reference design for the 1- to 10-GWh diurnal load-leveling unit was completed and has been issued as an eight volume report. The summary and recommendations of the study are included here. An alternative use of small superconducting coils for VAR control has been devised.

I. SUMMARY

The goal of the Los Alamos Scientific Laboratory's (LASL) Superconducting Magnetic Energy Storage program (SMES) is to develop electrical units to store energy in a magnetic field around a coil or inductor. The magnetic field is created by an electrical current flowing in a conductor that is in a superconducting state. Many materials, such as niobium-titanium, lose their resistance to electrical currents, that is, become superconducting, at low temperatures. Electrical utilities can use 1- to 10-GWh SMES units to meet diurnal variations in consumer power demand. During the night, when consumption is low, generators can supply energy to the unit. During the day, when demand is high, energy can be drawn from the SMES unit. In another application, smaller 30-MJ (8.3-kWh) SMES units can be used to damp out the short-term power oscillations in complex electrical grids that sometimes limit maximum power transmission.

This report describes the progress made in the design of the 30-MJ stabilizing SMES unit and testing of superconductor for the unit. A decision was made to make a point reference design of a 1-GWh diurnal load-leveling SMES unit as a system for which a larger market will exist for utility application. Extrapolation to a 10-GWh unit is straightforward. The components that must be considered for both systems are the superconductor itself; the coil; the dewar, which will contain the coil and liquid helium to cool it to a superconducting state; the cryogenic equipment to make liquid helium and keep it cold; the electrical equipment to connect the coil to the power grid; and finally, the monitor and control equipment to regulate the safe operation of charge and discharge of the coil.

The following have been accomplished this year. A contract was placed with General Atomic Co. for the fabrication design of the 30-MJ superconducting coil, and the design is essentially complete. The 4.5 K helium refrigerator was tested and accepted. A site at the Fite Substation, Tacoma, WA was chosen by the Bonneville Power Administration (BPA) for locating the stabilizing unit. This site is unmanned and the SMES unit is to be fully automated for remote operation. Contracts were placed for automating the refrigerator and installing it into a trailer. The converter and the protective energy dump circuit were ordered from Robicon Corporation. The converter transformer was ordered and an RFQ has been issued for the auxilary power transformers. A closed loop heat-rejection unit to be trailer mounted was designed and ordered. Work has been initiated for the computer controlled remote operation of the 30-MJ Superconducting Magnetic Energy Storage stabilizing system. The coil design was changed from multi layer helical wound to a spiral wound pancake design. The 5-kA conductor had to be changed accordingly and is still undergoing development. The only remaining feature to be solved for the conductor is adequate integrity of the insulation which must at the same time provide adequate helium ventilation to assure stability of the conductor.

A point reference design was completed for a 1-GWh Superconducting Magnetic Energy Storage system. The system is for electric utility diurnal load leveling; however, such a device will function to meet much faster power demands including dynamic stabilization. The study explored several concepts of design not previously considered in the same detail. Because the study is for a point design, optimization in all respects was not complete. The study examines aspects of the coil design; superconductor supported off of the dewar shell; the dewar shell, its configuration and stresses; the underground excavation and related construction for holding the superconducting coil and its dewar; the helium refrigeration system; the electrical converter system; the vacuum system; the guard coil; and the costs.

An alternative application of small superconducting energy storage controls for VAR control has been devised as an outgrowth of the SMES program. The Superconduction Application for VAR (SAVAR) control uses an asymmetric bridge circuit. A program proposal has been submitted to the Department of Energy Division of Electrical Energy Systems for development of the SAVAR system.

II. BONNEVILLE POWER ADMINISTRATION STABILIZING SMES UNIT

A. Introduction

The Pacific Northwest and southern California are part of the Western US Power System and are connected by two 500-kV, ac-power transmission lines, collectively referred to as the Pacific AC Intertie, and one ±400-kV dc-transmission line, the Pacific HVDC Intertie. The two ac lines have a thermal rating of 3500 MW, and the dc line has a rating of 1440 MW.

The stability of the Western Power System is affected by relative weakness of the tie provided by the 905-mile-long Pacific AC Intertie. In fact, studies made before energization of the Pacific AC Intertie showed that negatively damped oscillations with a frequency of about 20 cpm were likely to occur. In 1974 negatively damped oscillations with a frequency of 21 cpm (0.35 Hz) were observed. The peak-to-peak oscillation on the Pacific AC Intertie was about 300 MW. Subsequent to these instabilities, the BPA installed equipment on the HVDC intertie to modulate the power flow as a means of damping the oscillations. The maximum possible power modulation is ±40 MW. The modulation has increased the stability limit of the Pacific AC Intertie from about 2100 MW to 2500 MW whenever the HVDC Intertie is operating. However, the HVDC Intertie does not operate continuously. The line availability is 89.5%, and the southern terminal was down for six months as a result of earthquake damage. A back up stabilizing system could be used. Late in 1975, representatives of BPA and the LASL developed the concept of installing a small SMES unit for the purpose of providing system damping simiar to that now available through modulation of the Pacific HVDC Intertie. The design parameters of the unit to be installed at the Fite Substation near Tacoma are given below.

B. Superconducting Coil Design (Henke, Rogers, Thullen, Schermer; General Atomic Co. staff)

General Atomic (GA) has essentially completed Phase I of the 30-MJ coil design. Results include detailed engineering drawings, bill of materials, quality assurance plan, and collected calculations. The design was reviewed by five external consultants on December 13-14, 1979. Coil parameters are given in Table I, and an isometric drawing is shown in Fig. 1. Phase II for the fabrication of the coil should commence early in 1980, beginning with four months of materials procurement. A design effort has been started on the mechanical and electrical mounting of the coil.

A change in coil design occurred in midyear when GA presented a comparative study showing that a pancake-wound coil would be more economical to fabricate than the previously proposed layer-wound alternative. Analytical studies were then performed to investigate the detailed response of all structural elements to the various static and dynamic loads from gravity, thermal contraction, magnetic force components, and seismic loadings. Mechanical properties of the cabled conductor were obtained from experimental measurements. All other materials specified are those for which reliable cryogenic data exist. In general, stresses are considerably less than either one-half the yield strength or 40% of the ultimate strength and these satisfy general principles of conservative design.

TABLE I

PARAMETERS OF THE 30-MJ SYSTEM STABILIZING COIL

Energy stored at full charge, MJ	30
Energy stored at end of discharge, MJ	20.9
Current at full charge, kA	4.9
Maximum field at full charge, T	2.8
Inductance, h	2.6
Operating temperature, K	4.5
Mean radius, m	1.53
Height, m	1.21
Radial thickness, m	0.33
Number of turns	920
Winding pattern	double pancake
Number of pancakes	40
Number of turns per pancake	23
Conductor length, m	8844
Conductor mass, kg	6850
Strap mass, kg	4760

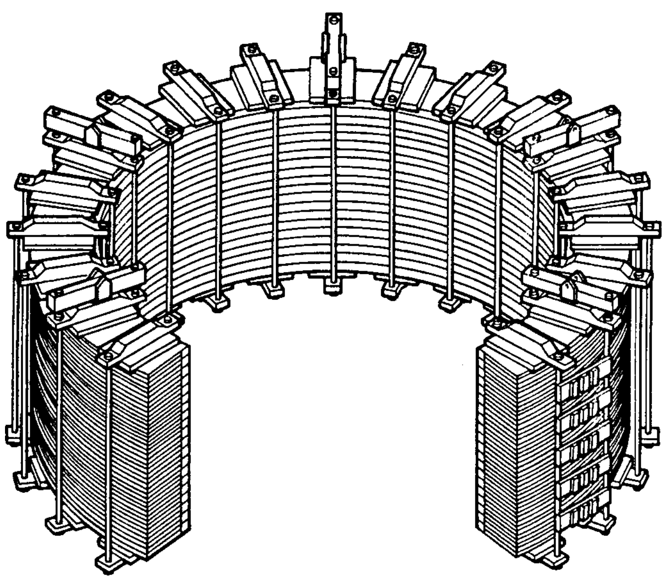


Fig. 1. 30-MJ SMES stabilizing coil.

The coil is in the form of a vertical stack of 20 double pancakes. The double pancake winding allows all joints to be at the outer radius, where they can be fabricated most conveniently. Between each of the 40 single pancakes is a 1/4 in. thick axial spacer plate of G-10CR, drilled with a triangular pattern of 1/2 in. holes on 0.9 in. centers and separated azimuthally into segments to allow for thermal contraction. A cyclic fatigue test will be run to verify that these plates will withstand the operating loads.

Axial preload is provided by 2024 aluminum tie bolts, located every 15^{o} around the inner and outer circumference of the winding. Aluminum was chosen so that the prestress would be maintained after cooldown. Preload level is sufficient to prevent the pancakes from slipping with respect to one another under a lateral acceleration of 1 g. The aluminum tie rods pass thru the ends of curved G-10CR clamping beams at the top and bottom coil faces. These beams transmit the preload to the coil.

Each double pancake is wound on an inner ring of glass reinforced epoxy. The radial build of a typical unit cell is shown in Fig. 2. The net outward force due to the axial component of the magnetic field is balanced by hoop tension in the stainless steel strap which is co-wound with the 5-kA conductor. In addition, the axial spacer plates bear on the steel strap rather than on the conductor, so that the axial load is accumulated in the steel. The chip-on-a-strip of LE grade cloth phenolic ribbon serves as turn-to-turn electrical insulation and also provides coolant passages on each side of the conductor.

The steel is wound under a tensile preload of 1 000 lbs to insure that the entire structure will remain in radial compression after the coil is cooled to 4.5 K and the magnetic field is fully energized. Stress calculations depend to some extent upon the measured value of a transverse compressive modulus for the conductor, which in turn depends strongly upon the mechanical history of the conductor. Therefore, a range of cases was calculated, all of which showed that the coil would remain in radial compression.

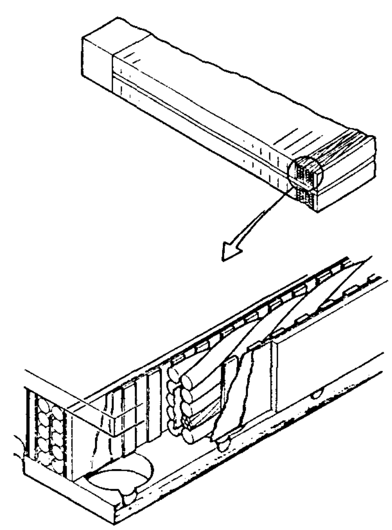


Fig. 2. 30-MJ SMES coil pancake section.

Short lengths of second subcable are to be soldered to make the joints and terminations. The cable transposition is disrupted in these regions. Both conditions increase the ac losses in the conductor. The proposed conductor, however, exhibits considerably lower losses than previously calculated because the first subcables are not soldered. Total calculated electrical losses are still within the 60 W originally allowed.

C. Stress Analysis of Pancake Coils (Thullen)

A number of simplified analyses of stresses in pancake windings and related structural elements have been performed to gain a greater understanding of this behavior of winding form and to serve as a check on analyses performed for the coil design. Three areas have received detailed attention. These are shear stress between the turns, winding pretension and the resulting pressure on the center bobbin surface, and buckling of the coil bobbin.

Many well founded analyses of stresses in solenoid magnets have been presented in the literature. The more sophisticated address the effects of anisotropy, winding tension, and differential thermal contraction. In all cases the coil is considered to be composed of concentric hoops. This, of course, is never the case since all windings are formed from a length of conductor with free ends. This is particularly evident in pancake coils which are wound in a fashion resembling a watch spring and can expand and contract much like a watch spring when placed under load. Gradients of tension exist in the turns of a pancake coil with high tension at or near the bore, low tension or compression at or near the outer surface of the coil, and no tension at some terminations. These gradients in tension require the presence of shearing forces on the conductor surface, which can be provided by either elastic deformation of a matrix or surface friction. The analysis undertakes a derivation of the normal, hoop, and shear stress in a pancake coil wound of membrane like turns incapable of resisting bending. It shows that the shear equation becomes decoupled from the normal and hoop stress equations for coils with a small pitch helical winding. This allows computation of normal and hoop stresses by conventional means and deduction of the shear stress from these results. Shear stresses, while small when averaged over the area of a turn in a potted coil, can become large when concentrated on a few spacers in a pool boiling cooled superconducting coil. Motion of the turns with consequent heat generation can result if insufficient shear strength is provided by the structure. This can cause quenching of a superconducting coil and insulation failure in a conventional coil. This analysis is the first that includes shear stresses and provides a simple method for calculating their magnitude based on existing algorithms and codes.

An integral expression for the pressure exerted on the surface of the coil central bobbin or former as a function of winding pretension for an isotropic winding was developed from the classical solutions to the Lame thick cylinder stress equations. This expression was compared with a numerical solution generated by the computer code STANSOL2 for a particular coil design and found to be in agreement. The formulation provides a simple expression for determination of the pressure at the inside of a coil winding which aids in design of the bobbin, winding spacers, insulation and other components.

An expression to determine the external load which will result in buckling of a winding bobbin was devised using the energy method. The bobbin is subjected to an external pressure load resulting from winding pretension and is at the same time supported by the elasticity of the surrounding winding. The behavior is similar to that of a beam on an elastic foundation. The winding pretension induced pressure at which the bobbin will buckle exceeds the buckling pressure of an externally pressurized cylinder.

These various analyses have demonstrated the accuracy of the solenoid stress analysis code STANSOL2 used in common by LASL and others and have allowed an independent verification of the stress calculations.

D. Superconducting Cable (Harkleroad, Henke, Prince, Rose, Smith, Schermer, Turner)

The goal of the conductor development activity for 1979 has been to obtain and test a manufacturing prototype of the final conductor for the 30-MJ coil. The change from layer winding to pancake winding produced a change in conductor geometry which has delayed attainment of this goal by several months. Conductor manufacture consists of a series of cabling, compacting, insulating and subsidiary operations. All but the final insulating operation have been fully defined, and the initial stages of material procurement and cable fabrication are proceeding without, as yet, impinging upon the coil delivery schedule. The present conductor design is shown in Fig. 3, and its specifications are given in Table II.

Conductor evaluation has consisted of a coordinated set of electrical and mechanical tests supported by theoretical work as necessary. Mechanical tests investigated the static and fatigue properties of the conductor under transverse compressive loading. Electrical tests investigated losses, current carrying capability of the superconductor, electrical resistivity of the copper, conductor stability, and current sharing among strands. The effect of cyclic loading and fabrication variables on these properties was determined. Some of the tests were performed on conductor at earlier development stages than that shown in Fig. 3. The present configuration should be superior in all aspects. All tests have revealed performance adequate to meet specifications.

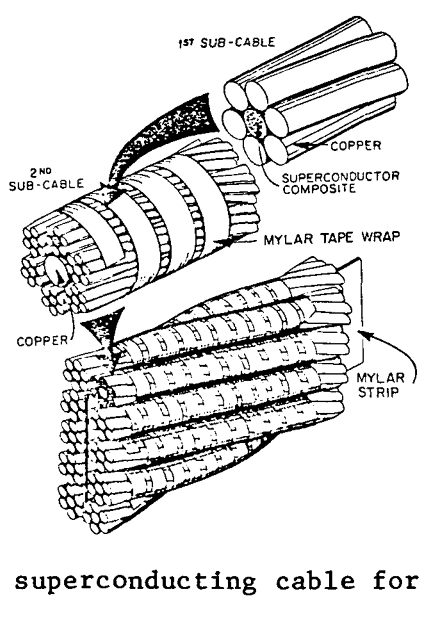


Fig. 3. 5-kA superconducting cable for 30-MJ coil.

TABLE II

CONDUCTOR SPECIFICATIONS FOR 30-MJ COIL

A. Superconducting Composite Core	
Area of NbTi, mm^2	4.85×10^{-2}
Filament diameter, μm	6.5
Number of filaments	1464
Strand diameter, mm	0.511
Cu to NbTi ratio	2.94:1
Twist pitch, mm	5.0
B. First Subcable	
(Six copper wires cabled about one core)	
Uncompacted diameter, mm	1.52
Compacted diameter, mm	1.37
Overall Cu to NbTi ratio	26.7:1
Twist pitch, mm	13.5
Direction of twist	L.H.
C. Second Subcable	
(Six first subcables around a copper core)	
Diameter, mm	4.25
Twist pitch, mm	42.5
Direction of twist	R.H.
Insulation, mm	Mylar*, adhesive 0.15 x 6.4
Insulation twist direction	L.H.
D. Finished Conductor	
(Ten second subcables around a Mylar strip)	
Strip dimension, mm	18-x-0.25
Conductor dimension, mm	23 x 9.2
Twist pitch, mm	140.0
Direction of twist	L.H.

*duPont trademark.

The overall goal of producing a prototype of first cable can be broken into goals for producing the various subcables as follows.

1. Superconductor. All of the original order for 0.51 mm NbTi, copper superconducting composite, a total of 1 870 000 ft, has been received, tested, and accepted as meeting specification. All of the strands will carry at least 110 A, at 3 T and 4.2 K for a detection sensitivity of 1×10^{-12} Ω-cm, or 120% of the operating requirement. Figure 4 is histogram of the results taken at 5×10^{-13} Ω-cm. Detailed consideration of conductor fabrication and coil winding requirements necessitates the purchase of an additional 200 000 ft of superconducting wire. The contract for the additional wire has been placed with Magnetic Corporation of America, supplier of the original wire. Delivery is expected in April 1980.

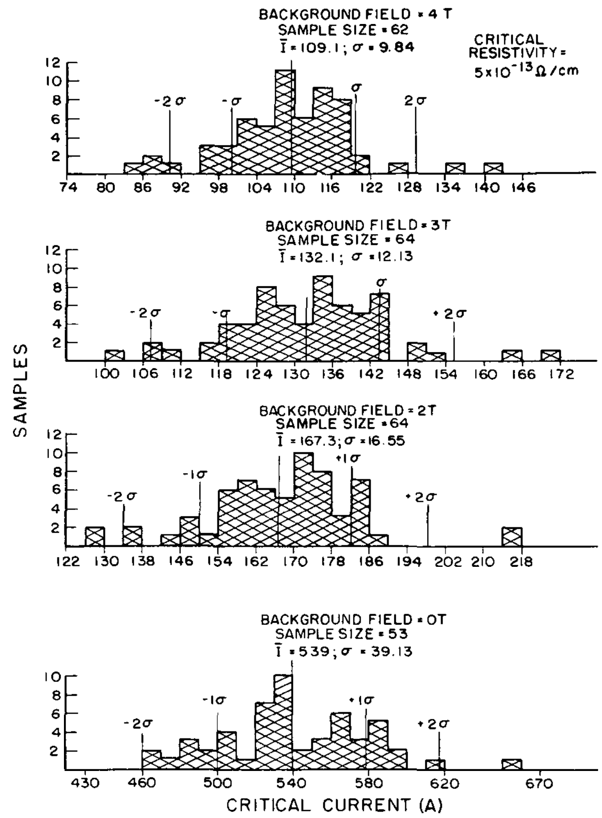


Fig. 4. Critical current of superconducting wire for 5-kA cable.

2. First Subcable Development. First subcable fabrication has been fully specified and tested. Solder filling of the first subcable was found to be neither necessary nor desirable. Unsoldered cable has identical electrical stability to soldered cable and has sufficient mechanical strength. The unsoldered cable exhibits one half the ac losses of soldered cable and costs roughly \$30 000 less to fabricate. The additional flexibility of unsoldered cable helps reduce insulation damage encountered in later fabrication steps. Insulation is neither necessary nor desirable for the first subcable. Eliminating the insulation eliminates problems caused by lack of current transfer among insulated first subcables. Further, the labor of insulation is reduced by a factor of four for a saving of roughly \$50 000. The first subcable is drawn to 1.37 mm during the cabling operation. This slight compaction should improve the fatigue resistance of the cable. The compacted cable was believed to be amenable to a wide set of insulation options; however, such is not the case and investigations for this purpose have been discontinued. The cabling operation and, of course, the compaction operation increase the electrical resistivity of the copper enough to require annealing after the first subcable is formed. An annealing schedule has been specified and the procedures of several fabricators have been qualified. A quality control procedure for this operation has been determined. The need for a

cleaning step prior to annealing remains an open question. All first subcable fabrication steps have been demonstrated commercially at speeds appropriate for full-scale manufcture.

3. Second Subcable Development. Second subcable fabrication has been fully specified and tested except for the question of insulation. Subcable geometry has been completely defined. The core is a 7-strand cable for additional flexibility. A suitable insulation has been chosen for the core, although the question of whether the core needs to be insulated is still unresolved. The second cabling operation does not significantly affect the electrical resistivity of the copper. The second subcable must be insulated so that neighboring second subcables in the final conductor do not contact electrically. Otherwise, large electrical losses will result. The insulation will have to be an overwrap but its exact nature is undetermined. Several types of Kapton* or Mylar* in the 0.001- to 0.002-in. thickness range have proved unsatisfactory. A prototype cable using 0.005-in. thick Mylar is currently in production. Prototype quantities of perforated tape to provide helium ventilation are being obtained.

4. Final Cable. As the final conductor is formed it is passed through a Turk's head roller to produce the flatted configuration. In this step unacceptable insulation damage has been encountered. The next prototype 5-kA cable to be produced in early 1980 uses much more flexible subcables to reduce the force needed to form the final flattened cable. The much heavier tape insulation and the smoother bearing surface of the compacted subcable should reduce or eliminate cut-through. The recovery current for fully taped conductor is roughly one half that of bare conductor when mounted in a representative 30-MJ heat transfer geometry. The recovery current of 80% taped conductor is virtually identical to that of bare conductor. Several options to obtain 80% coverage, including perforated tape, are being investigated. The recovery current of prototype second subcable, 80% tape covered, at 2.8 T is 600 A, compared to the operating requirement of 490 A.

E. Cyclic Testing of Prototype Cable (H. Boenig, M. D. Henke, D. O. Harkleroad, R. I. Schermer, W. D. Smith; A. P. Conley, E-5)

A microprocessor controlled instrumentation system was built to detect insulation breakdown in a multistrand cable. The tester displays the shorts among up to 70 individual strands and the number of cycles at which the shorts first occur. The tester was used during the cyclic tests at the National Bureau of Standards Boulder. Besides the insulation behavior of the prototype cable, the effect of cyclic strain on the residual resistance of copper in the first subcable was also measured. The results show that the cyclic strain levels of the 30-MJ coil do not deteriorate either Kapton wrapped insulation or the residual resistance.

*duPont trademark.

F. Superconducting to Normal Conducting Calculation (Hassenzahl)

The computer program QUENCH was developed about ten years ago by Martin Wilson of the Rutherford High Energy Laboratory in England and has been improved by several different users. The version from Saclay was further modified to include heat transfer to liquid and/or gaseous helium, variable time steps, and a propagation velocity that changes as the central region of the quench increases in temperature. This program is now operational on the LASL computer and is being used to study quenches in the BPA 30-MJ coil, the 20-MJ pulsed tokamak coil, and a 7-T solenoid. The results of the measurements on the BPA coil confirm preliminary calculations that quenches will propagate slowly but that the coil will not heat extensively if a 1-Ω protective resistor is placed across the coil within a few seconds. The maximum coil temperature for a 5-s delay is 60 K.

G. Nonconducting Dewars (Rogers, Schermer; Dunwoody, Bennett, Q-13)

The conceptual design of the containment vessels for the 30-MJ BPA coil was begun. Two designs were considered and conceptual drawings for both have been completed. One concept is to use axisymmetric half toroidal shells for the external and internal vessels with a flat lid closure. The second concept is to use a conventional cylindrical geometry pressure vessel with spherical end closures. For both concepts, numerous penetrations, support problems, and sealing problems are considered, along with details of assembly. Visits were made to the facilities of the three potential manufacturers of epoxy glass reinforced dewar shells. A decision was made to use the toroidal vessel concept based on the technical input from the manufacturers. Design of the structural support for the coil in the dewar and of the dewar itself is now begun. Static and dynamic loads that include seismic effects have been initiated.

H. Cryogenic System (Colyer, Harkleroad, Hassenzahl, Henke, Rogers, Schermer, Turner; Fretwell, P-10)

A complete cryogenic system is being manufactured and assembled to provide the liquid helium and gas storage for the 30-MJ coil. Plans and designs for separate trailers were made for testing the entire cryogenic system at LASL and then be transported to Tacoma, WA. The SMES system will be operated by automatic controls through a computer with control inputs from Portland, OR.

The cryogenic refrigerator was completed and tested successfully. The unit is now being installed in a special built trailer for this purpose. All the necessary automatic control elements are being added at the time of the installation. An evaporative cooler is also now being mounted on a trailer with its pumps and controls to serve as the heat-rejection system for both the cryogenic refrigerator and high pressure helium compressors. The design for installing the high pressure helium gas recovery compressors on still another trailer is underway.

An existing liquid nitrogen trailer was obtained to provide the coolant for the refrigerator and the liquid helium transfer lines connecting the refrigerator and coil dewar. Conventional gas tube trailers are to be used for high pressure gas storage.

All the trailers will be assembled and interconnected at LASL. This complete cryogenics system will be used to provide liquid helium to an existing 900 ℓ test dewar in place of the coil dewar.

The complete system will be tested and developed using both manual and automatic controls with a remote computer.

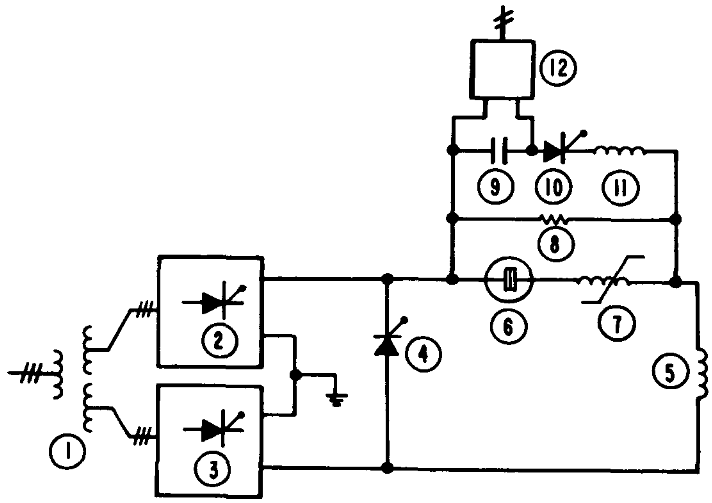
I. Electrical System

1. Converter and Energy Dump System (Boenig, Turner). Robicon of Pittsburgh, PA was selected as the manufacturer for the 2.5-kV, 5-kA converter. The converter consists of a series connection of two six pulse Graetz bridges, each driven by a 928-V three-phase system. Each leg of a bridge consists of eight 3.2-kV, 800-A Westinghouse Electric Corp. thyristors. Each bridge can be bypassed by a thyristor switch. See component 4 of Fig. 5. To release the coil energy quickly into a resistor in case of a coil malfunction a 5-kA, 5-kV dump circuit was designed. The dump circuit is being installed into the converter cabinets. The interlock, protection, and control logic was developed to allow remote operation of the electrical system. All mechanical and electrical drawings for the converter have been completed by Robicon Corp. and approved by LASL. The major components for the converter and energy dump circuit, such as cabinets, bus, fans, thyristors, ac vacuum breakers, capacitors, and saturable reactors have been received and are being installed in the cabinets. The assembly of the subsystems is proceeding. The converter will be performance tested at the manufacturer's plant in April 1980 and shipped to LASL. The converter will be connected to an existing six-phase, 3-MW transformer for testing at LASL. System tests will be performed with the converter, the refrigerator, and a dummy load with all components being remotely controlled by a PDP-11/34 digital computer.

2. Transformers (Boenig, Turner). The Niagara Transformer Co. of Buffalo, NY was the successful bidder for the converter transformer. Two three-phase, 6-MVA, oil insulated, aircooled step down transformers provide a voltage ratio of 13.8 kV to 928 V. Both transformers have delta connected secondaries; however, one primary winding is delta connected while the second is wye connected. By connecting one of the convention bridges to the delta-delta transformer and the other bridge to the wye-delta trnansformer, a 30^{o} phase shift is obtained for the twelve-pulse converter operation. See Fig. 5. Both transformers are scheduled to be delivered to the Tacoma, WA site in the third quarter of FY1980.

Technical specifications for the auxilary service transformers have been written and requests for quotations are being solicited from transformer manufacturers. These transformers are for 500 kVA, 13.8 kV/480 V and 75 kV, 480 V/220 V/120 V units.

3. System Control (Boenig, Hassenzahl, Kuckertz). The 30-MJ coil will be installed at the Tacoma substation of the BPA and will be controlled remotely by a microwave link from the BPA central dispatcher at Portland, OR. LASL is developing a complete computer control system that will have the capability of initiating cooldown of a warm system, monitoring all relevant parameters while the coil is brought to operating temperature, and adjusting the power flow to the coil based on control signals from the dispatcher.



1. CONVERTER TRANSFORMER
2. 6-PULSE BRIDGE (± 1.25 kV, 5 kA)
3. 6-PULSE BRIDGE (± 1.25 kV, 5 kA)
4. BYPASS SCR
5. SUPERCONDUCTING COIL (2.5 H)
6. VACUUM BREAKER (THREE-PHASE, 4.16 kV, 2kA)
7. SATURABLE REACTOR (0.1 Vs)
8. DUMP RESISTOR (1 Ω)
9. COMMUTATION CAPACITOR (60 μF)
10. COMMUTATION SCR
11. LINEAR REACTOR (15 μH)
12. POWER SUPPLY (5 kV, 30 J/s)

Fig. 5. Electrical schematic of 30-MJ SMES stabilizing system.

The computer control system has been under development since July and will use a PDP-11/34 computer, which will be compatible with the BPA computer communications network. The PDP-11/34 computer is available, and an evaluation of need to purchase additional core memory and a large tape unit for archival data storage is underway.

The operation of the refrigerator, cryostat, and gas handling system will be the most complicated part of the computer control system. This part has already been studied extensively and 14 sheets of logic drawings have been developed as a guide for the detailed programming of the computer. Similar logic drawings will soon be completed for the converter and the coil and dewar.

The refrigerator and the converter will be tested with the computer before the end of FY80.

J. <u>BPA Site Installation</u> (Boenig, Hassenzahl, Henke, Rogers, Schermer, Turner)

BPA has chosen the Fite Substation at Tacoma, WA for the installation of the SMES stabilizing unit. Visits were made to the Tacoma site and to the Portland headquarters. The manned substation requires operation of the SMES system from Portland, OR on a computer based microwave link. The work to be performed for the installation by LASL and BPA has been set forth in a letter agreement. All parties to the agreement have agreed upon its content, and it is being circulated for signatures.

A preliminary drawing of the SMES system layout at the Tacoma site has been forwarded to BPA. The equipment is located around the coil with an exclusion radius which corresponds to the 10 G magnetic field level to reduce forces between the coil and the steel components. A drawing of the converter and its 6 MVA transformer has also been sent to BPA for use in designing the concrete pad for mounting the converter and transformers.

K. Schedule

Four schedules are given in Figs. 6, 7, 8, and 9. The first shows the program history for the 30-MJ SMES stabilizing system. Figure 7 gives the 5-kA superconducting cable development schedule. Figure 8 gives the schedule for the cryogenic system progress, and Fig. 9 does the same for the electrical system.

III. 1- TO 10-GWh SMES DIURNAL STORAGE UNIT

A. Introduction

A study was undertaken to evaluate the magnitude in size, technical difficulty and detail, and cost of a 1-GWh SMES system for diurnal load-leveling for electric utility application. A 1-GWh size was chosen as being sufficiently large to make extrapolation to a larger size reliable and, unto itself, to be a size for which there could be considerable demand. Extrapolation of cost per unit of energy stored is, to the first order, inversely proportional to the maximum energy stored to the one-third power. The approach, used in the design, is to explore some variations to already conceived details of a SMES unit. In particular, these details are related to the dewar structure and the support and design of the conductor. Before any commitment is made to these or other concepts, a careful comparison is needed. To aid the study and establish credibility in areas in which unusual expertise is required, industrial consultants were used to assess the nature of the converters, the underground excavation for locating the superconducting storage coil, and high-purity aluminum to establish both methodology and costs.

A SMES unit is built around two major components. These are the storage unit that is a superconducting coil and an electrical converter to operate and transform the current between the ac transmission line and the dc coil. All other items in the system are ancillary to these two.

Several aspects of a large SMES unit determined by earlier work were retained as features of the reference design. These include the operation of the superconductor in a 1.8 K, 1-atm superfluid helium bath to reduce the cost of superconductor, the contoured, modular cold and warm wall helium dewar to accommodate thermal expansion and reduce material thickness, the location of the storage coil underground to reduce coil support construction costs, and a simple solenoid with a height to diameter ratio of about one-third. Some of these aspects should be evaluated further to assure that no viable alternatives exist.

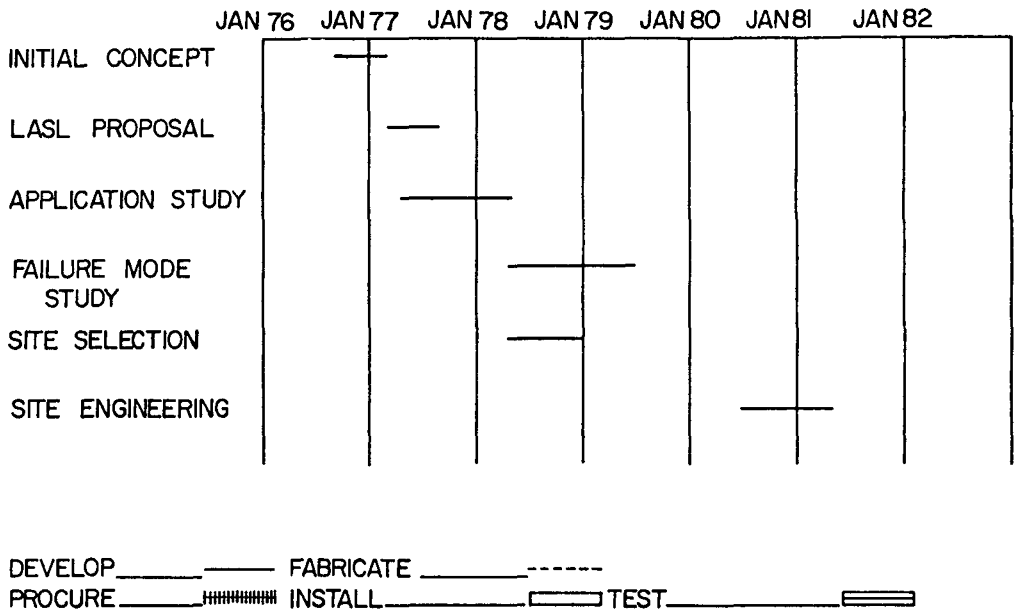


Fig. 6. 30-MJ SMES stabilizing system program history.

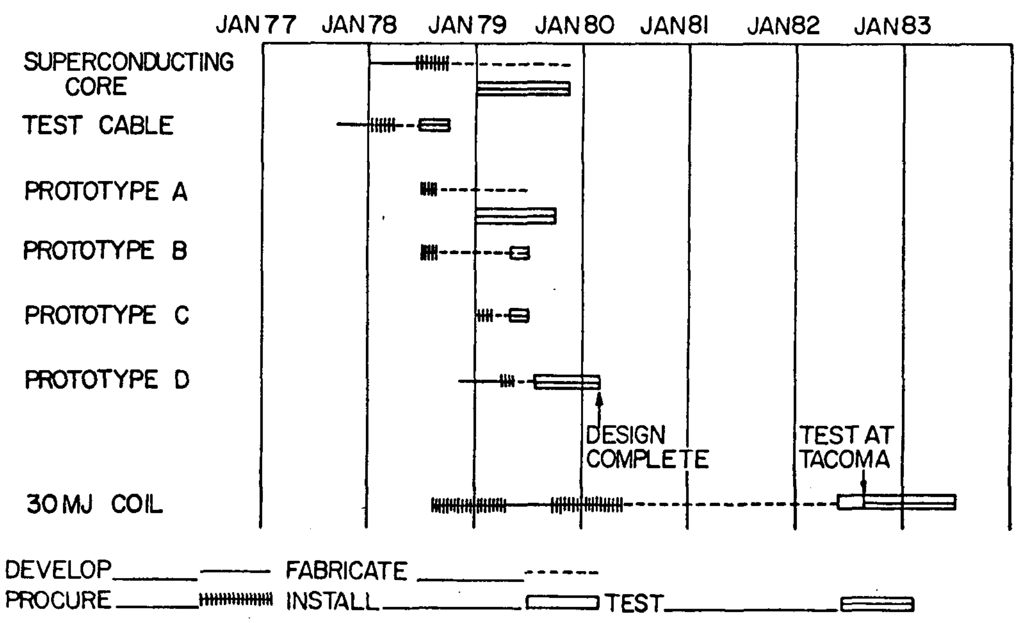


Fig. 7. 30-MJ coil superconductor development schedule.

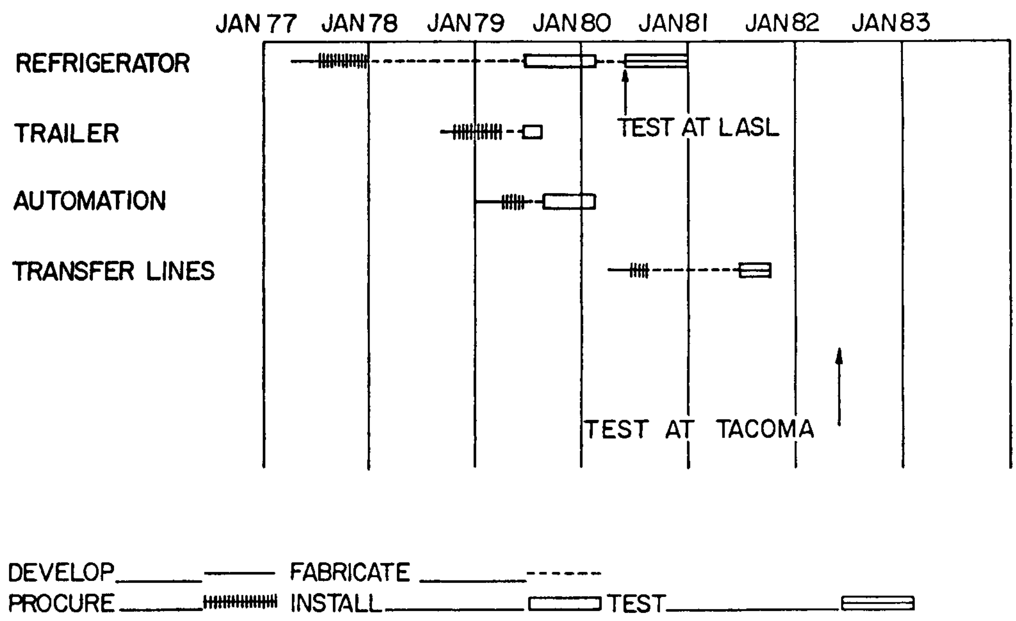


Fig. 8. Cryogenic system schedule.

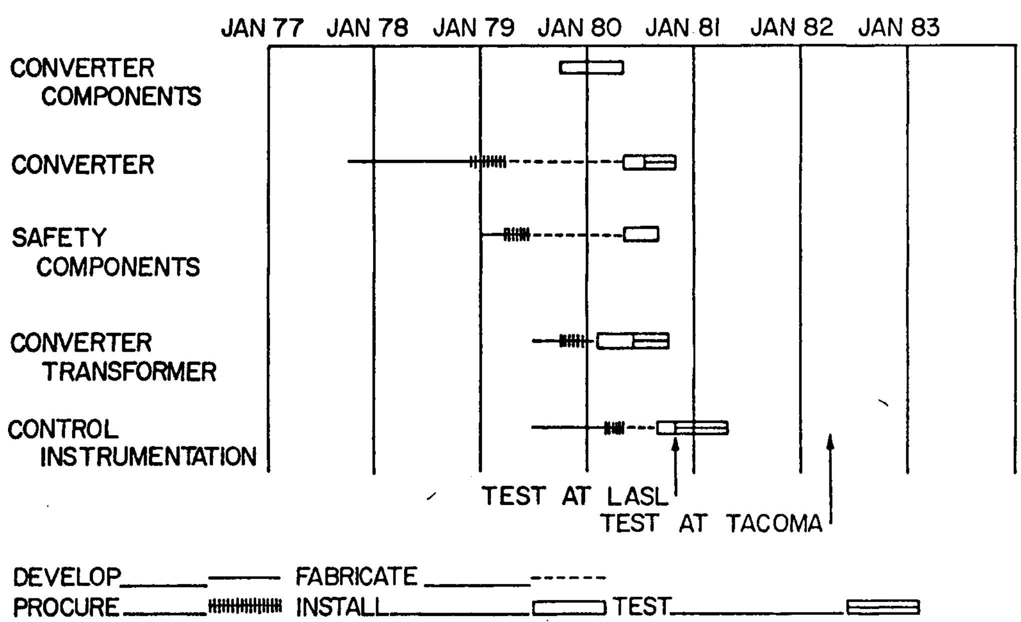


Fig. 9. Electrical system schedule.

Table III gives some of the parameters of the storage system. The technology base of the reference design and, hence, the parameters are considered to be within the state of the art. No discoveries or unusual inventions are needed to design and construct such a SMES system. At the same time, technology development is needed to establish construction methods that will be reliable. Also, improvements in the technology base could alter the economics of such a major capital project.

B. Costs

Table IV compiles the cost for a 1-GWh SMES system and adds profit, installation costs, and engineering design costs for those items and facilities in which they have not already been incorporated. Engineering is considered to include complete design and specification for manufacture, fabrication, field operations, installation, and construction; architectural services; and project management of the SMES system. In Table IV, if profit, installation and engineering design costs are not listed, they are already included in the base number. No land costs are included.

The principal costs for the system occur in five areas. These areas are the coil and conductor, the dewar and structural support, the cavern or excavation, the cryogenic system, and the electrical system. The costs represent current technology and are for a base reference design. Materials selection has been for those requiring the least development, such as a built-up welded stainless steel dewar. Costs are based upon information obtained on recent purchases, contracts, major installations, and studies

TABLE III

1-GWh SMES SYSTEM PARAMETERS

Energy exchanged	3.6×10^{12} J (1.0 GWh)
Maximum energy stored	3.96×10^{12} J (1.10 GWh)
Coil diameter	132 m
Coil height	44 m
Coil thickness	20 m
Tunnel width	3.0 m
Coil inductance	3170 H
Maximum current	50 kA
Minimum current	15 kA
Maximum field	4.5 T
Temperature	1.85 K
Minimum voltage	5.0 kV
Maximum voltage	16.7 kV
Maximum power	250 MW

TABLE IV
COST OF 1-GWh SMES UNIT

	$\$10^6$
Conductor and coil	72.90
Profit on aluminum matrix	0.57
Engineering at 15%	11.02
Winding machine	3.50
Dewar and structural support	90.56
Engineering at 15%	13.58
Cavern	33.80
Cryogenic system	
Transfer lines	5.04[a]
Valves	2.00[a]
Low pressure (12.5-torr) pumping system	3.58[a]
1.8 K heat exchanger	1.00
Cooling tower	0.03
Helium storage dewars	3.60
Liquid helium storage pumps	1.00
Refrigerator	9.25[a]
Installation[a]	5.96
Engineering[a]	2.98
Helium gas	1.68
Electrical system	15.40[b]
Vacuum system	0.83
Installation	0.83
Engineering at 15%	0.25
Guard coil	17.70
Engineering at 15%	2.66
Total	299.72
	\$300/kWh

[a]Installation and engineering are included for these items at 30 and 15%, respectively, of their cost. Similar costs for the other items of the cryogenic system are included in their base costs as given.

[b]This item is often assigned as a cost to power instead of energy.

conducted for this reference design. In some instances the sources of cost data are confidential and the amounts must be taken at face value. Engineering costs not originally included in the base numbers are added at 15%. Certain indications of possible reductions are developed and a lower cost list is presented in Table V.

The single largest cost for the conductor and coil at \$72.9 million is the 50-kA, graded superconducting cable at \$43.2 million. This amount is based on present day costs of NbTi superconductor for projects such as the energy doubler magnets for the Fermi National Accelerator Laboratory and the Brookhaven accelerators. The prospect of reducing this cost factor of 2 in a large scale operation is credible. The superconducting cable cost included in the \$51.3 million for conductor and coil in Table V is thus \$21.6 million. The major cost saving of using aluminum stabilizer is already incorporated in Table IV. No other significant cost reduction is anticipated in this item.

TABLE V

REVISED COST OF 1-GWh SMES UNIT

	10^6
Conductor and coil	51.30
Profit for aluminum matrix	0.57
Engineering at 15%	7.78
Winding machine	3.50
Dewar and structural support	42.49
Engineering at 15%	6.37
Cavern	30.00
Cryogenic system	
Transfer lines	5.04[a]
Valves	2.00[a]
Low pressure (12.5-torr) pumping system	3.58[a]
1.8 K heat exchanger	1.00
Cooling tower	0.03
Helium storage dewars	3.60
Liquid helium storage pumps	1.00
Refrigerator	9.25[a]
Installation[a]	5.96
Engineering[a]	2.98
Helium gas	1.68
Electrical system	15.40[b]
Vacuum system	0.83
Installation	0.83
Engineering at 15%	0.25
Guard coil	10.40
Engineering at 15%	1.56
Total	207.40
	$207/kWh

[a]Installation and engineering are included for these items at 30 and 15%, respectively, of their cost. Similar costs for the other items of the cryogenic system are included in their base costs as given.

[b]This item is often assigned as a cost to power instead of energy.

The dewar and structural support costs listed in Table IV are for a stainless steel dewar and G10CR epoxy fiber-glass structural supports. The fabricated shape materials cost of \$4 880/m^3 (\$0.80/lb) for aluminum is from an uninflated 1977 price list and of \$17 300/m^3 (\$1.00/lb) for A304-LN stainless steel is from a Lawrence Livermore Laboratory bid quotation for the Mirror Fusion Test Facility. The cost of G10CR currently ranges from \$6 to \$17/kg. This design study uses \$8/kg in Table IV.

The revised costs of Table V incorporate other changes. These are a change from a stainless steel dewar to aluminum, a support structure material cost of \$4/kg based on quantity production, and the use of a multiplier of 2 for the installed cost of polyester fiber glass composite and other materials. The change from stainless steel to an aluminum dewar requires a change from a

13-segment to a 25-segment dewar. This occurs because the thermal stress is exceeded for an aluminum dewar with fewer segments.

The cavern costs are fixed mostly by the materials and mining equipment. If the rate of excavation is doubled without additional labor and equipment, then a saving of about $3.8 million can be made.

The cryogenic system cost indicates an area for which engineering optimization would be most productive. Transfer line costs are based on estimates made available by Cryenco. The refrigerator cost, the installation cost, and the engineering cost are based upon a reasonable extrapolation of large liquid helium plants presently being installed in the United States. Optimization would possibly reduce the cryogenic system cost by 15 to 30%; however, there would be a compensating increase in the structural support cost for a lower overall net saving. Refrigerator costs corresponding to a reduced structural support thermal conductivity by a factor of 2 would create a total saving in refrigerator cost of $2.96 million. Such an optimization is not included in Table V.

The guard coil cost has been reduced by changes in both the superconductor and dewar costs corresponding to those made above for the main energy storage coil.

Thus, based upon the point reference design and on the material and fabrication costs presented in this report, the capital cost of storing energy in a 1-GWh SMES system ranges from $207 to $300/kWh. These values extrapolate inversely as the maximum energy to the one-third power. For a 10-GWh SMES unit the corresponding costs become $96 and $139/kWh. Clearly, the economy of size is important.

A realistic percentage reduction by optimization has been judged to be near 20%, although even this appears high for optimization of the entire system. On this basis the unit installed costs for a 10-GWh system would then range from $77 to $111/kWh. These costs must be recognized as being higher by factors of 2 to 3 than previously developed numbers.

C. General Program Development and Recommendations

Some aspects were inadequately treated in the reference design and in previous designs. These include maintenance, reliability, fault-mode analysis, site selection and evaluation, and efficiency. These may or may not influence the costs substantially. For example, design of the vacuum vessels for maintenance could be kept simple if space suit technology can be adapted to function in the cold vacuum space. Thus, a recommendation for the next phase of work is to identify the areas not adequately considered and to fold them into an engineered design, which leads to three related recommendations. The first is to reach a basic conclusion whether large SMES is economically competitive as determined from the analysis and evaluation of the divergent costs estimated by this and other studies. The second, if the conclusion of the first is positive, is to conduct a contracted industrial engineering design study and technology assessment for a prototype SMES unit. The third is to establish a development program to remedy identified technology deficiencies.

The recommended industrial engineering design study should be less effort than that for a Title I architectural design but sufficiently advanced to make an accurate cost estimate, identify all major engineering problems, assist in identification of all technology deficiencies, and guide the subsequent Title I work. Except to improve upon some peripheral details in very limited areas, the present SMES teams are not equipped to proceed with the prototype system without the expertise that is available from an industrial construction design firm.

D. Conclusions

A SMES system has the potential of providing a very advanced and efficient energy storage system for electric utility diurnal load leveling. The cost of constructing such a system may be high. Nevertheless a more thorough engineering design is warranted. SMES efficiency has been reevaluated in a utility operation simulation in a recent study by Arthur D. Little, Inc. Comparison with battery storage, underground pumped hydrostorage, compressed air energy storage, and conventional generation capacity shows that SMES is economically competitive and is the most attractive of the large systems when the rated energy delivered per year per unit power capacity is above about 1750 kWh/yr per kW. This result is predicated on system costs a factor of about 2 to 3 lower than those developed in the reference design and on efficiencies of at least 90%.

IV. SUPERCONDUCTOR APPLICATION VAR (SAVAR) CONTROL (Boenig, Hassenzahl)

Thyristor phase controlled reactors with a parallel connected capacitor bank are now used in static VAR systems to compensate for lagging load currents and to eliminate unbalanced loading of the three phase power system. In principle, a static shunt compensator consists of three air core reactors arranged in a delta configuration and connected to a pair of antiparallel thyristors, as shown in Fig. 10. A three phase capacitor bank provides a constant leading power factor. Reactor currents can be varied continuously from zero to the maximum value by proper phase control of the thyristor switches, thereby controlling the lagging power factor. Compensators with a power rating of 20 to 100 MVAR connected to a 13.8- or 34.5-kV bus typically have 1.2% losses. These losses can be broken down into 0.15% capacitor losses, 0.6% reactor losses, and 0.45% SCR losses. The absolute losses for a 40-MVAR system are given in Table VI.

Low frequency dc superconducting coils have low losses and can be used in the circuit shown in Fig. 11 as a replacement for a conventional inductor. A direct replacement of the room temperature coils in Fig. 10 by conventional superconducting coils would not result in a system with lower losses. The current in the coil is essentially constant but some 360 Hz harmonic exists in the coil and in the line currents. The superconducting coil must have acceptably low losses as this frequency.

A SAVAR coil using iron and a small superconducting coil is shown in Fig. 12. The superconducting coil has very low losses and a system consisting of the coil, refrigerator, and converter should be compact and economically competitive with conventional static VAR compensators. Table VII compares the costs of these different types of compensators.

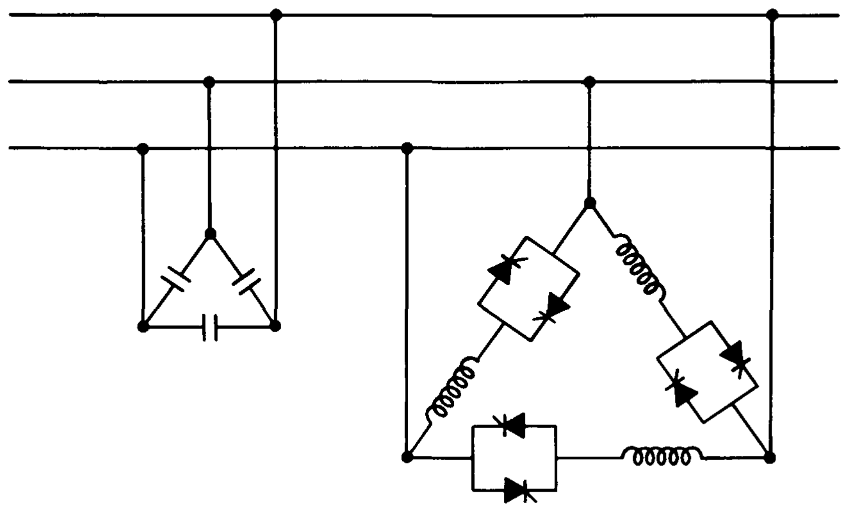


Fig. 10. Static shunt compensator circuit.

TABLE VI

LOSSES OF A 40-MVAR CONVENTIONAL STATIC VAR CONTROL SYSTEM

Losses	kW
Capacitor	60
Reactor	240
SCR	180
Total	480

During the last year the following accomplishments have been achieved. The electrical circuitry and control logic for single phase and three phase SAVAR systems, both with six and twelve pulse converters, have been developed. A superconducting coil with an iron core was found to be the best choice for a low loss coil in the first cycle of coil optimization. An initial cost and performance comparison of a 40-MVAR compensation system between an existing unit, consisting of six room temperature coils and three anti parallel, solid state switches, and a SAVAR unit with a six pulse converter and one superconducting coil was made. The comparison reveals that the costs for the power conversion equipment and the electrical performance are similar for both systems. However, the total losses of a SAVAR unit are about 50% lower than those of a conventional unit.

A four year development program beginning with a model system, a thorough analysis of the SAVAR components and other circuit options, and a study of the effectiveness of static VAR systems for electric utilities has been proposed. If the first year of analysis of this technology shows it to be technically and

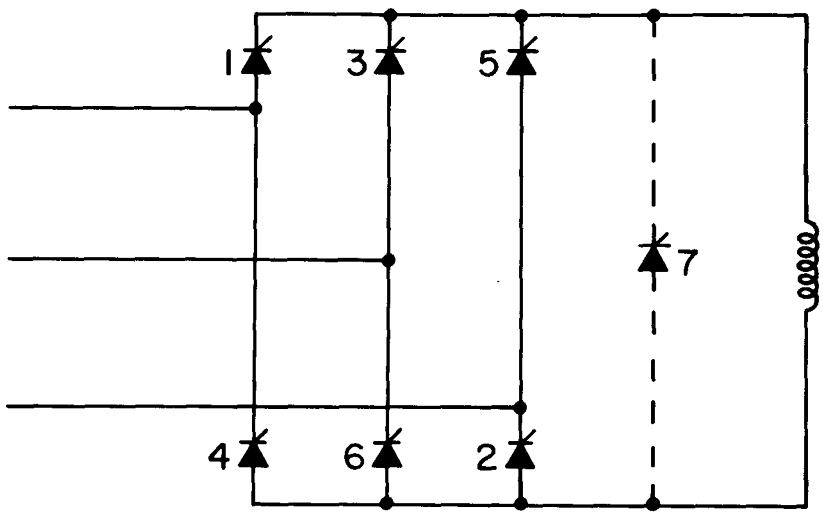


Fig. 11. Six pulse Graetz bridge.

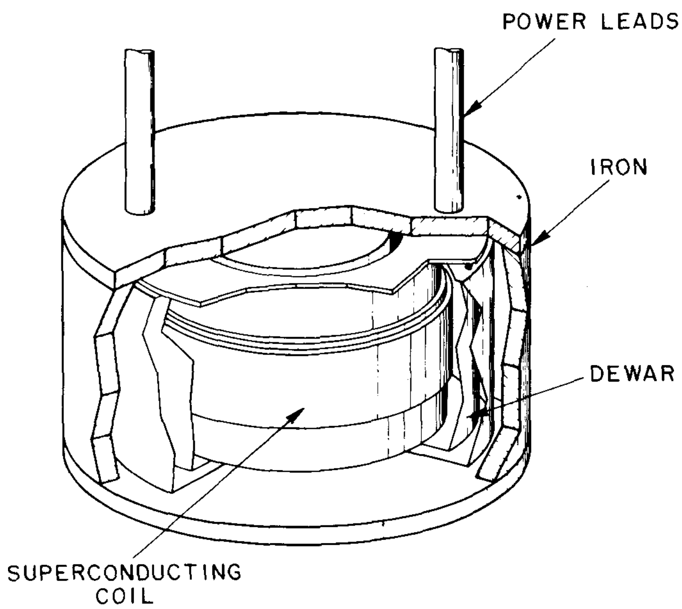


Fig. 12. A sectioned isometric view of the SAVAR coil showing the major components.

economically feasible, it is planned to carry the program through to the construction of a 40 MVAR system that will be installed and tested at an electric utility site.

TABLE VII

COST COMPARISON OF CONVENTIONAL AND SUPERCONDUCTING VAR CONTROL SYSTEMS

Component	$(10)^3$ Conventional	Superconducting
Reactor	300	50
Cooling system		160
Amortized operating and maintenance costs[a]	300	80
Total excluding power equipment	600	290
Power equipment[b]	1000	1000

[a]Based on $2000/kW of average real power consumed by the total system.

[b]Thyristors, capacitors, switchgear, etc.

V. MISCELLANEOUS

A. 20-kJ SMES Demonstration Unit (Boenig, Rogers)

A 20-kJ SMES demonstration unit was designed and built by Intermagnetics General Corporation for LASL and successfully demonstrated in Washington, DC at the Annual Energy Storage Contractors' Review Meeting.

B. Westinghouse Contract (Boenig, Rogers)

A contract has been let for DOE Division of Electric Energy Systems with the Advanced Systems Technology Division of Westinghouse Electric Corporation to evaluate the potential of using small SMES stabilizing units to damp subsynchronous resonances in electrical transmission systems.

C. 3-MW Power Supply (Harkleroad, Turner)

The 1.5-MVA induction voltage regulator (IVR) unit was repaired and reinstalled in the power system. During the initial energization phase, it suffered a 13.8-kV, line-to-ground fault that damaged one of the duplex rotor armature windings. The power system control center was relocated because of future interference with another project. Checkout of the relocated control system is in progress on a low priority. The power supply will be used to provide ac power to the SMES converter for testing at LASL.

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