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Superconducting Magnetic Energy Storage (SMES) Program

January 1—December 31, 1981

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SUPERCONDUCTING MAGNETIC ENERGY STORAGE (SMES) PROGRAM

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ABSTRACT

Work reported is on the development of a 30 MJ superconducting magnetic energy storage (SMES) unit for use by the Bonneville Power Administration (BPA) to stabilize power oscillations on their Pacific AC Intertie. The 30 MJ superconducting coil manufacture was completed. Design of the seismic mounting of the coil to the nonconducting dewar lid and a concrete foundation is complete. Parts for the seismic mounting are delivered and coil mounting has started. Manufacture of the nonconducting dewar has started. The stainless steel dewar lid has been made, and a second lower cost aluminum lid has been ordered for testing the dewar. Design of the 5 kA vapor cooled leads is complete and parts are being ordered. The refrigerator was repaired and tested for the first time at Los Alamos . The heat rejection system, the high pressure gas recovery system, the converter, and parts of the refrigerator have all been operated with computer control. The uninterruptible power supply was delivered and successfully tested. The damaged 6 MVA transformer was repaired and delivered to the Tacoma Substation. Detailed transient voltage analyses of the 30 MJ coil and related protective circuit were completed. The control and data acquisition system hardware is 95% complete and software is 70 to 80% complete. A health, safety, and environmental study of the BPA SMES installation was completed. BPA and the Los Alamos National Laboratory have established a schedule for installation and operation of the SMES unit at the Tacoma Substation.

The superconducting application VAR (SAVAR) control study indicated a low economic advantage and the SAVAR program was terminated.

An economic and technological evaluation of a superconducting fault current limiter (SFCL) was completed and the results are reported.

I. SUMMARY

The goal of the Los Alamos National Laboratory's SMES program is to develop electrical units to store energy in a magnetic field around a coil or inductor. The magnetic field is created by an electric current flowing in a conductor that is in the superconducting state. Many materials, such as niobium-titanium, lose their resistance to electric 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 that, in complex electrical grids, sometimes limit maximum power transmission.

This report describes the progress made in the design and hardware development of the 30 MJ stabilizing SMES unit. The components that must be considered for both systems are the coil; the dewar, which will contain the coil and liquid helium to cool it to the 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 control the charge and discharge of the coil.

The 30 MJ superconducting coil, designed and manufactured by General Atomic Company (GA), was completed.

Because the power oscillations to be damped on the Bonneville Power Administration (BPA) Pacific AC Intertie occur at a frequency of 0.35 Hz, the SMES coil must be contained in a nonconducting dewar to avoid coupling losses which would occur with a conventional metal dewar. A design and manufacturing contract was placed with Fiberglas Design to make the epoxy fiberglass dewar and manufacture has started. The stainless steel lid for the dewar was designed by the Los Alamos National Laboratory, manufactured by Monarch Machine, and delivered to GA for seismic mounting of the 30 MJ coil to the dewar lid.

The seismic mounting design of the 30 MJ coil to the dewar lid and external structural beams and concrete foundation was done by Los Alamos and given to GA for the actual coil mounting. Mounting parts, dewar lid, and the beams have all been supplied by Los Alamos. The foundation drawings were reviewed by BPA and modified in keeping with their recommendations.

The detailed design of the 5 kA vapor cooled leads for conducting current from 300 K at the dewar lid to the superconducting coil at 4.5 K in liquid helium is complete and parts are being ordered.

The Model 2800 refrigerator delivered by Koch Process Industries, formerly CTI-Cryogenics, was damaged during shipment to Los Alamos in 1980, was returned to the manufacturer and repaired, shipped again to Los Alamos , and finally operated at Los Alamos . A number of deficiencies still exist and are being eliminated.

The gas recovery system, to store excess helium in a railway tank car at the Tacoma Substation, was completed and successfully operated with computer control.

The heat rejection system, an ethylene glycol-water cooling heat dump, was operated in conjunction with the refrigerator and was successfully computer controlled.

The converter, the electrical a.c.-d.c. thyristor controlled interface between the 30 MJ SMES coil and the BPA bus, was completely tested with both resistive and inductive loads. The converter was also computer operated with a BPA simulated demand signal.

The 5 kVA uninterruptible power supply, to be the control system auxiliary power source from a BPA battery supply, was successfully tested.

The 6 MVA transformer, which goes from the BPA bus to the converter and was damaged in transit in 1980, was repaired, tested, and shipped to the Tacoma Substation.

Concern has existed about possible voltage enhancement from excitation of the natural frequencies of the 30 MJ coil from transient voltages. Of particular interest has been the possible high voltage switching pulse which may occur with the stray inductance of the protective dump circuit. The dump circuit and distributed capacitance of the coil were analyzed in detail. Effects are marginal and protective surge arresters are being considered.

The 30 MJ SMES system is to be computer controlled by microwave link from the BPA Portland area control center to the Tacoma Substation. The computer hardware is 95% complete and software is 70 to 80% complete. The major accomplishments in the SMES control and data acquisition system include (1) operation of several SMES subsystems from the supervisory computer, (2) completion of control specifications for several subsystems, (3) modification of control circuits in several subsystems to increase the effectiveness of computer control, (4) completion of the design for the supervisory software structure, (5) completions of the design, coding, and check of the a.c.-d.c. converter control software with the hardware, (6) completion of the design, coding, and check of the operator display software with the hardware, (7) design and coding of the control software for the high pressure gas recovery subsystem, (8) completion of the software executed by the slave computers, and (9) change of operating system from RT-11 to RSX-11M. The a.c.-d.c. converter, heat rejection, high pressure gas recovery, and portions of the refrigerator subsystems have been operated through the supervisory and slave computers. This accomplishment provides verification for the system cabling, signal conditioners, computer hardware, many programs in the supervisory and slave computers, and the supervisor data base. The control description of the Los Alamos-BPA computer interface subsystem has been sent to BPA for their review.

The environmental effect of the 30 MJ BPA SMES system is quite limited. Consequently, the environmental concerns were treated in a "Health, Safety, and Environmental Remark."

BPA and Los Alamos have established a schedule for installation and operation of the 30 MJ SMES system. To do this, BPA agreed to alter their research and development program and fund commitment.

The superconducting application VAR (SAVAR) control program undertook a conceptual design study and cost comparison. The result was that the competitive advantage was small and the program was terminated.

Power transmission systems can be built more economically if fault currents can be limited. Different concepts of fault current limiter design have been proposed over recent years. Superconducting fault current limiter (SFCL) concepts involving a diode bridge as proposed by Westinghouse Electric Corporation and also as modified by Los Alamos with an SCR bridge have been studied for both economic and technological evaluation. The results are included herein.

II. BONNEVILLE POWER ADMINISTRATION STABILIZING SMES UNIT

A. Introduction

The Pacific Northwest and southern California are part of the Western U.S. Power System and are connected by two 500 kV, a.c. power transmission lines, collectively referred to as the Pacific AC Intertie, and one ± 400 kV d.c. transmission line, the Pacific HVDC Intertie. The two a.c. lines have a thermal rating of 3500 MW, and the d.c. 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 use as a power source to modulate the power flow in the HVAC Intertie 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 at one time as a result of earthquake damage. A back-up stabilizing system could be used. Late in 1975, representatives of BPA and Los Alamos developed the concept of installing a small SMES unit for the purpose of providing system damping similar to that now available by modulation of the intertie. The small SMES unit has been developed to a very advanced hardware stage with component testing conducted at the Los Alamos National Laboratory. The unit is scheduled for installation from 6/82 through 9/82 with experimental and utility operation to run from 10/82 through 9/83 with a decision to be made in 9/83 by BPA to utilize the unit as a permanent part of their electric power grid.

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

A 30 MJ BPA SMES coil to store energy was designed and manufacture started in 1980. The coil was completed in 1981 and design was finished for seismic mounting of the coil to the dewar lid. Contractural arrangements have been made with GA to have the coil mounted.

Winding and stacking of the individual pancake coils was completed by mid February 1981. Assembly of the full 30 MJ coil was completed in early July, one month ahead of schedule and considerably below the contract cost. Throughout this period, procedures were under continuous review by Los Alamos representatives and GA staff. On February 3, 1981, a team of five outside experts was invited to inspect the nearly complete coil. This review led to the performance of several mechanical and high voltage tests and to some minor modifications in materials and procedures.

The separate pancake coils as wound were out-of-round and tended to warp out-of-plane. All reviewers felt that such irregularities were not serious provided they did not interfere with assembly. During stacking, the pancake coils were forced to be round by jacks, and the coil inner support rings were fastened together with scroll pins. Pinning also increases the inter pancake shear capability to resist the load required for seismic considerations. After assembly, clamps were used to compress the full coil to the theoretical designed height to remove any residual effect of warping. Before construction began there was some concern that possible creep in the plastic mandrel or conductor insulating tape could lead to relaxation of the winding preload. Accordingly, witness marks were made on the first two pancake coils to be wound. These marks showed zero creep after four months. Numerous minor variances, as fully documented in the final report, from what later became standard procedure occurred in the first few pancake coils. Although none of these were considered serious enough to require rewinding the pancake coils, alterations were made wherever physically possible.

A stainless steel strap is co-wound with the conductor and provides the force support. Questions were raised regarding the strength of the structure that terminates the outer end of the strap. GA fabricated a model and tested it mechanically. The assembly holds at least twice as much force as required in service and fails by slow elastic yielding. One of the straps was partly severed, by accident, in the outer termination region. An additional turn of strap was applied to this one pancake coil to provide extra support for the cut region that, by calculation, would probably still support the required force without any reinforcement.

Most of the modifications made were to the electrical and mechanical aspects of the superconducting cable joints. Insufficient high voltage withstand capability was corrected in part by replacing aluminum support blocks with NEMA grade LE linen phenolic. The linen phenolic, being hydroscopic, tracks badly along the fiber direction. Phenolic parts were redesigned to avoid this tracking, which interfered with testing but would not occur at low temperature during operation. All linen phenolic parts were sealed with a wash coat of epoxy as a further precaution. Mechanically, each joint was a special case and required individual hand fitting of special fixtures to provide adequate support to all second level superconducting cables. The actual joint soldering, performed with an electrically heated mold, was quite readily accomplished.

Care was taken during assembly of the entire coil to prevent debris from entering the structure. After completion, the coil was thoroughly vacuumed and was covered with plastic to await mounting.

C. Nonconducting Dewar (Rogers, Schermer; Bennett, Q-13)

Because the coil cycles continuously at a frequency of 0.35 Hz, the inner liquid helium vessel must be made of glass reinforced epoxy to avoid eddy current heating which would occur in a metal walled dewar. The outer room-temperature vessel can be constructed either of a suitable plastic or of 300 series stainless steel. Further, the vessels can be assembled with either demountable or permanent seals. RFQs were issued covering various combinations of these options for the vessels. Five responses were received to build a plastic dewar and one response for a room temperature stainless steel outer dewar vessel. The steel vessel was rejected, partly to avoid problems with pulsating loads and nonuniform potential gradients and partly to avoid the problem of a vacuum seal between the inner and outer vessels. Four vendors bid on the option with two plastic vessels assembled with a permanent seal. The contract was awarded to Fiberglas Design, Benicia, CA, on the basis of technical merit, experience, and cost. Lengthy contract negotiations ensued, due principally to the accounting practices and records of this very small company. The contract was placed and actual mold construction began in November 1981.

The inner vessel will be fabricated using hand lay-up techniques. Each day's epoxy layer will be cured at a slightly elevated temperature, roughly 80°C, overnight by sealing and warming the lay-up room. The outer vessel will be fabricated from polyester resin and chopped glass fiber and will be stiffened against buckling by circumferential ribs.

The vessel lid is a major structural element. Seismic forces must be transmitted through the material to the coil mounting structure to avoid numerous penetrations to accommodate these structural elements. A G-10 epoxy fiberglass lid of the size required would have to be laminated from numerous small segments of sheet material, would be more difficult to machine than steel, and would be more expensive. For these reasons a 1 1/2 in. thick stainless steel lid was chosen with whatever high voltage insulation problems resulted. The lid was designed at the Los Alamos National Laboratory and fabricated by Monarch Machine, Los Angeles. Originally, the steel lid was to have served as a template for drilling the dewar flange bolt holes and as a cover during dewar testing prior to being sent to GA for coil mounting. The long delay in dewar procurement no longer permits this schedule. Instead, a 1 1/4 in. thick aluminum lid has been ordered to serve as template and test cover. In addition, this lid will be left in place during shipping as it stiffens the vessel flanges and makes handling the vessel far easier and safer.

The dewar flange design continued in 1981 with two finite element representations. To investigate the lid closure seal, the bolt design, and the stresses in the flanges for the 30 MJ coil SMES dewar, two finite element models of an upper portion of the vessel were constructed with the finite element computer code, ADINA.[1] The first model, shown in Fig. 1, was a coarse grid, axisymmetric model. The purpose of this model was to determine the stresses under the operating condition of 15 psig (103 kPa) and a fault condition of 30 psig (207 kPa) in the lid near the flanges so a detailed model of these regions could be studied. The detailed model, shown in Fig. 2, applied the shear and moment to the lid as determined from the whole model of Fig. 1 at the equivalent section of the lid. The design finally adopted uses a 4 in. wide by 2 in. thick flange on the epoxy fiberglass inner vessel with a 1/2 in. by 1/2 in. fillet region at the juncture of the 1 in. thick vessel wall. Maximum

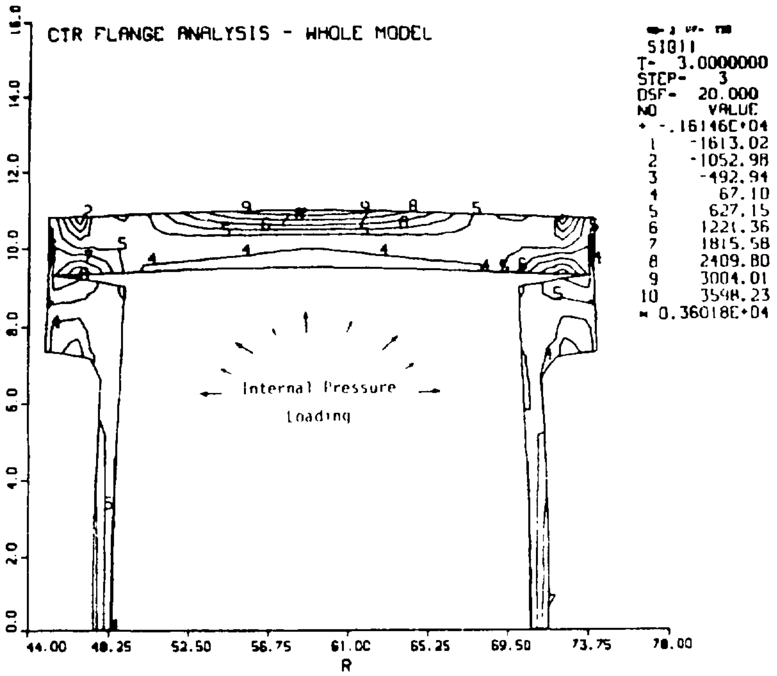

Fig. 1. Maximum principal stresses for vessel and lid under internal pressure - coarse grid.

stresses in the plastic under normal operating conditions are below the 5 ksi (34 MPa) creep limitation for this material. The vessel, as finally designed, tapers from 1 in. at 10 in. below the flange to a 1 1/2 in. thick wall at the juncture. Great care is being exercised in mold construction to produce a flange face flat and smooth enough to eliminate machining.

The flange and wall are very flexible in bending and, under applied pressure, rotate until restrained by the lid or bolts. This is a qualitatively different situation than found for a metal vessel. In addition, it creates difficulty in computer modeling. To control the rotation, the lid should not be undercut; rather, the lid and flange must contact along their outer edges. When this occurs, the displacement between the lid and flange face at the O-rings is only 0.006 in. (0.2 mm) under normal operating conditions.

The 1 in. flange bolts undergo fairly high stresses, 18 ksi (124 MPa) tension and 42 ksi (288 MPa) bending at 30 psig internal pressure. ASTM A-325 bolts of weathering steel have been specified for the application.

The dewar vendor has prepared a detailed drawing of the inner vessel geometry. The design has been subjected to finite element analysis, with particular attention paid to stress, displacement, and possible buckling in the vicinity of the torispherical bottom end. The pressure history of the dewar under various assumed faults was calculated to size the relief vent and rupture disks; to check that the calculated dewar buckling pressure, 35 psig, is

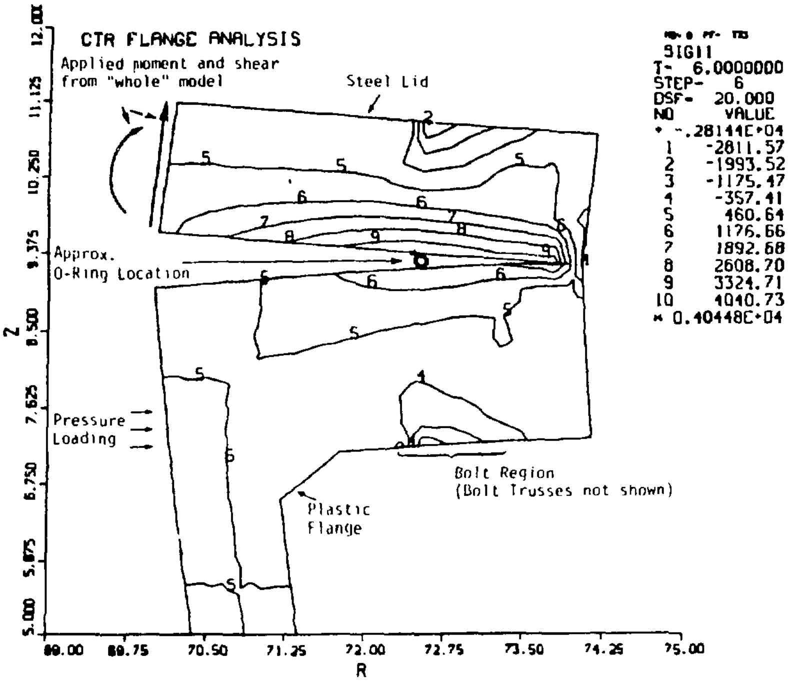

Fig. 2. Maximum principal stress in right hand flange from ADINA model with displacements exaggerated by a factor of 20.

adequate; and to aid in preparing a safety analysis of the system. Coil shutdowns, triggered by quench detection, low liquid helium level, or helium pressure rise, will limit the dewar pressure to 9 to 10 psig and will not even lift the relief vents, which will be set for 18 psig. If all these safeties fail or if the vacuum fails catastrophically, the pressure will rise to 23 psig and the two 6 in. rupture disks will blow. Vacuum failure deposits roughly 60 kW in the helium while a fully normal coil deposits 600 kW. At 600 kW, disk rupture occurs in 10 s. The pressure continues to rise another 1.1 psi while the warm gas column from the upper section of the vessel vents, which takes 0.3 s. Even if the fully normal coil remains on, the pressure then drops rapidly to 24 psig and continues to fall and then falls for the next 10 to 20 s as the helium vents. The disks are also adequate to protect the dewar under any conceivable accident involving room temperature helium gas during system cleanup or startup. Relief vents add little to system safety. They have been sized to handle normal dewar boil-off in case various valves are accidently closed.

Superinsulation techniques will rely heavily on engineering performed for other large magnet projects, in particular ISABELLE at the Brookhaven National Laboratory. Double aluminized Mylar* will be striped to disrupt eddy current

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*duPont trademark.

loops and then laid in batts ten layers thick with Nexus* cloth separators. Nexus, a non-woven polyester product, is not hydroscopic and creates less vacuum pumping load than previously used nylon separators. The batts will be held together with nylon clothing tag fasteners, tapered to fit properly over the cured vessel end, and set in place flange to flange on the vessel. Electric scissors will be used for cutting and shaping batts. Installation will proceed azimuthally around the vessel. Succeeding layers of batts will be arranged to overlap joints in lower layers until a total of 100 layers of superinsulation are applied. The batts will be supported at their upper edge with Nylon grommets and braided glass lacing cord.

Vacuum pumpdown is greatly facilitated if the Mylar is perforated, with 1/16 in. holes on 3/8 in. centers. Perforation, however, is a very expensive process according to the only bid obtained. This problem has not been solved.

D. Coil and Dewar Structural Support (Henke, Schermer; Ellard, ENG-2; Bennett, Butler, Q-13; General Atomic Co. staff)

Coil support presented an unusual problem. At Tacoma, WA, the system will be installed in a Zone C seismic region, with design accelerations of 0.24 g horizontal and 0.16 g vertical. Large magnets are usually enclosed in a welded metal dewar that can be routinely supported in a variety of ways. Permanent encapsulation of the 30 MJ coil in its epoxy fiberglass dewar, which must be free of seals or joints to avoid helium leaks is deemed inappropriate. Further, the ASME Unfired Pressure Vessel Code recommends against using a plastic vessel as a structural element. Therefore, a stiff support system was designed to suspend the coil freely within an open mouth helium vessel. Computations were performed based on the response spectra technique, and finite element codes and analysis rules were developed for nuclear reactor systems. One sixth of the support system is shown in Fig. 3. The shear panel, a 3/8 in. thick plate of G-10 CR, resists a lateral load of up to 18,000 lb. The panel is mounted to transmit low vertical loads to the coil clamping structure. Vertical loads, which vary between 19,000 lb tension and 7000 lb compression, are taken by a stainless steel support tube with ball joint ends to avoid bending. Coil motion is less than 0.060 in. in any direction. All loads are transmitted through the 1 1/2 in. thick stainless steel dewar lid and six steel support beams to concrete columns.

Partial decoupling of loads in the vertical trusses from lateral motion was accomplished by using kinematic joints on both ends of the trusses and on the tops of the shear panels. Such decoupling is necessary to maintain the frictional restraint in the 30 MJ coil design. However, the amount of coupling between the vertical and lateral coil motion is still significant enough that care was exercised in selecting the stiffness of the supporting vertical trusses and shear panels. Making the shear panels quite stiff considerably lowered the forces in the trusses but produced prohibitive loads on the panels themselves. Several partial analyses to obtain modal participation factors were performed to determine an optimum design. A shear panel thickness of 0.375 in. (0.95 cm) was finally selected to distribute the loads appropriately among the components. The relative displacements between the coil and dewar and absolute displacements laterally along the dewar cover where the magnet vertical trusses attach were calculated. The results are summarized in Table I.

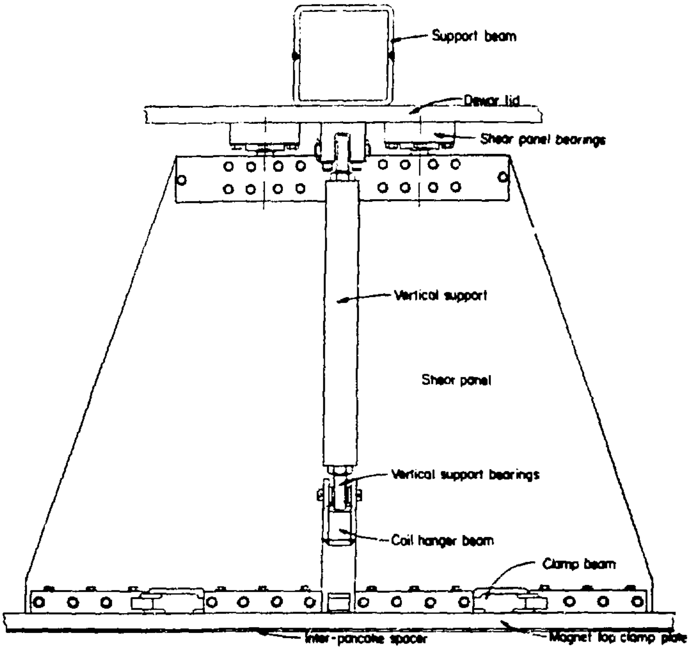

Fig. 3. One 60^0 segment of the coil support system; vertical section normal to radius.

TABLE I

DISPLACEMENTS OF MAGNET SUPPORT SYSTEM FROM A 0.25 g EARTHQUAKE

Magnet displacement relative to dewar	
z (vertical)	0.044 in.
x (lateral)	0.053 in.
y (lateral)	0.063 in.
Maximum vertical displacement of dewar cover	
z (vertical)	0.0043 in.

All the support elements have been fabricated and received. Under Phase III of the 30 MJ coil contract, GA will perform the support mounting and will equip the dewar lid with all necessary baffles, instrumentation, and protective devices. The coil will be shipped from San Diego to Tacoma with all these components in place.

Foundation design was done by the Laboratory group, ENG-2. At their request, a soil sample analysis was performed at the proposed coil location in the Tacoma, WA substation of BPA. Core samples revealed a five foot layer of peat below a ten foot surface layer of sand and gravel. Calculations, based upon compaction tests, indicated that the concrete structure would settle 10 in. during the first year. Although the settling would be acceptable if it were uniform, a 2° tilt would make coil and dewar installation impossible. Finished foundation drawings call for a 2 ft thick monolithic concrete slab supported on pilings. Reinforcement for the slab and coil support columns uses fiber reinforced polyester and stainless steel reinforcing bar as much as possible to avoid coupling forces to the coil in the dewar from the fringe magnetic field.

E. Helium Vapor Cooled 5 kA Electrical Leads (Harkleroad, Harrison, Henke, Schermer, Singleton)

Each of the ten superconductor subcables must equally carry a 450 A share of the average d.c. coil current. As the series resistance varies among subcables from variations in joint resistance and in the number of cold welds in the superconducting core strands, a known resistance of 10 to 100 μΩ must be placed in series with each subcable. Providing each of the ten subcables with its own electrically isolated power lead supplies the necessary resistance. The power leads for the 30 MJ coil are more complex than those for other superconducting magnets. Copper with a low RRR has numerous advantages for power leads compared to higher purity copper with a RRR in the 100 to 300 range. Leads formed of impure copper have much better thermal stability as they contain larger amounts of copper; they do not overheat as badly when subjected to a higher current or gas flow lower than the design value; and they have a lower heat leak when not carrying current. Material availability, at least in small quantities, is limited almost entirely to phosphorus deoxidized copper in the form of water service tubing. Accordingly, a decision was reached to form the subcable leads from tubes of length and cross sectional area appropriate to the measured RRR. Each subcable lead is formed from a 40 in. length of 7/8 in. o.d. by 0.045 in. wall, type L tubing, made of copper alloy CDA 122, so called "DHP" copper. A 1/2 in. long sample was cut from each of 28 tubes, 8 to 12 ft long. The samples were then fabricated into rolled, annealed strips and resistivity measurements were performed. Sixteen tubes with RRR in the range 7.14 to 8.18 were retained for further processing; the remainder were returned to stock.

Each tube was cleaned, annealed in hydrogen, and flattened by pressing and rolling over a flat, brass mandrel to form a flat tube 1.312 in. wide with a 0.040 in. inside channel for gas flow. The flattening process increases gas velocity and improves the heat transfer.

The tubes will be furnace brazed into a heavy copper collector that forms the room temperature electrical termination; and the entire assembly is then sealed into a G-10 epoxy fiberglass box that forms the primary electrical insulation between the copper parts at high potential and the stainless steel lid at ground potential. Parallel flow paths tend to be unstable because, if one tube warms slightly, its flow impedance increases causing it to warm still more. This instability is avoided by controlling the flow through the tubes with orifices that are all attached to the same massive copper structure at room temperature. Further, because all the tubes are within the same G-10 box, they are in thermal contact through the intervening gas space although they are electrically insulated from each other.

Detailed shop drawings for the lead have been completed. Bids have been solicited for the G-10 parts, the bellows assembly, and for machining several complex copper parts. In addition, some or all of the room temperature copper parts will be formed of free machining copper to reduce machining costs.

F. Cryogenic System (Buteau, Dean, Harkleroad, Schermer, Smith)

The cryogenic system for providing the liquid helium to the 30 MJ superconducting coil and gas storage is nearly complete. The trailer mounted major components--refrigerator, heat rejection system, and high pressure gas recovery system--have been delivered and undergone extensive testing.

1. Refrigerator. The refrigerator, delivered by Koch Processs Industries, formerly CTI-Cryogenics, to Los Alamos in September 1980, was damaged in shipment. The refrigerator was returned to Koch for repair. The repairs were completed by June of 1981 and system performance was demonstrated at Koch's plant. A special container was made to hold the cold box heat exchanger assembly, which was shipped separately from the trailer mounted refrigerator.

A Koch engineer was in Los Alamos during November 1981 to participate in the field operation of the refrigerator and to train operating personnel. About a week's work was required before operation began. The system was operated first as a liquefier at a rate of about 70 ℓ/hr and then as a refrigerator at 200 W. Several control problems were detected that need be remedied before full computer operation begins. Subsystems of the refrigerator, including the compressors, have been operated from the computer. A cost holdback is being maintained until the defects are repaired by Los Alamos and a backcharge is intended to be made.

The refrigerator system was attached to the trailer mounted heat rejection system cooling tower, and flow through the compressors was checked. Two of the screw compressor oil aftercoolers were plugged. One was cleaned and unplugged at Los Alamos , the other was replaced by the manufacturer. The heat exchanger passages were blocked by calcium and magnesium carbonates precipitated out of Koch's cooling system. To accomplish the cleaning, mild acid solutions were circulated through piping. Cleaning solutions were also pumped directly through the aftercoolers with one becoming unplugged and the other not.

One of the gas bearing turbine expanders was damaged during the refrigerator testing at Koch. The turbine was repaired at manufacturer's cost and delivered to Los Alamos .

2. Gas Recovery System. The gas recovery system is to store in a railway tank car at the BPA Tacoma Substation excessive helium gas evolved from the 30 MJ coil dewar during upset operation or from intentional warming. The Corblin compressors of the high pressure gas recovery system were mounted with necessary piping and electrical wiring into a trailer by a contractor. One of the two compressors lost its oil prime during startup with damage occurring to a cylinder and piston. These parts were replaced and the system is operational. The gas recovery system and the heat rejection system have both been operated with computer control.

G. Electrical System

1. Converter. (Boenig, Buteau, Grant, Harkleroad, Loya, Ruppert, Smith, Trudell, Turner) Eight power terminal transitions through the converter roof were built and installed. The converter terminals were connected by 4/0 cables to the 3.25 MW transformer terminals. A stainless steel, 1 MW load dump was built and connected to the converter to be used for load testing. The heat rejection system was connected to the load dump to provide ethylene glycol-water coolant.

The converter was tested with ohmic-inductive load and all the SCRs were checked for current sharing. During the test, the converter a.c. supply voltage regulator developed a ground fault. After bypassing the faulty device, the test was continued.

One high current SCR had to be replaced in one phase of a bridge to provide better current sharing. Different tests with the converter, which included the simulation of fault conditions, show that the converter is conservatively designed and will properly respond to different operating conditions expected for the SMES system at Tacoma. The converter was operated under computer control with BPA demand signal simulation.

2. Uninterruptible Power Supply. (Boenig, Buteau, Turner) A 5 kVA Westinghouse uninterruptible power supply was ordered, received, and tested with a battery power source and meets specifications.

3. Transformers. (Boenig, Turner) The damaged 6 MVA transformer was repaired at the Niagara Transformer plant in Buffalo, NY; and the acceptance tests were witnessed by Los Alamos personnel. The transformer was shipped to the Tacoma Substation where it is being stored. The 0.5 MVA auxiliary service transformer also was delivered to Tacoma.

4. Transient Voltage Analysis. (Anderson, Chowdhuri) Previously reported work indicated that the most serious transient voltage across the 30 MJ coil will be generated by the opening of the d.c. vacuum circuit breaker in the protective dump circuit of Fig. 4. The analysis was extended by varying several parameters of the dump circuit to determine their effects on the transient voltage across the coil. Figure 5 shows the effect of the self-inductance, L_2, and of the dump resistor, R. Higher self-inductance of R would increase both the positive and negative peaks of the transient voltage. The transient voltage is very sensitive to this parameter. Therefore, the dump resistor should be designed with the least possible self-inductance. Figure 6 shows the effect of the counterpulse capacitor precharge voltage level, V_c. The higher this voltage is, the higher would be the positive peak of the transient voltage across the SMES coil; the negative peak of the transient voltage is insensitive to V_c. In Fig. 6, the negative peak for $V_c = 5$ kV is higher than that for $V_c = 6$ kV. This is because the voltages are expressed in per unit. They are nearly equal when converted to kilovolts. The transient voltage across the SMES coil has two components as already mentioned. The first component is caused by the forced zero of current through the d.c. circuit breaker and the second component by the residual voltage in the counterpulse capacitor bank, C. The negative peak belongs to the first component, and the positive peak belongs to the second component.

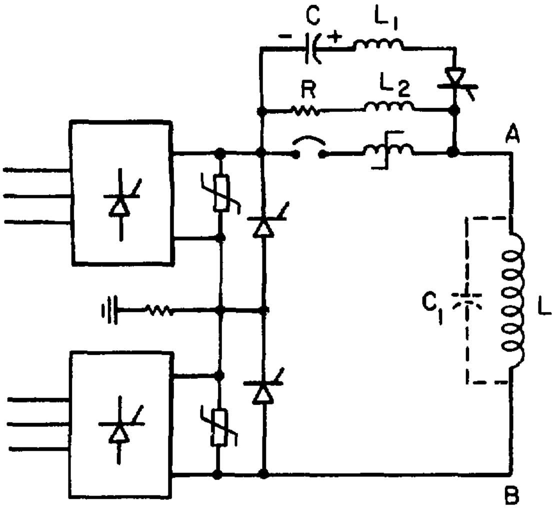

Fig. 4. Schematic of the protective dump circuit of the 30 MJ SMES system. L = coil, C_1 = capacitance across coil, C = counterpulse capacitor bank, L_1 = waveshaping inductor for counterpulse circuit, R = dump resistor, L_2 = self-inductance of R.

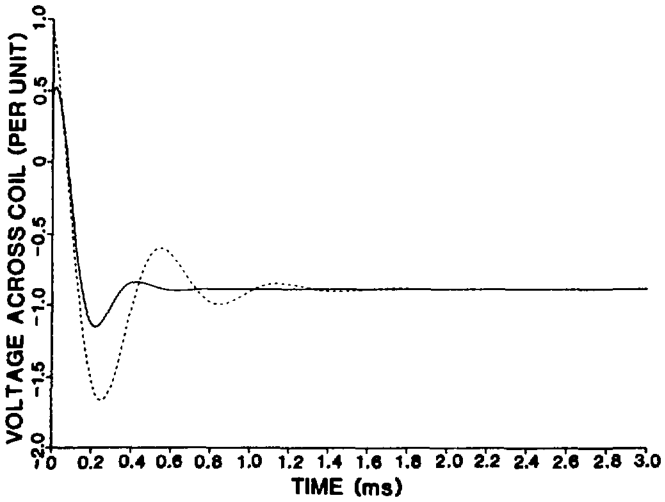

Fig. 5. Transient voltage across SMES coil caused by current interruption by d.c. circuit breaker; effect of dump resistor self-inductance. V_c = 5 kV, I_L = 4.9 kA, L = 2.6 H, L_1 = 36 µH, C = 60 µF, C_1 = 0, R = 0.9 Ω. Solid curve L_2 = 20 µH. Dotted curve L_2 = 100 µH. Per unit voltage = counterpulse capacitor precharge voltage, V_c.

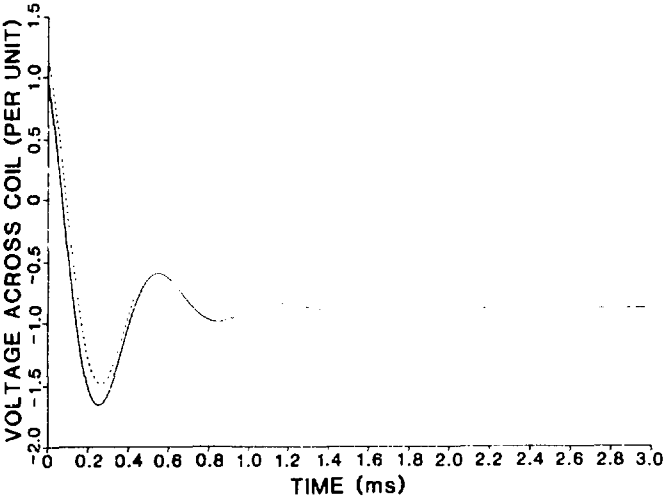

Fig. 6. Transient voltage across SMES coil caused by current interruption by d.c. circuit breaker; effect of precharge voltage level of counterpulse capacitor. I_L = 4.9 kA, L = 2.6 H, L_1 = 36 μH, L_2 = 100 μH, C = 60 μF, C_1 = 0, R = 0.9 Ω. Solid curve V_c = 5 kV. Dotted curve V_c = 6 kV. Per unit voltage = counterpulse capacitor precharge voltage, V_c.

Figure 7 shows the effect of capacitance across the SMES coil. A capacitance across the SMES coil would produce oscillations. These oscillations are accentuated when the self-inductance, L_2, of the dump resistor, R, is higher. This also would produce a higher peak voltage. The beneficial effect of C_1 is to reduce the slope of the front but not the amplitude of the positive peak as shown in Figs. 5 and 7. A steep front of the transient voltage could produce highly nonuniform voltage division within the coil with the possibility of turn to turn dielectric failure in the coil. The capacitor, C_1, may also be used to modify the frequency components of the switching surge, so that these frequencies are not coincident with the natural frequencies of the coil; otherwise, internal overvoltages would be developed by resonant oscillations. A surge arrester to limit voltage surge across the coil and capable of dissipating 30 MJ of energy of the SMES coil, would be impractical. An alternate approach would be to connect a stack of nonlinear resistors with low internal inductance across the dump resistor. The nonlinear resistors must be designed so most of the 30 MJ stored energy would be dissipated in the dump resistor and would conduct only when the transient voltage exceeds 7.5 kV.

An RFQ for a surge protector was sent to several manufacturers who responded negatively. A surge protector will be designed from standard nonlinear resistors.

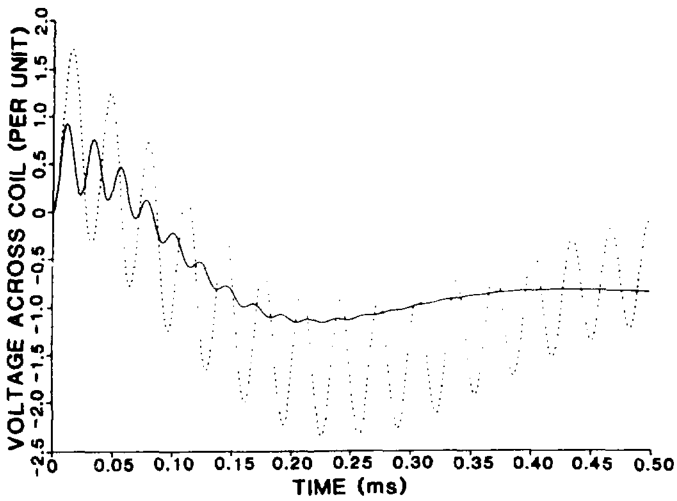

Fig. 7. Transient voltage across SMES coil caused by current interruption by d.c. circuit breaker; effect of capacitance across coil. V_c = 5 kV, I_L = 4.9 kA, L = 2.6 H, L_1 = 36 μH, C = 60 μF, C_1 = 1 μF, R = 0.9 Ω. Solid curve L_2 = 20 μH. Dotted curve L_2 = 100 μH. Per unit voltage = counterpulse capacitor precharge voltage, V_c.

The natural frequencies of the multiple pancake coil are determined by considering the coil as a lumped network as shown in Fig. 8. Once the coil has been divided into an N-section ladder network, it can be solved by the state variable method. Thus,

$$dX/dt = AX + BV, \tag{1}$$

$$U = SX + DV, \tag{2}$$

where X(t) = state vector,
U(t) = output vector of node voltages,
V(t) = applied voltage, and
A,B,D, and S = matrices of constant coefficients.

The eigenvalues of the matrix A are the natural frequencies of the coil. The output voltage at each node of the network can also be obtained for any type of applied voltage.

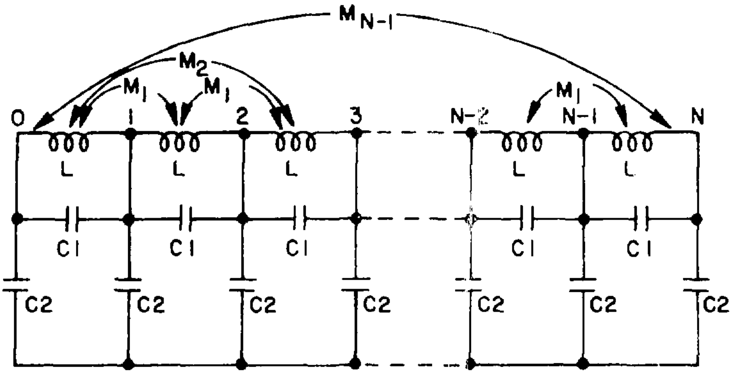

Fig. 8. Schematic representation of a coil as a lumped circuit.

The various capacitances, such as turn to turn, pancake to pancake, and coil to return lead, were calculated. Cylindrical symmetry or parallel plate configuration was assumed, and different dielectric constants were included for the coil structure materials. The total series capacitance, C_s, of the coil was determined from the following equation to evaluate Eqs. 1 and 2.

$$C_s = 2C_eC'_e/\left[4C_e + (N_p - 2)\, C'_e\right], \tag{3}$$

where C_e, $C'_e = c_p\left[1 + \left(\coth\,(n+1)\theta\right)\left(\coth\,(\theta/2)\right)\right]$,

$\theta = \cosh^{-1}\,(1 + k/c_t)$,

$k = 2\,c_p$ for C_e,

$k = c_p$ for C'_e,

c_p = capacitance between two corresponding turns on neighboring pancakes, and

c_t = capacitances between two neighboring turns within a pancake.

TABLE II

CALCULATED RESONANT FREQUENCIES OF 30 MJ COIL

	First Harmonic kHz	Second Harmonic kHz
Insulating Dewar	8.8	15.8

Table II shows the first two calculated space harmonics of the 30 MJ coil. The resonant frequencies of the SMES coil were also measured at room temperature in air without a dewar by two methods. For both methods, a variable frequency sinusoidal voltage source was connected across the coil. The applied voltage and the coil current were observed on an oscilloscope during the first method of test. The coil current showed maxima at resonant frequencies. The voltages at the 1/4, 1/2, and 3/4 points along the coil were measured during the second method. The midpoint of the coil showed a maxima at the first space harmonic. The 1/4 and 3/4 points showed maxima at the second space harmonic.

The first two space harmonics were measured at about 7.3 kHz and 15.3 kHz when the voltages at 1/4, 1/2, and 3/4 points of the coil were measured. However, no resonances were detected at these frequencies when the coil current was measured with a 10 Ω resistor. Both methods of measurement gave strong evidence of resonance again at about 335 kHz and 607 kHz.

H. Control and Data Acquisition System (Brown, Criscuolo, Cummings, Seamons, all E-8)

The Control and Data Acquisition (CDA) subsystem will function as the central communications point of the SMES system. The CDA system will respond to commands from BPA, or a local operator, by adjusting SMES system control parameters and will determine the system's state by monitoring data from each of the subsystems.

The tasks required of the CDA system will be divided among three LSI 11-23 computers from Digital Equipment Corporation. The organization of the CDA system is illustrated in the CDA system block diagram of Fig. 9 from the 1980 annual progress report and briefly reviewed here for clarity.

The controller, the supervisory computer and its resources, will function as the central communications point and supervisor for the CDA system and will accept information which describes the desired state for the SMES system from BPA or the local operator. The instantaneous state of SMES will be described by the information from the Cryogenic Data Acquisition System (CDAS) and the Energy Data Acquisition System (EDAS), also referred to as slave computers. After comparing the information from these sources, the controller adjusts the control parameters to bring SMES to the new state being requested. The controller will also display the state information to the local operator and BPA.

The state of the SMES system will be continually monitored by the CDAS and EDAS. These subsystems are capable of acquiring data at a high rate and storing this data for post failure examination. Attaining a high data rate is the primary reason for separating the control function from the monitoring function. The CDAS and EDAS will be responsible for reporting parameter limit excursions to the controller. The 1981 work report follows.

The resources available to the supervisor computer and the slave computers are shown in Figs. 10 and 11, respectively. This hardware and the SMES system control software will provide

a. Unmanned control of the system for extended periods of time of weeks to months,

Fig. 9. Control and data acquisition system block diagram.

b. Data storage that will aid in analyzing system performance and diagnosing system faults,
c. Display system performance in a manner that facilitates system operations and maintenance, and
d. Safe and reliable shutdown of the system during emergency conditions.

The major accomplishments in the SMES CDA subsystem include (1) operation of several SMES subsystems from the supervisory computer, (2) completion of control specifications for several subsystems, (3) modification of control circuits in several subsystems to increase the effectiveness of computer control, (4) completion of the design for the supervisory software structure, (5) completions of the design, coding, and check of the a.c.-d.c. converter control software with the hardware, (6) completion of the design, coding, and check of the operator display software with the hardware, (7) design and coding of the control software for the high pressure gas recovery subsystem, (8) completion of the software executed by the slave computers, and (9) change of operating system from RT-11 to RSX-11M. Each accomplishment is described below.

The a.c.-d.c. converter, heat rejection, high pressure gas recovery, and portions of the refrigerator subsystems have been operated through the supervisory and slave computers. This accomplishment provides verification for the system cabling, signal conditioners, computer hardware, many programs in the supervisory and slave computers, and the supervisor data base.

Control specifications for the a.c.-d.c. converter, heat rejection, high pressure gas recovery, and BPA interface subsystems have been completed. These specifications include a description of the subsystem functions, detailed flow

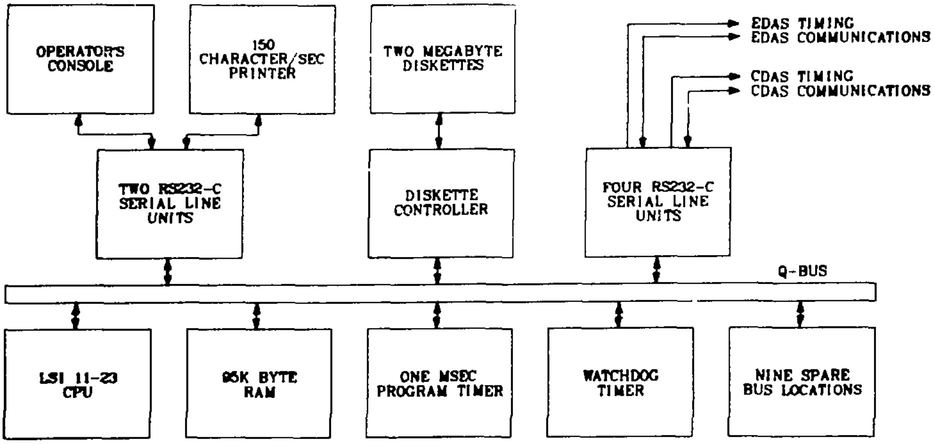

Fig. 10. Supervisory computer resources.

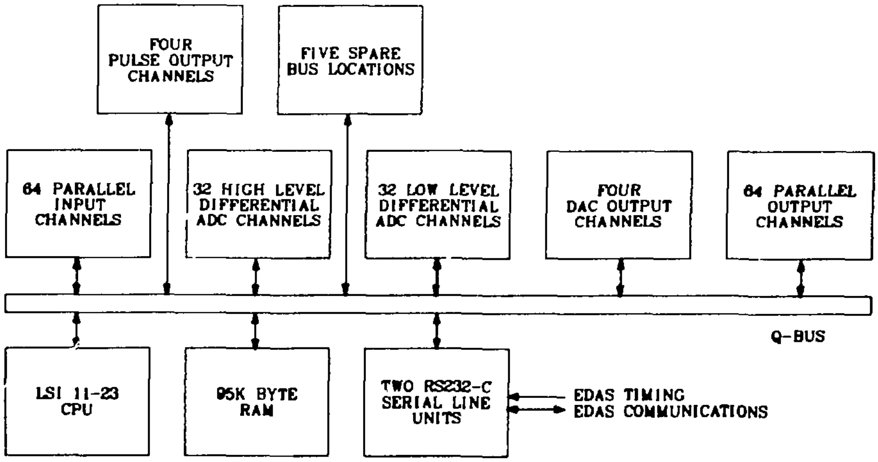

Fig. 11. Slave computer resources.

charts defining the control sequence for the subsystem, definition of each interface signal, and wire lists with computer channel assignments for each signal. The specifications constitute the basic document from which the control software may be generated.

The a.c.-d.c. converter, heat rejection, and high pressure gas recovery subsystems required modification of some control circuits to allow a smooth transition from manual to computer control and to provide more reliable computer control. These modifications have been completed. The refrigerator subsystem will require similar modifications.

Before the supervisory software structure design accomplishment is described, the following introductory remarks are useful. The supervisory computer has many programs that are executed at various times. These programs may be conceived as existing at different levels in a software hierarchy. The highest level is occupied by the operating system that is supplied by the computer manufacturer. The next level is occupied by a supervisory program that has been designed by the laboratory minicomputer group. The lowest level is occupied by the programs that are specific to the application. These programs are designed by the minicomputer group in conjunction with the SMES project team members.

In the SMES system the highest level of software is the RSX-11M operating system. This system provides many functions that are generally used, including editors, program language compilers, memory management, file management, task priority management, and sharing of the central processor. Initially, RT-11 was the operating system used in SMES but has been replaced by RSX-11M, which has more capabilities to offer the SMES application.

The supervisory program second level software was designed and coded and is in the early stages of debugging. Tasks that have been checked in the supervisory program include communications between the supervisory computer and slave computers, operator display, keyboard communications, printer, and data base modification. The principle task that remains to be checked is the communication and coordination with the application programs.

The control of the a.c.-d.c. converter through the computer has been completed. The converter has been brought from an unpowered state to an operating state by an operator interacting with the computer. The computer responds to the operator commands and monitors converter interlocks and set points. The converter output has also followed a simulated BPA power demand signal through the computer.

The operator interfaces with the entire SMES system through the console. The console contains a typewriter keyboard and a video screen. The operator enters commands and requests status by typing specific character strings. The computer verifies that the commands are correct and appropriate before execution. The readiness of all SMES subsystems is discernable on the video display. The operator may obtain detailed status on each subsystem by requesting that the display be dedicated to that subsystem. Features such as inverse video, blinking, and high brightness are used to accent data points that are abnormal. The program that manages the display is operational.

The slave computer software is completed and operating. This software allows the slave to communicate with the supervisory computer, acquire analog and binary data from the SMES subsystems, set analog and binary control points, maintain the real time clock, and store data in the transient buffer. The slaves have been operating for several months with no apparent software problems.

I. BPA Site Installation

1. Health, Safety, and Environmental Remark. (Turner, BPA staff) Consideration was given to environmental concerns for the 30 MJ SMES system to be installed at the BPA Tacoma Substation. A conclusion was reached that the environmental effect is quite limited and the matter was treated in a document entitled "Health, Safety, and Environmental Remark for the 30 MJ Superconducting Magnetic Energy Storage Installation at the Bonneville Power Administration Tacoma Substation, Tacoma, Washington."

2. Dewar and 30 MJ Coil Foundation. (Henke, Schermer; Ellard, ENG-2; BPA staff) Detailed construction drawings were made for the dewar and 30 MJ coil foundation for the Tacoma Substation installation. The drawings were reviewed by BPA and revised to meet their recommendations. See Sec. II.D of this report for more information.

3. Computer Control Interface. (Boenig; Brown, Criscuolo, Cummings, E-8; BPA staff) The 30 MJ SMES system will be computer controlled through a microwave link from the BPA Portland, OR area control and dispatch center to the Tacoma Substation. The control description for the interface subsystem between the Los Alamos computer system and the BPA microwave-computer terminal at the substation was completed and sent to BPA for review.

4. SMES Installation Schedule. (Rogers, BPA staff, DOE staff) Meetings were held at BPA Portland, OR and DOE Washington, DC to schedule the installation and operation of the 30 MJ SMES system at the Tacoma Substation. BPA has agreed to alter their research and development program and fund commitment to accommodate the installation of the system in FY 82 and to accomplish all experimental and Los Alamos observed utility operations in FY 83 prior to a BPA decision to accept the system on a permanent basis. The schedule follows and is quite sensitive to early FY 82 adequate funding for Los Alamos.

Activity	Date
Tacoma site preparation complete	6- 1-82
Shipment and installation at Tacoma started	6- 1-82
Installation at Tacoma complete	10- 1-82
Experimental operation started	10- 1-82
Utility operation started	2- 1-83
Decision for permanent accceptance of SMES system	9-15-83

III. SUPERCONDUCTOR APPLICATION VAR (SAVAR) CONTROL (Boenig, Rogers, Westinghouse staff)

Westinghouse Electric Corporation delivered the final reports of the SAVAR converter design and cost comparison study of the coil optimization study. A Los Alamos report describing the experimental SAVAR test results was completed. These three reports represent the extent of the SAVAR work. DOE was advised to discontinue funding for the SAVAR program because the economic position of a SAVAR unit compared to a conventional static VAR system appears marginal. Further, to establish a reasonable competitive position would require unusual superconductivity technology advances as reported last year. SAVAR program funds were diverted to the SMES program. Anticipated continuing improvements in thyristor ratings and expected increases in energy cost are possible factors that might give additional economic benefits to SAVAR in the future.

IV. SUPERCONDUCTING FAULT CURRENT LIMITER (SFCL) (Boenig, Chowdhuri, Rogers, Schermer, Weldon, Wollan)

The Power Electronics Laboratory of Westinghouse Research and Development Center approached

Los Alamos to cooperate with them on the development of a superconducting current limiter for a.c. transmission systems. The Westinghouse circuit was analyzed and a prototype current limiter with a room temperature coil was tested in the laboratory and found to function as predicted.

Several possible circuit improvements have been examined. One possibility would be the replacement of the superconducting coil by a saturable reactor. The reactor core is premagnetized by a control current in the control winding. The no fault bias current of the bias winding puts the operating point at the knee of the B = f (H) curve. When the fault current through the bias winding increases, the reactor becomes unsaturated and limits the fault current. The saturable reactor is to accomplish two objectives, namely, low losses during non-fault conditions and high impedance during fault conditions. This device is not too unlike a superconducting limiter devised by the British. Another possibility, to replace the diodes in the Westinghouse circuit by SCRs, shows promise as a solid state circuit breaker with current limiting characteristics. For this circuit, a smaller coil and a disconnect switch instead of a breaker can be used. If the SCR version of the current limiter is used, then the mechanical breaker is replaced by a reliable all solid state breaker. All these technical advantages must be weighed against the installation and operating cost of a more conventional current limiter.

The possibility of using a superconducting fault current limiter in electric arc furnace plants is being investigated. Contacts with three arc furnace plants in El Paso, TX; Pueblo, CO; and Stirling, IL were made. The current limiter inserted in the primary side of the furnace transformer could reduce short circuit current, reduce graphite electrode consumption, extend the life span of the main furnace breaker by reducing the frequency of breaker action, prevent electrode breakage, and reduce loss of operation time.

An economic and technological evaluation of the SFCL was completed. Tables III through IX give the results of that study. Table X gives the superconducting wire and cable characteristics. The diode circuit is that of Westinghouse and the SCR circuit is the Los Alamos modified circuit.

A study[2] performed for the Electric Power Research Institute (EPRI) by Westinghouse Electric Corporation examined resonant circuit fault current limiters with normal conducting reactors. The EPRI report gives costs in 1978 dollars for a 145 kV, 300 MVA current limiter which can be compared with the 138 kV, 287 MVA SFCL of this study. The preferred low loss circuits of the EPRI study at 15 kA peak let through current followed by steady fault current of 2.8 kA cost from $850 to 920 thousand. These same circuits cost from $760 to 1160 thousand for steady fault currents ranging from 2 to 4.4 kA after the peak let through current occurs. These 1978 costs should be inflated by 33 to 40% for comparison with the 1981 amounts listed in Table IX for the 138 kV circuits. On this basis the SFCL SCR circuits cost close to the same (33% factor) or show some real advantage (40% factor).

TABLE III

SFCL COIL PARAMETERS

Voltage kV, rms	Cycles	Circuit	Inductance mH	Length cm	Thickness cm	Turns	B_{max} T	Energy MJ
69	2	diode	330	55	5.2	680	2.5	2.6
138	2	diode	660	70	5.2	845	2.5	5.3
230	2	diode	1100	83	5.2	1000	2.5	8.8
69	0.5	SCR	85	35	5.2	430	2.5	0.7
138	0.5	SCR	165	44	5.2	545	2.5	1.3
230	0.5	SCR	275	52	5.2	640	2.5	2.2

TABLE IV

SFCL COSTS FOR ONE COIL AND CABLE

Voltage kV, rms	Circuit	Cable Length m	Coil Loss kJ	Cable $\$(10)^3$	Insulation $\$(10)^3$	Coil[a] $\$(10)^3$
69	diode	2350	12.4	23.5	6.8	147.8
138	diode	3716	19.6	37.2	16.5	213.6
230	diode	5215	27.5	52.2	31.6	344.8
69	SCR	946	5.0	9.5	2.8	59.8
138	SCR	1507	7.9	15.1	6.5	93.3
230	SCR	2091	11.0	20.9	12.4	129.4

[a] Includes superconducting cable and insulation.

TABLE V

POWER ELECTRONICS PARAMETERS FOR SINGLE PHASE SFCL

Voltage kV, rms	Circuit	Arrester Break-Away Voltage, kV	Number Diodes/SCRs	Protection Factor	Losses[a] kW
69	diode	75	64	1.54	83
138	diode	150	128	1.54	156
230	diode	190	208	1.50	247
69	SCR	75	80	1.57	143
138	SCR	150	160	1.57	276
230	SCR	190	256	1.51	435

[a] Includes 10 kW losses for bias power supply.

TABLE VI

POWER ELECTRONICS COSTS FOR SINGLE PHASE SFCL

Voltage kv, rms	Circuit	Bridge $\$(10)^3$	Bias Supply $\$(10)^3$	Arrester $\$(10)^3$	Breaker $\$(10)^3$	Total $\$(10)^3$
69	diode	60	25	5	30	120
138	diode	100	30	8	60	198
230	diode	180	35	12	100	327
69	SCR	100	25	5	10	140
138	SCR	160	30	8	20	218
230	SCR	290	35	12	33	370

TABLE VII

MYLAR* INSULATION FOR ONE SUPERCONDUCTING COIL

Voltage kV, rms	Circuit	BIL kV	Insulation Cost, $\$(10)^3$ Material	Labor	Shields	Total
69	diode	350	0.6	4.2	2.0	6.8
138	diode	550	1.6	10.1	4.8	16.5
230	diode	750	3.0	19.4	9.2	31.6
69	SCR	350	0.3	1.7	0.8	2.8
138	SCR	550	0.6	4.0	1.9	6.5
230	SCR	750	1.2	7.6	3.6	12.4

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*duPont trademark.

TABLE VIII

DEWAR, BUSHINGS, AND VAPOR COOLED LEADS FOR ONE COIL

Voltage kV, rms	Circuit	Dewar, $\$(10)^3$		Bushings $\$(10)^3$	Leads $\$(10)^3$
		Metal	Plastic		
69	diode	10.0	27.0	2.0	40.0
138	diode	16.0	43.0	4.0	40.0
230	diode	22.5	62.0	6.0	40.0
69	SCR	5.0	12.0	2.0	40.0
138	SCR	6.5	18.0	4.0	40.0
230	SCR	9.0	24.0	6.0	40.0

TABLE IX

SFCL OVERALL COSTS FOR THREE PHASES

Voltage kV, rms	Circuit	Total Cost, $\$(10)^3$	
		A	B
69	diode	1134	1185
138	diode	1590	1670
230	diode	2396	2514
69	SCR	915	936
138	SCR	1260	1295
230	SCR	1838	1883

A = total cost with metal dewar
B = total cost with plastic dewar

TABLE X

SUPERCONDUCTING WIRE AND CABLE CHARACTERISTICS

Wire	
Diameter, mm	0.5
Superconductor	NbTi
Number filaments	1250
Filament diameter, μm	10
Copper to NbTi ratio	1
Critical current at 4.5 K and 2.5 T, A	250
Critical current density at 4.5 K and 2.5 T, A/cm^2	$2.5\ (10)^5$
Cable	
First level, 6 Cu around 1 NbTi, soldered	
Second level, 16 first level in Rutherford lay	
Dimensions, mm	3 X 12

Full load losses for the EPRI resonant circuit limiter rated at 145 kV and 300 MVA are given as a function of steady fault current at about 0.07 to 0.14% of the throughput rating. Full load losses, based on Table V, are 0.16 and 0.29%, respectively, for the diode and SCR SFCL 138 kV, 287 MVA circuits.

The power electronics of the SCR circuits for the SFCL cost 60 to 80% more than for the diode circuits. Because the SCR circuits permit suppression of the fault current in one-half cycle instead of two, the superconducting coils are smaller and the circuit breakers are replaced by much less costly disconnect switches. The result, see Table IX, is that the SCR circuits have cost advantages of 79, 77, and 75%, respectively, at 69, 138, and 230 kV.

V. MISCELLANEOUS

A. Superconducting Coils for HVDC Transmission Lines (Boenig)

HVDC transmission lines usually have room temperature reactors connected in each line at each converter station. These reactors serve several purposes.

1. To decrease harmonic voltages and currents in the d.c. line,
2. To smooth the ripple in the direct current sufficiently to prevent the current from becoming discontinuous at light load,
3. To limit the short circuit current, and
4. To prevent commutation failure.

These reactors are room temperature reactors and usually have an inductance of 0.4 to 1.0 H, although lower inductance reactors have also been used. The steady state current in the d.c. line and reactor is on the order of about 2 kA and results in a stored magnetic energy of 0.8 to 2 MJ. The suggestion has been made to replace the room temperature reactors by superconducting coils to reduce the losses of the reactors. General Electric Company, a supplier of HVDC equipment, and several utilities, which operate HVDC lines in the U.S., were contacted to determine the electrical parameters of existing HVDC line reactors, especially the losses. The Pacific Intertie utilizes reactors, for example, with an inductance value of 0.4 H and 810 kW of losses at rated current. A superconducting coil could reduce the losses considerably.

B. SMES Stability Study

The final draft of the Westinghouse Subsynchronous Resonance Stability study was reviewed and corrections sent to Westinghouse to be incorporated in the final report which has been received.

C. Static Var Control Studies

Study contracts for static reactive power compensators for high voltage power systems with General Electric and Westinghouse were monitored. Satisfactory final reports were received from both companies.

D. Professional Committee Work

Chowdhuri participated in the first revision of IEEE Standard 518-77, particularly in the writing of the radio frequency interferences and attended the ANSI Committee 63 meeting in Boulder, CO as an IEEE delegate.

E. Geological Superconducting Survey Device

Thullen and Chowdhuri participated in a review of the geological superconducting survey device at the Richmond Field Station of the University of California to provide consultation on high voltage problems and on design of the superconducting magnet system. This was done on a reimbursible basis from Exxon, the project sponsor.

VI. PAPERS PRESENTED, PUBLICATIONS, AND REPORTS

1. H. J. Boenig, "SAVAR Prototype Experiments," Los Alamos National Laboratory document LA-UR-81-591, February 23, 1981.

2. J. D. Rogers, "Superconducting Magnetic Energy Storage (SMES) Program, January 1 through December 31, 1980," Annual Progress Report Los Alamos National Laboratory report LA-8777-PR (March 1981).

3. R. I. Schermer, H. J. Boenig, J. Dean, "30 MJ Superconducting Magnetic Energy Storage for BPA Transmission Line Stabilizer," 7th International Conference on Magnet Technology, March 30 through April 3, 1981, Karlsruhe, Germany; Los Alamos National Laboratory document LA-UR-81-939.

4. R. D. Turner, J. D. Rogers, "30 MJ Superconducting Magnetic Energy Storage for Electric Transmission Stabilization," 16th Intersociety Energy Conversion--Engineering Conference, August 9-14, 1981, Atlanta, GA; Los Alamos National Laboratory document LA-UR-81-1535.

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