TITLE: 30-MJ SUPERCONDUCTING MAGNETIC ENERGY STORAGE FOR BPA
TRANSMISSION-LINE STABILIZER

MASTER

AUTHOR(S): R. I. Schermer

SUBMITTED TO: Applied Superconductivity Conference,
University of Wisconsin, Madison, WI,
October 19-23, 1981

University of California

By acceptance of this article, the publisher recognizes that the U.S. Government retains a nonexclusive, royalty free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes.

The Los Alamos Scientific Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy.

LOS ALAMOS SCIENTIFIC LABORATORY

Post Office Box 1663 Los Alamos, New Mexico 87545

An Affirmative Action/Equal Opportunity Employer

**30 MJ SUPERCONDUCTING MAGNETIC ENERGY STORAGE
FOR BPA TRANSMISSION LINE STABILIZER***

R. I. Schermer

**Los Alamos National Laboratory
Los Alamos, NM 87545**

ABSTRACT

The Bonneville Power Administration operates the transmission system that joins the Pacific Northwest and southern California. A 30 MJ (8.4 kWh) Superconducting Magnetic Energy Storage (SMES) unit with a 10 MW converter can provide system damping for low frequency oscillations. The unit is scheduled to operate in late 1982. Progress to date is described. The coil is complete. All major components of the electrical and cryogenic systems have been received and testing has begun. Computer control hardware is in place and software development is proceeding. Support system components and dewar lid are being fabricated and foundation design is complete. A contract for dewar fabrication is being negotiated.

INTRODUCTION AND SUMMARY

The Pacific Northwest and southern California are part of the Western U.S. Power System and are connected by two 500 kV, ac-power transmission lines, collectively referred to as the Pacific AC Intertie and one $\pm$ 400 kV dc-transmission line, the Pacific HVDC Intertie. These transmission lines are operated by the Bonneville Power Administration (BPA).

[*]Work performed under the auspices of the U.S. Department of Energy.

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, BPA installed equipment to modulate the power flow on the HVDC Intertie as a means of damping the oscillations. The maximum possible power modulation on the HVDC Intertie is 40 MW. 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 Los Alamos Scientific Laboratory (LASL) developed the concept of installing a small SMES unit for the purpose of providing system damping similar to that now available through modulation of the Pacific HVDC Intertie. The design parameters of the unit to be installed at the Tacoma Substation near Tacoma, WA, are summarized in Table 1.

Several descriptions of the project have appeared previously,^{1,2,3,4,5} and should be consulted for details.

Figure 1 is an isometric view of the 30 MJ system components in their planned arrangement. At the upper left of the figure is the ac-dc converter flanked by two, 6 MVA, transformers. The right half of the figure is occupied by the cryogenic system -- refrigerator, heat rejection subsystem, gas recovery subsystem,

TABLE 1

DESIGN PARAMETERS OF THE 30-MJ SYSTEM STABILIZING SMES UNIT

Maximum power capability, MW	10
Operating frequency, Hz	0.35
Energy interchange, MJ	9.1
Maximum stored energy, MJ	30.0
Coil current at full charge, kA	4.9
Maximum coil terminal voltage, kV	2.18
Coil operating temperature, K	4.5
Coil lifetime, cycles	10 ⁸
Heat load at 4.5 K, W	<150
Coil diameter, m	3.0

Fig. 1. Isometric view of 30-MJ system layout.

liquid nitrogen supply, and gaseous helium supply with each subsystem housed in its own trailer. Not shown is the control trailer, located immediately behind the cryogenic system trailers, that houses the mini-computers which permit the system to run unattended. All of the above subsystems have been assembled at Los Alamos for test under computer control prior to final assembly at Tacoma. The coil and nonconducting dewar will be shipped directly to Tacoma without a test at Los Alamos.

In the center of Fig. 1 is the coil, contained within its fiber-reinforced-plastic liquid helium vessel. The coil is complete and is waiting at General Atomic to be attached to the seismic mounting elements and the dewar lid. Dewar procurement has been delayed by contract placement difficulties; the dewar is the critical path item.

SITE PREPARATION

The SMES unit will be located at the Tacoma Substation of the BPA transmission system, which is situated in an industrial area several miles east of Tacoma, WA. A small masonry building on the site was originally proposed to house the system, but after an inspection by a team from Los Alamos and BPA, it was decided that a flat area, 300 ft x 300 ft, in the center of the substation will be much more suitable. The site should avoid complaints about noise, esthetics, or magnetic field effects. A liquid-nitrogen supplier is located within a few miles. The site has limited water, so that a closed-loop system must be used to supply cooling water for the refrigerator components.

The only problem with the substation is that it is manned only 4 hours per day. This led to an unanticipated requirement for automated control of the entire system. There are no sites available, however, at stations which are manned around the clock. BPA has argued, in addition, that any SMES system which operates commercially will certainly need a high degree of automation, and that a part of the present experiment is to solve such problems.

All the cryogenic, electrical and control equipment has been placed in location at Los Alamos, with all necessary interconnecting plumbing and electric power, control and signal cables. All of the interconnecting hardware will be usable at Tacoma without modification.

Foundation plans have been transmitted to BPA but no work has begun at the Tacoma Substation. BPA is responsible for providing 13.8 kV switchgear, A.C. and D.C. buswork and for pouring concrete to Los Alamos' specifications. Design work must begin shortly in order to meet a July 1982 installation date.

CONDUCTOR DEVELOPMENT

The final cable design for the 30 MJ coil is shown in Fig. 2 and specified in Table 2. This design has passed all planned mechanical and electrical tests and meets or exceeds all specifications. Details of conductor development and testing have been reported elsewhere.^{6,7,8} A stability test was run on a 7-m length of pre-production finished conductor. The sample was wound in a single layer on a special toothed form using chip-on-a-strip and support slats to simulate actual coil geometry as closely as possible. From the results, the finished New England Electric Wire (NEEW) conductor is expected to carry up to 8200 A at 2.8 T and recover if only one second cable goes normal and 7900 A at 2.8 T if all the second cables go normal.

The PDOF copper wire as re-annealed had a ratio of electrical resistance at 300 K to resistance at 4.0 K of 321 ± 25 , as measured on 21 samples. Conductor design was based on a ratio of 150, so the copper is much better than actually required. After compaction, the first subcable was annealed at 325° C for 2 hr.

Preliminary experiments had indicated that relatively small gaps in an insulating wrap on a cable were very effective in permitting heat transfer to the liquid helium. Mylar strip, 0.25-in. wide, 0.005-in. thick, perforated with two staggered rows of 1/16-in. holes on 1/8-in. centers, appeared to provide sufficient ventilation while simultaneously preventing accidental contact between second subcables. A series of experiments were done with such insulation. As a result, the advantage of

Fig. 2. Low-Loss cryostable cable for 30-MJ coil.

perforated strip does not overcome the additional expense of perforation and the fabrication problems produced by the lack of adhesive on the strip. Therefore, the final conductor employs unperforated, adhesive backed, 0.005-in. thick, 0.25-in. wide, Mylar tape wrapped with 0.040-in. gaps. Alternating current loss calculations show that a short between second subcables can be tolerated at an approximate rate of one short per one-hundred conductor twist pitches or about one short every 60 ft. Tests on production cable at NREW clearly show that shorts do occur but less frequently than this limit. At present there is no way to measure quantitatively the frequency of inter-cable shorts. To control ac losses, it is important that shorts not develop between second subcables during the coil lifetime.

The only significant cyclic load applied to the conductor is radial compression, that is, pressure normal to the wide face. Calculated maximum stress values range from 200 psi if $E = 1.3 \times 10^4$ psi to 420 psi if $E = 2 \times 10^5$ psi. Preliminary measurements made on actual 5 kA cable indicate a value of $E = 1.5 \times 10^5$ psi, so that a test based on $E = 2 \times 10^5$ psi should be conservative. Cyclic loading at 4 K can be conducted at a rate of 500,000 cycles per day, and a larger load must be used at 10^6 cycles to simulate the effect of 10^8 cycles. A study of existing data between 10^5 and 10^6 cycles for steel, copper, cloth-based-phenolic, and glass-based-epoxy indicates that a

TABLE 2
CABLE SPECIFICATIONS FOR 30-MJ COIL

A. Superconductor Composite Core	
Area of NbTi, mm ²	4.85×10^{-2}
Filament diameter, μ m	6.5
Number of filaments	1464
Strand diameter, mm	0.511
Cu to NbTi ratio	2.94:1
Twist pitch, mm, and direction	5.0; R.H.
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, and direction	13.5; L.H.
C. Second Subcable: Six first subcables around a stranded, insulated copper core	
Diameter, mm	4.11
Twist pitch, mm, and direction	34.9, R.H.
Insulation type	Mylar, adhesive
Insulation size, mm	0.15×6.4
Insulation pitch, mm, and direction	8.64; L.H.
D. Finished Cable: Ten second subcables around a Mylar strip	
Strip dimension, mm	15×0.25
Conductor dimension, mm	23.6×7.6
Twist pitch, mm, and direction	200; L.H.

stress multiplier of 1.5 should conservatively cover the worst case. Therefore, the test sample was cycled between a maximum stress of $1.5 \times 420 = 630$ psi and a minimum stress of $2/3$ this value.

The sample was a full-scale coil section, 4 turns high in the axial direction, 2 turns thick in the radial direction, and 4 in. long. All of the second subcables in seven out of eight conductors, were continuously monitored for inter-cable shorts. No shorts developed and no damage occurred for 1.1×10^6 cycles in liquid helium.

COIL DESIGN AND CONSTRUCTION

The coil was designed by General Atomic with significant input from Los Alamos Scientific Laboratory and was built by

General Atomic.⁹ Coil construction was completed in July 1981, ahead of schedule and under budget.

The coil will be immersion cooled in liquid helium at 4.5 K and will have an open wound construction very similar to that employed in existing coils. The unusual features of the coil are the very low heat generation allowed, despite the unusually short cycle time, and the very large number of operating cycles expected over its life.

Design Features

The magnet is a superconducting solenoid. It consists of twenty individual coils, each wound in double pancake fashion, stacked on top of each other and held together by 48 aluminum tie rods.

The basic dimensions are shown in Fig. 3 and the basic design parameters in Table 3.

Fig. 3. Magnet assembly.

TABLE 3

30 MJ COIL - BASIC PARAMETERS

Stored energy, peak	30 MJ
Peak current	4900 A
Peak magnetic field	2.85 tesla
Pulse amplitude	4000 A to 4900 A (20-30 MJ)
Design operating life	10 years
Design cycles	10^8
Peak emergency discharge voltage	7 kV
Ampere-turns	4.51×10^6
Coil type	Superconducting solenoid
Orientation	Vertical axis
Cooling	Liquid helium bath, 4.5 K (nominal)
Conductor:	
Material	NbTi/copper
Configuration	Rutherford cable
Coil Configuration	Double pancake modules (20)
Number of layers	40
Number of turns per layer	23
Winding I.D.	107.4 in.
Winding O.D.	133.1 in.
Coil height	47.7 in.
Total weight	37,800 lb

Each of the twenty coils consists of an inner support ring--a filament wound fiberglass-epoxy composite--the conductor, a stainless steel support strap, interturn insulator and interlayer spacer plates.

The stainless steel support strap is anchored to the inner support ring with several fasteners and interwound with the conductor to carry the hoop stresses and axial loads. Strap tension during coil winding is held to 1100 lb. This tension will give a preload sufficient to prevent the coil from lifting off the bobbin during energization.

An insulator strip, also providing coolant passages, is wound into the coil at both sides of the conductor (see Fig. 4).

A plastic ramp inserted at the circumference guides the conductor to the outside of the coil. The stainless steel strip is tied to itself and winding tension is maintained by an adjusting screw. There is plastic insulation between the two

Fig. 4. Single coil assembly, isometric view.

parts of the tensioning clamp to avoid a closed loop. The voltage drop across this connection is 8.75 volts.

There is no splice between the top and bottom layer of each double pancake. A perforated and grooved interlayer spacer plate is inserted between the top and bottom layer of each coil and also in between the coils.

The magnet is assembled, using twenty of the above-described double coil subassemblies stacked and aligned. It is held together by 48 aluminum tierods. Each pair of tierods connects an upper and lower plastic clamping beam, which provide the clamping forces to hold the magnet together. A stack of Belleville washers at the upper end of each tierod provides the necessary elasticity of the system to avoid overstressing the tierods during cooldown and operation. This is necessary because the tierods are

thermally insulated from the coil and will cool down first. In addition to these vertical clamping devices, spiral pins are driven through adjacent inner support rings to provide shear resistance during the design base earthquake. Installed in the cryostat, the magnet is supported by six hanger beam assemblies which are designed so that any three can carry the full weight.

The electrical connections between each of the twenty double pancake coils is made in a staggered pattern around the outside of the coil. Six inches of the cable are straightened out and each individual subcable is soldered to an individual subcable of the next coil with a 3 in. overlap. All ten connections are insulated from each other and clamped down on a splice plate.

The lead-in and lead-out connections are made in a similar way on top of the magnet. The lead entering the bottom coil is brought down the outside, well supported and clamped with an extra copper bar for additional stability in case of low helium level within the dewar.

The coil is natural convection immersion cooled at 4.5 K in liquid helium. The conductor is designed to facilitate intimate contact between coolant and copper strands. Channels, grooves and vent holes are provided in all plastic components to aid natural convection and removal of gases from inside the coil.

Analysis

Pulsing Losses. The operational pulsing loss in the coil is estimated to be 48 watts. The superconductor hysteresis loss is the major loss component (37 watts). The eddy current coupling loss in the conductor is estimated to be 9 watts. The rest of the pulsing loss arises from eddy current heating in the cable splices and other metallic components.

Fatigue Life Considerations. All components have been designed and analyzed to fulfill the requirement of 10^8 operating cycles at 0.35 Hz. An operating cycle is defined as changing from 100% load to 67% load and back up to 100% load.

Winding, Cooldown and Operating Stresses. Two key design criteria are: limiting the conductor hoop stress to 15,000 psi or less through stainless steel interturn support and assurance that the coil remains under radial compression under operational loading to avoid relative motion between coil components. A computer program was prepared to evaluate the conductor, support strap and inner support ring operational stresses.

COIL SUPPORT

At Tacoma, the 30-MJ system will be installed in a Zone C seismic region, with design accelerations of 0.24 g horizontal and 0.16 g vertical, based on a 135 yr earthquake. Because support of a superconducting coil against seismic loads had never been addressed previously, there are no existing conceptual guidelines and a significant engineering effort was required. Other large magnets are usually supported against the walls of a metal dewar, which is constructed piece-by-piece about the coils and welded closed. This approach is not suitable for a plastic dewar, which should be constructed completely without seals or joints to be free of helium leaks. The design of a stiff support system was necessary to suspend the coil freely within a separately constructed, open-mouth helium vessel. Numerical computations were performed based on the response spectrum technique and finite element codes and analysis rules developed for seismic studies on nuclear reactor systems. Coordination with General Atomic on the seismic design resulted in the pinning together of the coil inner support rings to increase the inter-pancake shear capability. The coil is suspended from the dewar lid by a system of six shear panels and six vertical struts. Fig. 5. The shear panel system

Fig. 5. 60-degree segment of coil support system.
View along radius from coil o.d.

has been designed to withstand a lateral load of 17,000 lbs per panel. Each vertical load strut has been designed to withstand from 20,000 lb tension to 7000 lb compression. Vertical and lateral loads are transmitted through the dewar lid to six external transverse support beams, which in turn rest upon six pairs of concrete pillars. The outer pillars are visible in Fig. 1. The entire support system has a lowest resonant frequency of 9.0 Hz, above the 3 to 4 Hz maximum in the seismic spectrum. Coil motion within the helium vessel is less than 0.060 in. in any direction, considerably less than the 1-in. minimum design clearances.

Fabrication drawings for all the support elements were prepared at Los Alamos. These elements have been procured and will be installed by GA under an extension of the coil construction contract.

A major component of the support system is the stainless steel dewar lid, which is also a complex interface for the coil electric and cryogenic systems. Lid design at Los Alamos extended into the late spring of 1981. Current scheduling calls for the lid to be completed in October 1981 and to be shipped to GA to facilitate alignment and assembly of the support components. The lid will then be shipped to the dewar vendor -- approximately in February, 1982 -- to be used in the dewar acceptance test and also as a template for the dewar flange bolt holes. Finally, the lid will be returned to GA where it will be permanently mounted to the coil supports. The coil will be shipped to Tacoma with the supports and lid attached.

Design of the concrete pillars and foundation for the coil and dewar was performed by a Civil Engineering group at the Los Alamos National Laboratory. In response to a Los Alamos request, BPA performed a soil test at the proposed coil location in their Tacoma, WA, substation. This test shows a 10 ft. thick surface layer of sand and gravel, underlaid with 5 ft. of peat, resting on a base of sand and gravel. Because of the measured high compressibility of the peat, an unsupported foundation would settle approximately 10 in., which would be unacceptable if the structure tilted so that the support pillars were no longer vertical. A decision was made to use pilings under the foundation to eliminate the settling. Structural drawings were prepared and transmitted to BPA.

ELECTRICAL SYSTEM

Fig. 6 shows the electrical circuit. The 2.5 kV, 5 kA line commutated, air cooled, 12 pulse, converter, consisting of two six pulse bridges, a bypass across each bridge and a 5 A dc breaker,

Fig. 6. Protective circuit for the 30 MJ coil.

will be connected at BFA to two 6 MVA, 13.8/0.93 kV transformers, which have already been tested and shipped to Tacoma. The converter was shipped to Los Alamos to be tested under computer control with a 1.5 MW resistive load. The converter has been run at its rated output current and has been HIPot tested to 10 kV. (We do not have the power available to run simultaneously at rated current and rated voltage.) Control logic has been tested by simulating anticipated faults such as ac line loss, line overvoltage, line unbalance, overcurrent, thyristor heat sink overtemperature, ground fault, loss of air flow, and blown fuse. All of the converter functions are already operable from the computer console, but the detailed software is still being de-bugged. Simultaneously, some minor hardware problems are being repaired in the converter.

An extensive computer analysis has been performed on the voltage distribution within the coil and on transient voltage produced across the magnet terminals when the dc breaker is counter-pulsed or when external sources, such as lightning, are present. The discussion refers to Fig. 6. Transients occur principally because the 0.9 Ω dump resistor, R, has a stray inductance, L_2 . L_2 is not well known and measurements yield values between 75 μ h and 100 μ h. In addition, the coil has a stray capacitance between terminals, calculated as approximately 170 pf. This capacitance leads to 3 MHz oscillations with a peak of 12 kV superimposed on a 1.8 kHz oscillation with a peak of 8 kV, all values calculated for the worst case with $L_2 = 100 \mu$ h. While actual voltage waveshapes

will be determined during a converter test with a 50 mH ambient temperature coil, the coil-ground insulation apparently should be capable of withstanding 12 kV. We are investigating the use of metal-oxide varistors to limit the voltage transient peaks to 7 kV or less.

Potential distribution along the coil was calculated using standing wave theory for an applied step function voltage of magnitude V_0 . The initial voltage distribution is nonlinear with a maximum gradient at terminal A, Fig. 6. The voltage across the first two turns is $0.0134 V_0$ and across the first two pancakes is $0.0585 V_0$ compared to, respectively, $0.0108 V_0$ and $0.0500 V_0$ for a uniform gradient.

CONTROL AND DATA ACQUISITION SYSTEM

The control and data acquisition (CDA) system is the central communications point of the SMES system. The tasks required of the CDA are divided among three Digital Equipment Corp. LSI 11-23 computers. The CDA provides the following capabilities to the SMES system: unmanned system operation for two weeks, data storage that will aid in analyzing system performance and diagnosing system faults, display system performance in a manner that facilitates system operation and maintenance, and, safe and reliable shutdown of the system during emergency conditions.

One of the three computers acts as a supervisor while the remaining two are data acquisition units for, respectively, the cryogenic and electrical systems. The supervisor engages in two-way communication with BPA or the local operator and adjusts system parameters as required. The data acquisition units continuously monitor the state of the various subsystems and report parameter limit excursions to the supervisor. Monitor and control functions were separated to allow a high data acquisition rate, if necessary. The CDA system will handle 350 digital and 200 analog signals.

All of the major components for the CDA have been received, checked and integrated into the system. All necessary intersystem cabling and interfacing is complete, including the optical couplers that feed signals to the computers. Control logic is in an advanced state of development.

VAPOR COOLED ELECTRICAL LEADS

Each of the ten second subcables of the conductor will have its own pair of power leads, providing approximately 200 $\mu\Omega$ of series resistance to ensure sharing of the 4.5 kA average current

among the subcables. Each set of ten leads will be made into a single mechanical package for convenience of manufacture and insulation. Conceptual design utilizes ten parallel copper tubes, 7/8 in. o.d. by 0.045 in. wall, flattened to provide a 0.040 in. gap through which helium gas flows. Sufficient phosphorus deoxidized tubing with a resistance ratio between 8.0 and 9.0 has been selected from laboratory stock to form these leads. The tubes will be electrically isolated from each other except at the room temperature end, where they join the busbar to the converter. Possible thermohydraulic instabilities among parallel flow channels will be eliminated by establishing the pressure drop in each channel with a warm orifice.

DEWAR VESSEL

The coil cycles continuously at a frequency of 0.35 Hz. To avoid eddy current heating, the liquid helium vessel will be made of 1 in. thick epoxy-fiberglass fabricated by using hand lay-up and room temperature cure. The vacuum vessel, fabricated of chopped glass fiber reinforced polyester, will be permanently bonded to the inner vessel to avoid problems associated with a demountable vacuum seal between the two plastic surfaces. A contract is under negotiation for dewar fabrication.

The helium vessel operates, during cooldown, at a pressure of 30 psia. The vessel, designed for a buckling pressure of 45 psia and a creep stress limitation of 5000 psi in the glass-epoxy during operation, is protected by spring loaded vent valves set for 33 psia and rupture discs set for 38 psia. The vacuum space is protected by a rupture disc set for 18 psia.

From previous experience, steady diffusion of helium is expected into the vacuum space. The vacuum will be continuously pumped by a 6 in. oil diffusion pump, located at the dewar, backed by a 22 1/s mechanical pump located at the refrigerator.

An open mouthed dewar vessel is highly unusual in the size needed for the 30 MJ coil. Because the vessel has a vertical surface area of roughly 50 m² and a room temperature lid with an area of 5.9 m² above the liquid helium, improper cryogenic design could produce excessive losses. Conduction from the top, the largest heat source, is composed of conduction through the helium gas, 191 W; through the vessel walls, 83 W; through the shear panels, 12 W; and through the vertical struts, 23 W. Fortunately, these contributions may be reduced by allowing the helium gas generated to flow upward in counterflow heat exchange. As a penalty, the heat leak appears as a liquefaction load on the refrigerator rather than as a refrigeration load. The actual reduction in heat leak depends upon the detailed dependence of

thermal conductivity versus temperature. Calculations give a predicted heat leak of 9.4 W and a boiloff of 13.3 l/h of liquid helium.

Radiation heating from the vessel walls and bottom will be reduced by the use of 100 layers of double aluminized Mylar superinsulation alternating with Nylon paper. The heat leak through the superinsulation is 20 W, calculated by using a conservative value of effective thermal conductivity $k = 1 \times 10^{-6}$ W/cm-K. Radiation from the lid, 30 W, reduced by the use of multiple reflecting surfaces, will be absorbed by heat exchange with the counterflow helium gas. Perhaps the most difficult problem will be to make radiation paths small around the many penetrations through the reflecting shields. A liquefaction load of 1.5 l/h is assigned to this heat source.

Power leads represent a liquefaction load when carrying current of 1.5 l/kA-h/lead, for a total load of 15.0 l/h. When not carrying current the load will be 8.0 l/h.

The background heat load, before the coil is energized, would appear to be 23 l/h plus 20 W, but these are not additive. Detailed calculations indicate that, when the gas boiled off by radiation is used to cool the power leads and conduction sources, very little additional heat leak results from these sources. The total background heat load is thus expected to be 30 l/h, including transfer line losses.

CRYOGENICS

The refrigerator is a CTI Model 2800 with three variable flow screw compressors, two Sulzer gas bearing turbines, and liquid nitrogen precooling, rated for 300 W, 90 l/h, or any linear combination. The unit was successfully tested both before and after installation in its trailer. It was damaged during initial shipment to Los Alamos, was repaired by CTI, and is now at Los Alamos again undergoing checkout.

A flow diagram of the cryogenic system is given in Fig. 7. Initial system cleanup will be accomplished by purging warm helium gas through the 12,000 liter free volume of the dewar until the air concentration drops to about 1%. Subsequently, one compressor will be used to circulate the mixture through several liquid nitrogen cooled dryers and purifiers until desired refrigerator start-up purity is obtained. The clean-up operation should theoretically take one hour.

Fig. 7. Cryogenic flow diagram of 30 MJ system.

Cooldown to about 150 K will use helium gas cooled by liquid nitrogen in the top heat exchanger of the cold box, while cooldown from 150 K to 4.5 K will involve the use of the turbine expanders. The process will take five days. Cold gas will be introduced at the bottom of the coil, while liquid helium may be introduced at either the bottom of the coil or at the top through a liquid-vapor separator. Calculations performed by GA verify that thermal stresses during this cooldown sequence will be acceptable.

During cooldown and operation, interception of the dewar background heat load by removing warm gas from the top of dewar is important. This fact was verified in an experiment using a CTI 1400 refrigerator and a dummy heat load designed to test the CTI 2800. The load consists of a 4 ft. diam. dewar with 500 lbs. of phenolic as a thermal mass, level sensors, heaters, and thermocouples. There was a dramatic increase in cooldown rate and a decrease in the temperature gradient above the phenolic when the dewar heat leak intercept gas flow was started. Further, this dewar heat leak makes it very difficult to produce liquid helium initially because the gas returning to the cold box is unusually warm and upsets the functioning of the coldest heat exchanger. One scheme to cure this is incorporated in Fig. 7. Once the dewar and coil have been cooled to 5 to 6 K by the refrigerator, the

initial charge of liquid will be obtained from a 500 l storage dewar. The boil off gas will then be cold enough to allow proper heat exchanger operation.

The gas recovery system, consisting of two 2500 psi compressors with 250 psi ballast tanks and associated plumbing and controls, has been successfully tested after being mounted in its trailer. The heat rejection system, consisting of a cooling tower and its peripheral assemblies has had all its components and controls tested separately and will receive a full load test under automatic control while cooling the resistive load for the full current converter test.

REFERENCES

1. H. J. Boenig, J. C. Bronson, D. B. Colyer, W. V. Hassenzahl, J. D. Rogers, and R. I. Schermer, June 1978, "A Proposed 30-MJ Superconducting Magnetic Energy Storage Unit for Stabilizing an Electric Transmission System," Los Alamos Scientific Laboratory report LA-7312P.
2. J. D. Rogers, H. J. Boenig, J. C. Bronson, D. B. Colyer, W. V. Hassenzahl, R. D. Turner, and R. I. Schermer, Jan. 1979, "30-MJ SMES Unit for Stabilizing an Electric Transmission System," IEEE Trans. on Magnetics, Vol. MAG-15, Jan. 1979, pp. 820-823.
3. R. I. Schermer, Dec. 1979, "The Stabilization Unit for Bonneville Power Administration," Proc. 1979 Mech. and Magnetic Energy Storage Contractors' Review Meeting, CONF-790854, pp. 10-19.
4. R. I. Schermer, Nov. 1980, "30-MJ Superconducting Magnetic Energy Storage for BPA Transmission Line Stabilizer," Proc. 1980 Mech. and Magnetics Energy Storage Contractors' Review Meeting, CONF-801128, pp. 255-262.
5. R. I. Schermer, Aug. 1981, "30 MJ Superconducting Magnetic Energy Storage for BPA Transmission Line Stabilizer," Proc. 1981 Mech. and Magnetic Energy Storage Contractors' Review Meeting, to be published.
6. M. D. Henke and R. I. Schermer, Nov. 1979, "Fabrication of Built-Up Conductors for Large Pulsed Coils," Proc. Eighth Symp. Eng. Probl. Fusion Res. IV, IEEE Service Center, Placataway, NJ, pp. 1743-1746.

7. J. D. Thompson, J. J. Wollan, B. Turck, and R. I. Schermer, "Losses in a Built-Up Conductor for Large Pulsed Coils", *ibid*, pp. 1739-1742.
8. R. I. Schermer, H. J. Boenig, M. Henke, R. D. Turner, and R. Schramm, "Conductor Qualification Tests for the 30-MJ Bonneville Power Administration SMES Coil," 1980 Applied Superconductivity Conference, Santa Fe, NM, Sept. 29-Oct. 2, 1980.
9. E. Hoffman, J. Alcorn, W. Chen, Y-H Hsu, J. Purcell, and R. Schermer, "Design of the BPA Superconducting 30 MJ Energy Storage Coil," *ibid*, Paper FA-34.