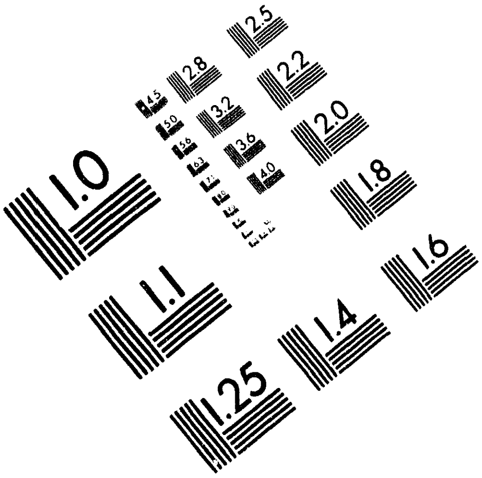

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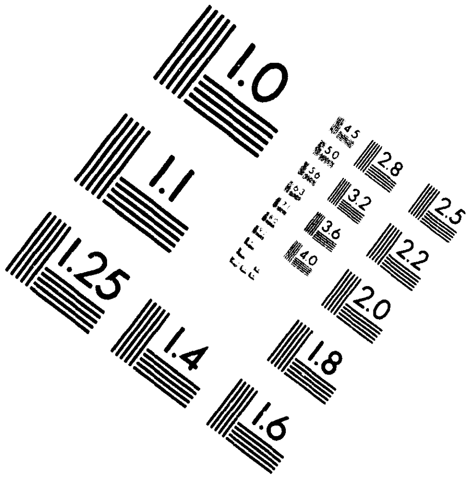

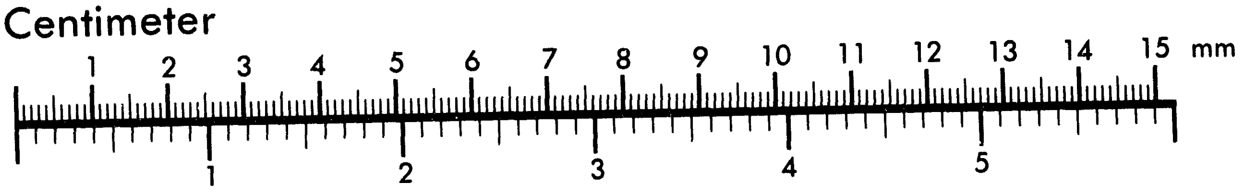

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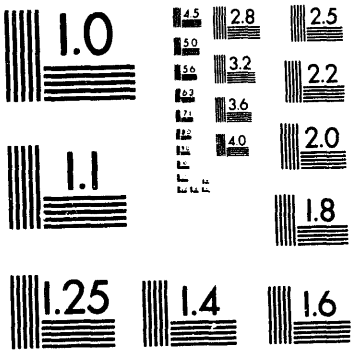

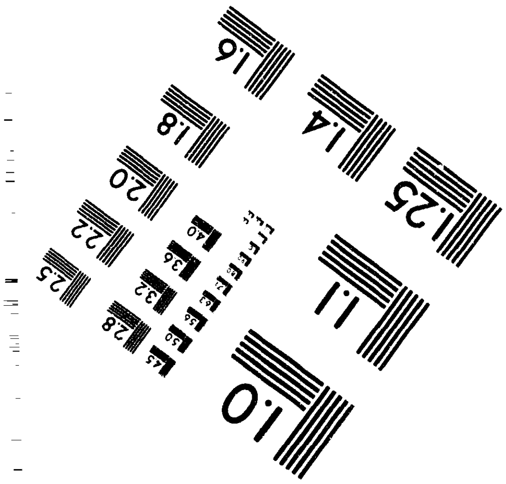

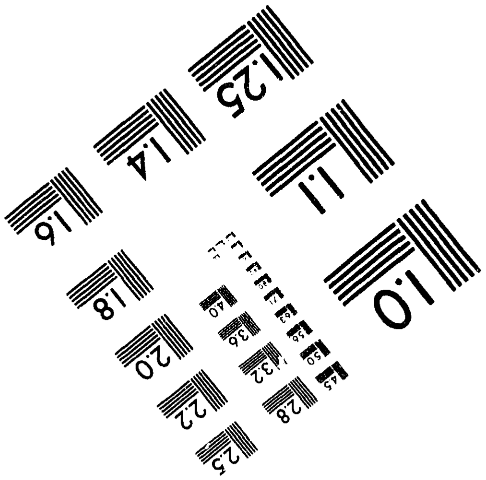

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Conf-930926--40

Test Results of Superconducting AC Magnets for Magnetic Refrigeration Experiment

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Abstract — Magnetic refrigeration can be achieved by cycling the magnetic field while leaving the magnetic material and the magnet stationary to avoid the large electromagnetic force problem. Two superconducting magnets were used to test this approach. First, we reconfigured a force-cooled cable-in-conduit magnet to operate with liquid rather than supercritical helium. Limited by the available power supply voltage, the fastest charging rate achieved was 10 s to 5 T. A second low loss magnet was acquired for operation to 7 T with a 6-s duty cycle. This is a bath-cooled magnet with potted sub-coils. The conductor is a 20-strand Rutherford-type cable with Ebanol insulation on each strand. This magnet quenched prematurely at 6.4 T. It was charge rate sensitive and the fastest charging rate achieved was 10 s to 5.8 T.

I. INTRODUCTION

Magnetic refrigeration - refrigeration based on the magnetocaloric effect - has been used for years as a technique to achieve temperatures below 1 K. More recently, the technology has been extended to refrigeration applications in temperature ranges from 1 to 77 K and near room temperature [1]. The applications near room temperature include heat pumps, refrigerators, and the upper stages of magnetic refrigerators for lower temperatures. Experimental prototype designs include having the magnetic material or the magnet in reciprocating or rotary motion and a static magnetic material with charging and discharging magnets.

Leaving the magnetocaloric material and the magnet stationary obviates the mechanical support problem associated with moving against large electromagnetic forces. However, since superconducting magnets are needed to increase the overall efficiencies of the system, the ac losses incurred in the magnet that operates at He-temperature due to the charging and discharging of the magnet can be prohibitively high. The advancement in the high temperature superconducting magnets holds promise to reduce this loss and make the stationary approach more attractive.

To prove the principle of the stationary magnetic heat pump approach, two superconducting magnets have been employed in separate experiments. A cable-in-conduit superconducting magnet built earlier was re-configured for the first experiment. A low loss ac magnet was acquired for the second experiment. This paper describes the pulse test results of these magnets and their performance in the magnetic refrigeration experiments.

II. CABLE-IN-CONDUIT MAGNET TEST SETUP

A superconducting magnet was built and tested [2], [3] successfully in the early 80's with NbTi cable-in-conduit (CIC) superconductor. It had a 95-mm clear bore and a length of 203 mm, big enough to produce a high field zone for a magnetic sample. The magnet produced 7.5-T central field at 4.2 K in forced-cooling by supercritical helium. It did not show training or any other instabilities. Although it was built as a dc magnet and the fastest charging test was 45 s to 7 T (limited by the available voltage of the power supply), it was believed that faster charging rates which is required for the magnetic refrigeration experiment would be possible with this magnet.

The magnet developed some leakage in previous tests, probably in the conduit overlap splices and the hydraulic connections. Some re-conditioning work was needed. The bobbin and the original potting can of the magnet were stripped off. A new stainless steel concentric can with a welded bottom disk was made to house the coil. The magnet was then re-potted with Stycast epoxy. The clear bore was increased to 104 mm. A new set of manifolds was built for the inlet and outlet of helium to the conductor. Parallel hydraulic paths were maintained for the magnet with additional paths added to reduce the longest (outermost) path length from 145 to 71 m. Table I lists the parameters of the re-furbished CIC magnet.

An existing 457-mm (18") bore dewar was just big enough to house the magnet. A clear through warm bore of 76 mm was added to the dewar to accommodate the room temperature Gd magnetic sample and its cooling column. Liquid helium from a storage dewar was supplied to the inlet manifold of the magnet. The outlet manifold was open to the magnet dewar to accumulate a bath of liquid helium. By adjusting the pressure on the supply dewar a good level of liquid helium in the magnet dewar was maintained. In this mode the CIC superconductor was cooled by a flow of liquid helium at pressures of up to 1.4 atm. Fig. 1 shows a sketch of the dewar, the CIC superconducting magnet, and the liquid helium cooling scheme used in the present test.

[*] Research sponsored by the AIC Division, Office of Industrial Technologies, U.S. Department of Energy under contract DE-AC05-84OR21400 to Martin Marietta Energy Systems, Inc.
Manuscript received September 20, 1993

TABLE I

CABLE-IN-CONDUIT MAGNET PARAMETERS

Item	Parameter
Superconducting strands	0.72 mm bare NbTi wire
Cable pattern	12 x 3 SC subcables around a 7 x 3 Cu-core
Cu/SC ratio	1.8 : 1 in SC strands 3.4 : 1 overall
Conductor conduit	8.56-mm OD 304 stainless steel
Void fraction	43%
Refurbished magnet dimensions	104 mm ID x 445 mm OD x 330 mm Height
Hydraulic paths	Series-parallel combination of layers
Minimum length	7.7 m
Maximum length	71 m
Maximum central field	7.5 T
Current at Maximum field	4.8 kA
Conductor current density	8.3 kA/cm^2
Stored magnetic energy	270 kJ

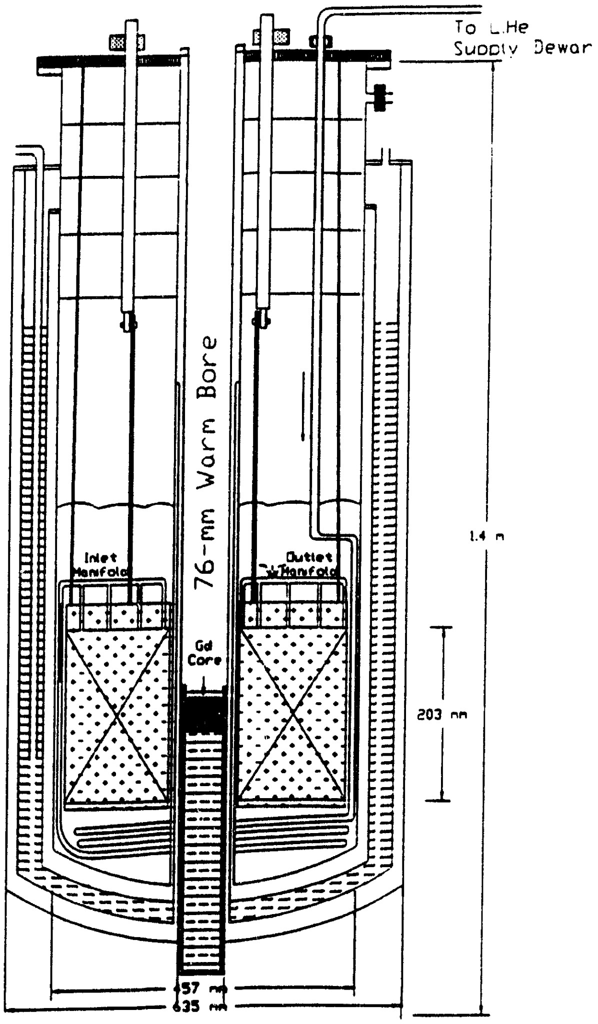

Fig. 1. L.He Cooling for the CIC Superconducting Magnet

III. PULSE TEST OF THE CIC MAGNET

The magnet ramp test was run at successfully higher field levels and charging rates. Maximum central field of 7.1 T was achieved in 18 s. Again, there was no quenching or any other ill behavior of the magnet during this series of test. The ramp rate was limited by the power supply voltage and the voltage drop in the long power leads used to connect the power supply to the magnet.

Repetitive pulsing of the magnet in triangular wave form was successfully run for more than 15 minutes at 10-15 s ramp-up time to 5 T, and 15 s ramp-up time to 7 T.

Attempts were also made to measure the ac losses during the repetitive ramp test. The helium supply valve was shut off and the liquid level in the magnet dewar was recorded to measure the thermal loss. The recorded loss rate varied from 17 to 24 ℓ/h. The background loss rate was about 16 ℓ/h, due mostly to the high current (5 kA) vapor-cooled leads. Earlier estimations of the ac losses in the magnet for these runs showed losses of 7 - 11 ℓ/h. Thus the measured total loss rates were reasonable, except that changes in the thermal conditions of the leads prevented a consistent comparison. The same ac loss calculation showed that if the ramp-up time were to shorten to 1 s, the loss would be prohibitively high.

During the ac loss measurement runs, the helium supply was shut off and the only connection to the helium bath was at the outlet manifold. Thus the CIC magnet was bath-cooled through 7.7- to 71-m long cooling channels inside the conduit. The fact that the magnet worked stably in this mode is another indication that the ac loss of this bare and Cu-matrix-strand cable-in-conduit magnet must still be reasonably small at ramp rates of up to 0.5 T/s. The 7-T run at 15-s ramp-up time ended with a quench after 15.5 minutes of cycling when liquid helium dropped to the level of magnet outlet manifold.

The magnet was subsequently used in a magnetic refrigeration test. An array of Gd plates housed inside a 50-mm diameter stainless steel tube was used as the magnetic core. This was stationed at the center of the magnet. The magnet was charged in trapezoidal wave form. Cycles of 60-s period were used in the test: The magnet was charged up in 15 s, the coolant bath in which the magnetic core resided was raised to its highest position in another 15 s while the field was held steady, the magnet was discharged in 15 s, and the coolant was lowered to its original position in the last 15 s. The cycle repeated again. Maximum field of 5 T and up to 60 cycles was run for the test. The magnet ran well, but the refrigeration experiment did not produce the expected result.

IV. ACQUISITION OF A LOW LOSS AC MAGNET

To improve the magnetic refrigeration experiment and to reduce the helium consumption, a new low loss ac magnet was designed and acquired from industry. The maximum field in the warm bore was limited to 7 T so that NbTi superconductor could be used. The field ramp duty cycle was specified to be from zero to 7 T in 1 s, followed by a 2-s hold. The field would then be ramped down to zero in 1 s and held for 2 s before starting the next ramp. This 6-s duty cycle would be continued for up to one hour.

Since ac magnet was not an established technology, a contract based on best efforts was awarded to a magnet manufacturer. The vendor chose to use a 0.577-mm diameter NbTi mixed-matrix wire as the basic strand for the conductor. The matrix around the filaments was CuMn and that inside and around the filament pattern was pure Cu. The strands were insulated with an Ebanol coating. A 20-strand Rutherford type cable was made into a 5.76 mm x 1.03 mm conductor. The estimated critical current @ 7 T, 4.2 K was 2800 A.

A bath-cooled coil with potted winding was chosen for the magnet. The conductor was wet laid-up wound into a 26 layers, 39 turns/layer solenoid. In order to get the ac loss heat out of the winding, axial cooling channels were provided in the winding pack. Thus the magnet was like formed from 5 concentric sub-coils with axial cooling channels between them. The finished magnet has the dimensions and other parameters listed in Table II.

TABLE II

LOW LOSS AC MAGNET PARAMETERS

Item	Parameter
Central field specification	7 T
Field ramp requirements	1 s up, 2 s hold, 1 s down, 2 s hold; repeated for 60 minutes
Field uniformity requirement	± 5% within a 38-mm diameter x 102-mm long cylinder
Superconducting strands	0.577 mm Ebanol insulated wire
Strand composition	NbTi + CuMn + Cu mixed matrix
Cu/SC ratio	1.97 : 1
Cable pattern	20-strand Rutherford cable
Conductor dimensions	5.76 mm x 1.03 mm
Winding & cooling scheme	Potted winding with axial cooling channels on every 4-5 layers
Winding dimensions	112 mm ID x 192 mm OD x 267 mm Height
Overall magnet dimensions	98 mm ID x 200 mm OD x 305 mm Height
Design current at 7 T	1680 A
Conductor current density at design field	28.3 kA/cm^2
Stored magnetic energy	80 kJ

V. TEST RESULT OF THE AC MAGNET

A warm-bore dewar similar to that shown in Fig. 1 was also purchased for the ac magnet for use in the magnetic refrigeration experiment. A clear through warm bore of 63.5 mm, a cold wall of 82.6-mm OD, and a helium reservoir ID of 305 mm were used to accommodate the magnet and the magnetic sample. Because of the pulsed magnetic nature of the operation, special care was taken to prevent large eddy currents in the warm bore tube, e.g. vertical slots were required on the radiation shield used in the warm bore vacuum space.

A generator set which can supply dc currents of up to 17 kA and voltages of up to 350 V was used to charge the magnet. Voltage signals from the magnet terminals and an approximate center tap were fed to a detection circuit for quench detection. An external dump resistor was used to protect the magnet in the case of a quench, although the very high current density magnet was calculated to be self-protecting.

Slow charging of the magnet was done first to test the design maximum field. At a ramp rate of 10 A/s, the magnet quenched prematurely at 1440 A. This produced a central field of 6.4 T, 9% lower than the design value. The quench current was only about 42% of the expected critical current of 3400 A @ 6.4 T, 4.2 K, although the conductor current density was quite high — 24.3 kA/cm^2. No training of the magnet was observed. Two more attempts ended with about the same quench current at ramp rates as low as 1 A/s.

Fast ramp test was successful at 130 A/s to 1310 A, i.e. 0.58 T/s to 5.8 T. At 260 A/s ramp up rate, the coil quenched prematurely at 920 A (4.1 T). Repetitive ramp cycles of 20 s up, 20 s hold, 20 s down, and 20 s hold to a top current of 1140 A (5.1 T) were successfully run for 10 cycles. An attempt for the same 60-s duty cycle to 1350 A (6.0 T) failed on the down leg of the first cycle. Fig.2 illustrates the performances of this ac magnet as compared to the expected critical currents.

The background loss rate of the magnet-dewar system was about 6 ℓ/h, due again mostly to the vapor-cooled leads (rated at 2 kA). The helium loss rate as shown in Fig.3 during the 60-s duty cycle run was indistinguishable from the background loss. The magnet showed that it was of low loss.

This magnet was then used in the second series of the magnetic refrigeration experiment. It performed well, but

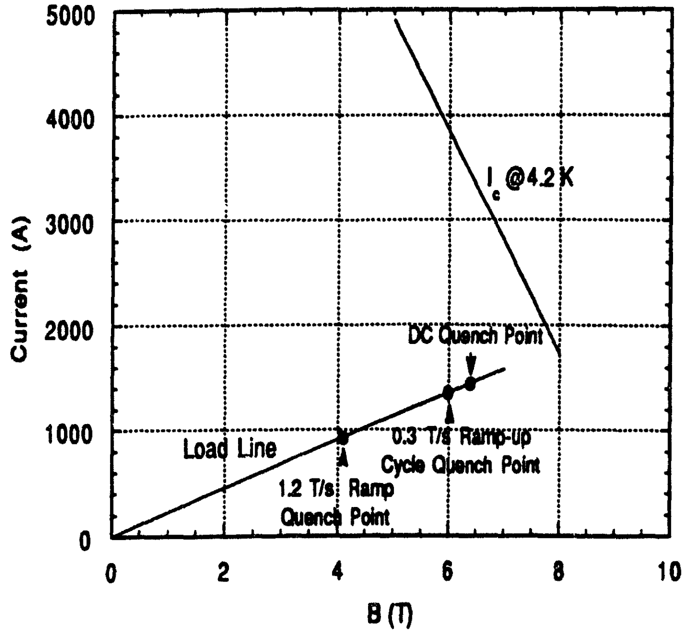

Fig. 2. Quench Points of the ac Magnet.

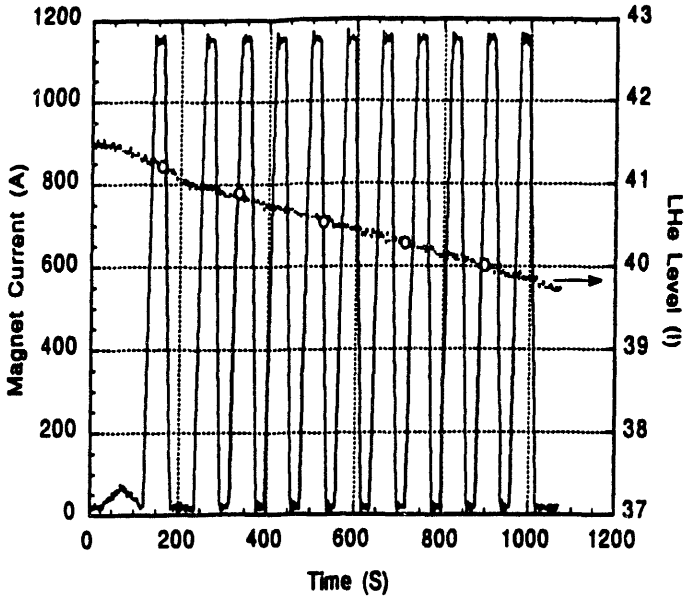

Fig. 3. 60-s Duty Cycle Run of the ac Magnet

the field was limited to 5.6 T and the duty cycle was limited to 60 s due partly to the ramp rate sensitivity of the magnet.

The premature quenching of the magnet at very slow charging rate might be a result of wire motion — in the strands of the cable or in the conductor of the sub-coils next to the cooling channels. The ramp rate dependence of the coil might be attributed to the ac losses and the poor current distribution among the strands due to the insulation on the strands. The quenching of the coil on the discharging cycle indicated that cooling was still insufficient despite the embedded cooling channels.

VI. SUMMARY

Two superconducting magnets were used in magnetic refrigeration experiments with a static magnetocaloric material while the magnet was charged and discharged cyclically. A cable-in-conduit magnet which was built earlier for dc operation was reconfigured to operate in a liquid helium bath. It ran well in the repetitive pulse mode and provided 5 T to the magnetic sample in 60-s duty cycle runs.

A newly acquired ac magnet quenched prematurely at 6.4 T, as compared to the 7 T design value. The quench field was also found to be ramp rate dependent, down to 4 T at 1.2 T/s. These results show that low loss ac magnet is still not readily available.

ACKNOWLEDGMENT

The authors are thankful to W. J. Kenney for his work in refurbishing the cable-in-conduit magnet and his help in running the experiment with that magnet.

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