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TITLE: DESIGN AND OPERATION OF THE 30-MJ SUPERCONDUCTING MAGNETIC-STORAGE SYSTEM ON THE BONNEVILLE POWER ADMINISTRATION BUS.

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DESIGN AND OPERATION OF THE 30-MJ SUPERCONDUCTING MAGNETIC-
STORAGE SYSTEM ON THE BONNEVILLE POWER ADMINISTRATION BUS

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INTRODUCTION

A superconducting magnetic-energy-storage (SMES) unit is suitable for power-system stabilization because it can provide positive damping by absorbing or releasing energy with a relatively fast response time, 10 ms. In the fall of 1982, a SMES unit was installed at the Tacoma Substation of the Bonneville Power Administration as an experiment in monitoring, predicting and improving system stability. This paper reports principally on the system testing. Several descriptions of the project have appeared previously,¹⁻⁴ and should be consulted for details. Important parameters are summarized in Table I, which also compares design values with those achieved experimentally.

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TABLE I
PARAMETERS OF THE 30 MJ SYSTEM STABILIZING SMES UNIT

	<u>Design</u>	<u>Achieved</u>
Maximum power capability, MW	10	11.5
Maximum frequency, Hz	1.0	1.1
Energy interchange maximum, MJ	9.1	--
Maximum stored energy, MJ	30.0	38.5
Coil current at full charge, kA	4.9	5.4
Maximum coil terminal voltage, kV	2.18	5.4
Coil operating temperature, K	4.5	--

Figure 1 is a photograph of the 30 MJ system components installed at Tacoma. In the foreground of Figure 1, from left to right, are trailers housing: 1 MW cooling tower, 2000 psi compressors for gas recovery, refrigerator, liquid nitrogen supply, control trailer/workshop, and helium tank car. Beyond the control trailer is the ac-dc converter, flanked by two transformers of which only the buswork is visible. In the center background is the coil, contained within a liquid helium dewar and suspended from concrete mounting pillars.

Fig. 1. 30 MJ SMES installation at the BPA Tacoma Substation.

Much of the system was tested at the Los Alamos National Laboratory, and laboratory tests were performed on the conductor, power leads, and dewar; but the coil was not pre-tested and a number of questions were still unanswered when the project was moved to Tacoma in August, 1982. This paper presents experimental evidence that the system behaves very much in accordance with prior expectations and that no major problems have developed thus far to interfere with successful operation.

DEWAR

A. Construction

The cryostat is the world's largest, fiber-reinforced plastic, open-mouthed dewar. It is toroidal in shape, with a room temperature bore. There were concerns about helium permeation and outgassing of the vacuum space and about proper design to minimize heat leak.

The liquid helium vessel is made of fiberglass cloth/epoxy, hand fabricated using wet layup techniques. The larger diameter wall is 1.75 cm thick while the smaller diameter wall, which can fail by buckling, is 2.54 cm thick. Design buckling pressure is 3.1 MPa. The room temperature vessel is made of polyester/chopped glass and is roughly 4.3 cm thick. The vacuum seal between the two vessels is permanent, made by hand layup of fiberglass cloth and epoxy. The helium space is sealed by two O-rings, with the grooves machined into the steel lid. The vacuum space is continuously pumped by a 6 in diffusion pump. Thermal insulation is provided by 100 layers of double-sided superinsulation, interleaved with Nexus cloth, and applied as batts 10 layers thick. The aluminum on the superinsulation is divided into 1 cm wide strips to avoid eddy currents.

The 97 cm distance from the lid to the average liquid level is divided horizontally by five aluminum foil covered baffles, which have minimal openings for support structure, piping, and wiring to reduce radiant heat transfer. Gas that moves upward, extracting heat from the baffles and structure, is collected just under the lid at six circumferential locations. The underside of the lid is covered with a 5.1 cm layer of urethane foam.

The vacuum space exhibits little water adsorption. When backfilled with ambient air it pumps below 100 microns overnight. A helium leak detector was attached to the vacuum space during the initial liquid helium test at Lawrence Berkeley Laboratory. A helium signal of 4×10^{-6} cc/sec at room temperature decreased during cooldown to 4×10^{-9} cc/sec with 1000 L of liquid in the dewar. The vacuum space was valved off for one week during March,

1983, during a pumping system repair. There was no detectable pressure rise or loss in refrigerator performance. Thus, there are no detectable problems with outgassing or helium permeation.

We have had serious leaks at the inner O-ring seal on three occasions, and one location continues to leak gas at a rate equivalent to several liquid litres per day. We believe the leaks to be caused by differential thermal contraction.

B. Thermal Performance

On several occasions the dewar has been isolated from the refrigerator and allowed to vent freely to the atmosphere. The gas vent rate, monitored for up to eight hours, drops sharply for one or two hours and then is stable, with the power leads venting gas equivalent to 15 L/h and the dewar 12 L/h liquid. There are three major contributions to the dewar heat leak in this configuration:

1. Conduction down the coil supports, dewar walls, and, most important, down the helium gas column. It is vital that this heat be intercepted by upflowing helium gas. One dimensional computer calculations predicted a 13 L/h boiloff.

2. Conduction down the power leads, intercepted by upward gas flow. Calculated boiloff rate of 8 L/h for both leads at zero current assumed a lead of constant cross sectional area. The real leads have a very heavy section for the upper 20% of their length. Laboratory measurements yielding 15 L/h were performed in a lossy dewar and are thus as difficult to interpret as the present results. The measurements did show, however, that boiloff rate was independent of current up to 5 kA.

3. Radiation through the dewar sides and bottom, calculated at 28 L/hr for an assumed effective thermal conductivity of 1×10^{-6} W/cm-K.

These three effects are not additive. Calculations show that gas boiled off by radiation can be used to intercept the conduction loads on almost a one-for-one basis. Radiation cannot be separately estimated unless it is bigger than the total dewar plus-lead flow. In that case the dewar lid and lead tops would run unusually cold, contrary to observation.

The separate dewar and lead flows adjust to provide minimum total boiloff consistent with valve settings. Further, we have determined that a dewar vent rate of 12 L/h minimizes the refrigerator load. Thus, each separate vent rate must be close to minimum.

CRYOGENIC SYSTEM

The refrigerator is a CTI Model 2800 with two Sulzer turbines, three screw compressors, and liquid nitrogen precooling. The cryogenic system comprises, in addition, the cooling tower, gas storage tank car, and high pressure gas recovery compressors.

A. Operating History

A refrigerator acceptance test was performed at CTI and the entire cryogenic system was run for several weeks at Los Alamos National Laboratory into a test dewar. In principle the system has a capacity of 90 L/h or 300 W, but undersized turbine nozzle rings limit gas flow through the high pressure side of the cold box. We have produced, as a maximum, 60 L/h in a 500 L dewar. Thus, as of August 1982, it was not known if the system had sufficient capacity and reliability was questionable as the number 1 turbine had already failed twice.

Cooldown started in early November 1982 using liquid nitrogen pre-cooling of circulating helium gas, with the turbines isolated from the system. Maximum cooling rate was 2 K/h. This initial phase continued for two months, due principally to problems with water contamination. Finally, in January 1983, with the magnet temperature at approximately 120 K the turbines were started. The coil/dewar cooled to 4.5 K and helium liquefaction was begun; the dewar was finally filled with liquid from a highway transportable dewar. Since early February the system has been shut down once for cold box cleanup and three times due to electrical power failures.

B. Water Contamination

The refrigerator is equipped with a multipoint humidity sensor, two full flow molecular sieve dryers at the cold box inlet, and additional water adsorption capability in the charcoal filters of the compressors. Water vapor in the system arises from water adsorbed on the coil and dewar surfaces. An insufficient amount of this water was removed during the purging operation used to reduce air contamination. During the initial cooldown phase, gas returned to compressor suction had a dew point that tracked the coil temperature from about 280 to 200 K, at which value it stayed constant for two months, although the coil was below 150 K. Thus, 10 to 20 kg of water entered the refrigerator during the first week of operation, requiring a shutdown. By early December, 1982, gas entering the cold box still carried 10 ppm water, or 80 g/day. There was no evident improvement after the cold box was again pumped and purged, the dryers were bypassed, and the compressor charcoal was replaced. Humidity has slowly decreased with time to its present level of 0.2 ppm. System moisture should

slowly migrate to, and be trapped by, the liquid nitrogen heat exchanger. Our experience indicates that this exchanger will tolerate several kilograms of water without undue pressure drop, and a shutdown of a few hours without actually warming these exchangers permits the pressure drop to recover. Finally, it appears that the frost is entrained in the gas stream and migrates to the internal 77 K adsorbers, from whence it can be evacuated by routine cleanup procedures without shutdown.

C. Refrigerator Performance

With the refrigerator attached to the coil dewar in closed cycle operation there are three additional heat sources in the system:

1. A calorimeter heater located at the high pressure side of the Joule-Thompson (JT) valve can be used to introduce a known amount of power into the system for calibration.
2. When the coil is modulated, heat is deposited in the helium bath. Heat load at constant current is less than 5 W.
3. The helium transfer lines are liquid nitrogen traced and should have a heat leak of 5 W. There are two obvious cold spots at joints, however, that seriously affect system performance.

As the load on the system changes the refrigerator automatically adjusts its capacity to meet the changed load. Consider, for instance, an increase in coil modulation that results in a transient excess of dewar boiloff over liquefaction. System pressures rise, and because the compressor throughput is directly proportional to the suction pressure the liquefaction rate rises until it just matches the new boiloff rate. The mass of liquid drops imperceptibly and, in fact, the liquid level rises noticeably due to thermal expansion. System time constant is very long, due principally to the presence of 5700 L of liquid helium. Thus, without any operator intervention, the system follows slowly changing loads, ignores rapidly fluctuating loads, and operates very stably at constant load.

Figure 2 shows calibration data in the form of compressor suction pressure as a function of calorimeter power. All points were taken with at least a 12 h equilibration time. Non-linearity may be because system temperatures also change with heat input, leading to changes in turbine and JT valve efficiencies. Figure 2 represents only changes from equilibrium; an absolute calibration results if one accepts the advertized performance of 200 W at 1.29 MPa (18.7 psia) compressor suction pressure with full LN₂ flow. This suction pressure requires 35 W of calorimeter heat. The background heat load of 165 W is comprised of 90 W (27 L/h)

Fig. 2. Experimental results for refrigerator performance calibration. Compressor suction pressure vs electrical power applied to the internal calorimeter.

for the dewar and leads and 75 W of transfer line losses. Because the dewar/lead flow is completely satisfied, however, any small incremental heat input into the system can be observed.

We can obtain about 220 W at maximum compressor discharge pressure. With some safety margin, therefore, the system will tolerate 45 to 50 W of incremental, steady state power.

ELECTRICAL SYSTEM

The electrical system consists of two 6 MVA, 13.8 kV/0.92 kV transformers, each feeding a six-pulse, line-commutated bridge. The two bridges are connected in series and can provide a continuously variable terminal voltage between +2.2 kV to -2.0 kV. A bypass circuit across each bridge provides an alternate current path in case of bridge malfunctions. A dc breaker that inserts a 1Ω resistor in series with the coil is activated upon detection of ac line loss or a converter failure. The power level during coil charge/discharge can be regulated continuously by voltage control of the converter.

Series connection of two bridges allows us to obtain the desired real power output of the unit with the reactive power as a variable. For example, a real power output of 4 MW, with a coil current of 5 kA, must be achieved with a converter voltage of 800 V. This voltage is obtained as the sum of individual bridge voltages: 300 V plus 500 V, 100 V plus -200 V, etc. Each combination results in a different reactive power. Modulation with equal bridge voltages (parallel operation) gives maximum real power output, but produces reactive power modulation with twice the frequency. Real power variation with constant reactive power (constant Q mode) produces less confusing data. Also of interest is a mode with only reactive power variations and constant real power.

A. System Performance

At Los Alamos the converter was supplied with 95 V rms ac and was used to drive a resistive load at 5 kA. While this tested the cooling system and much of the control logic, it did not place the converter in its most vulnerable state, which occurs at a maximum SCR firing angle in the inverter mode.

At Tacoma, the electrical system has been used to energize the 30 MJ coil for more than 100 h covering the full range of expected operating demands. All emergency shutdown schemes have been repeatedly tested. In general, the system has worked well from the outset.

The tap changers on the input transformers are at their lowest setting, permitting a coil power modulation of ± 10 MW. The resultant waveforms have too much harmonic content for test purposes, so the converter is usually run at ± 8.3 MW with parallel bridge operation. With "constant Q" the system is limited to ± 4.7 MW. Now that minor system flaws have been removed, a 10% gain can be achieved by moving to the highest transformer taps.

COIL OPERATION

The predicted power loss, P , in the 30 MJ coil when modulated sinusoidally at frequency f and peak modulation power P_m is given by

$$P = 36 \left(\frac{P_m}{10} \right) + 16 \left(\frac{P_m}{10} \right)^2 \left(\frac{0.15}{f} \right) \quad (1)$$

with P in W, P_m in MW, f in HZ. The coefficients in equation (1) are derived from laboratory measurements⁵ on pre-production samples of 30 MJ conductor. The first term on the RHS, representing hysteresis loss, is based on measured critical current vs field curves, although such calculations were 20% lower than direct measurements on the superconducting wire. The second term represents the total contribution from eddy and coupling currents, including the effect of soldered, untransposed conductors at joints.

B. Cyclic Losses: Measurements

The only technique available for coil loss measurements is to note the steady state change in compressor suction pressure caused by coil cycling at fixed P_m and f , and compare the result with that shown in Figure 2. These measurements are tedious and error prone due to the long system time constant and the resultant uncertainty caused by slow diurnal drifts in system pressure and temperature. The minimum detectable power increment is about 3 W. Table II gives experimental results at two values of P_m and three different frequencies, compared to predicted results from Eq. 1.

C. Cyclic Losses - Bridge Ripple

At any constant current the bridge generates 1280 V peak-to-peak pulses at a 720 s^{-1} repetition rate. The ripple decreases with increasing bridge voltage; thus maximum heating is predicted at constant current. Simple hysteresis calculations predict 12 W of loss at constant current, but more detailed calculations invoking shielding predict a loss of less than 1 W. No loss attributable to ripple has been observed. The incremental loss at 5 kA, including lead heating, is less than 5 W; loss is unobservable below 4 kA.

E. Fatigue

TABLE II
EXPERIMENTAL AND EXPECTED RESULTS
FOR CYCLIC LOSSES

P_m (MW)	f (Hz)	Exper. Loss (W)	Predicted Loss (W)
8.4	1.0	54	34
4.4	1.0	32	17
4.4	0.4	33	19
4.4	0.2	34	21

The coil has undergone approximately 100 current cycles between zero and 4.5 kA, usually performed at full bridge voltage. Design assumed 10^3 such cycles. Further, the coil has undergone approximately 2×10^5 cycles at maximum modulation, much of this at 4.2 MW between 0.1 and 1.0 Hz. Design was for 10^7 cycles at 10 MW and 0.35 Hz. We have thus barely begun the coil's design life.

It is possible that the extra observed loss is due to mechanical friction effects, which would mimic hysteresis loss. Such losses might increase as coil cycling proceeds, and would be revealed by a repetition of loss measurements at a future time.

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