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February 11, 2005

Dr. Peter Shirron, Technical Officer
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Greenbelt, MD 20771

Re:
Grant NAG-5-10713, Support of NASA ADR/ Cross-Enterprise NRA Advanced Adiabatic Demagnetization Refrigerators for Continuous Cooling from 10K to 50mK, Development of a heat Switch

Dear Peter:
Enclosed is the Final Report on then above referenced grant.

Sincerely Yours

Paul L. Richards

P. L. Richards
Principal Investigator

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February 9, 2005

Final Progress Report for:

Grant NAG-5-10713, Support of NASA ADR/ Cross-Enterprise NRA Advanced Adiabatic Demagnetization Refrigerators for Continuous Cooling from 10K to 50mK, Development of a heat Switch

5/1/01-4/30/04

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BACKGROUND

Mechanical heat switches are used in conjunction with sorption refrigerators, adiabatic demagnetization refrigerators and for other cryogenic tasks including the pre-cooling cryogenic systems. They use a mechanical actuator which closes Au plated Cu jaws on an Au plated Cu bar. The thermal conductance in the closed position is essentially independent of the area of the jaws and proportional to the force applied. It varies linearly with T. It is approximately 10mW/K for 200 N at 1.5K. In some applications, the heat switch can be driven from outside the cryostat by a rotating rod and a screw. Such heat switches are available commercially from several sources. In other applications, including systems for space, it is desirable to drive the switch using a cold linear motor, or solenoid. Superconducting windings are used at temperatures $\leq$ 4.2K to minimize power dissipation, but are not appropriate for pre-cooling a system at higher temperatures

This project was intended to improve the design of solenoid activated mechanical heat switches and to provide such switches as required to support the development of Advanced Adiabatic Demagnetization Refrigerators for Continuous Cooling from 10 K to 50 mK at GSFC. By the time funding began in 5/1/01, the immediate need for mechanical heat switches at GSFC had subsided but, at the same time, the opportunity had arisen to improve the design of mechanical heat switching by incorporating a "latching solenoid". In this device, the solenoid current is required only for changing the state of the switch and not during the whole time that the switch is closed.

An efficient heat switch design should give high conductance when closed, low parasitic conductance when open, and a minimal power dissipation over the cycle of operation, all with manageable levels of current drive and low mass. Design optimization depends on the proposed application. Simple mechanical heat switches, such as the one designed by the P. I. for the SIRTF ADR, close when current flows through the coil of a solenoid. A weak spring holds the switch open when there is no current. This mode of operation is appropriate when the time the switch is closed is short compared with the time when the switch is open. Solenoids can be optimized to minimize the drive current and the mass for a given conductance in the on-state. The current is minimized by using many turns of fine wire. Increasing the coil dimensions, however, increase the mass of the coil and the flux return. The flux return must be thick enough to avoid saturation at the required field and force. A solenoid, which is used far below its rated maximum force, will consequently have more mass than necessary.

Solenoid Selection

We have based our investigation on the commercial Lucas Ledex 5SF solenoid, whose performance is summarized in Figure 1. This solenoid was chosen because of the efficiency of the magnetic design and the availability of a series of similar solenoids, 4SF, 5SF, 6SF, which can provide a useful range of forces. The force in a solenoid increases rapidly as the magnetic circuit is closed. In order to insure that the heat switch jaws close before the magnetic circuit bottoms out, it is only practical to make use of the

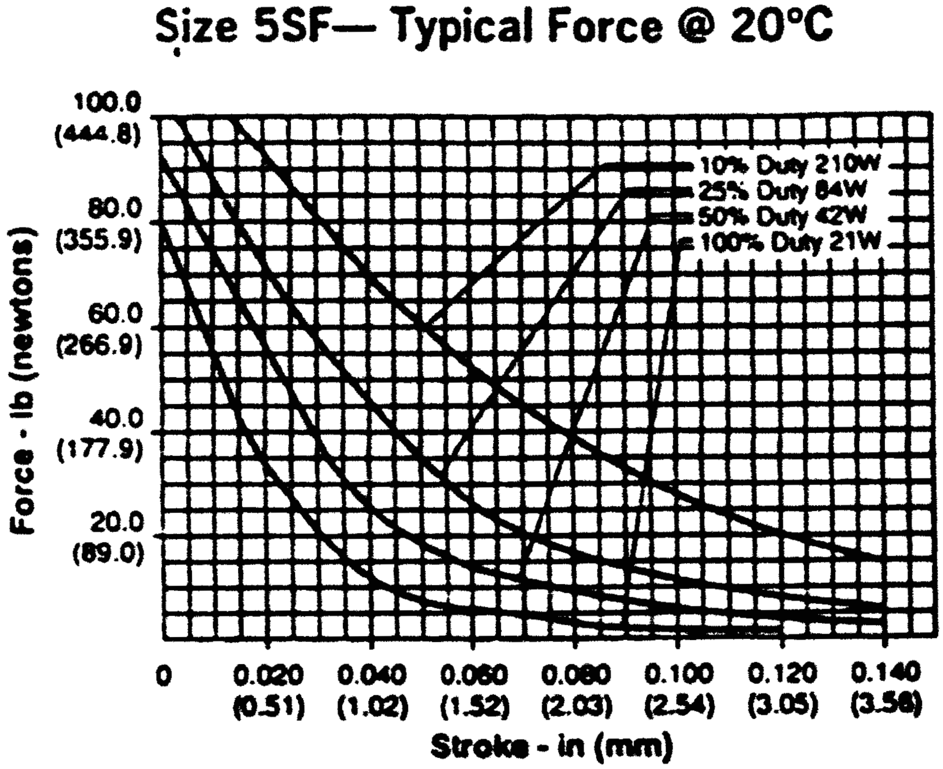

Figure 1. Dependence of the force on the gap in the 5SF solenoid for various values of current. The top curve corresponds to 2730 Ampere-turns, which is the maximum value for the Cu coil.

force with an opening in the magnetic circuit ≥0.1 mm. The 5SF solenoid is rated for 2,730 Ampere-turns for a limited duration, giving a force of 465 N with an opening of 0.1 mm. The solenoid mass is 255gm. The current limit is set by heat in the Cu wire. At LHe temperatures, the resistance of copper wire is reduced. Once heating begins, however, this advantage is rapidly lost. For low temperature operation, we replace the Cu coil by a superconducting coil purchased from Cryomagnetics. The bobbin is filled with ~ 4000 turns of 5-mil Cu-clad NbTi wire and has a rated current of 2A, giving a maximum of ~ 8000 Ampere turns. The performance of this superconducting coil has been verified over the temperature range $1.5 \leq T \leq 4.2K$. Table 1 shows the performance anticipated from mechanical heat switches based on the Ledex 4EF, 5SF and 6SF solenoids with copper and superconducting coils, using a linear extrapolation, which assumes that there is negligible saturation of the magnetic flux return. However, it was anticipated that the flux returns in the Ledex solenoids were designed for minimum weight, so that they could be assumed to saturate for field values above those produced by the rated number of ampere-turns. The switches would therefore give significantly smaller forces and conductances than the estimates in Table 1.

Solenoid	Mass (gm)	Current (A-T) warm	Force (N) warm	Current (A-T) cold	Force (N) cold	G at 1.5 K (mW/K)
4EF	170	2250	302	7564	<1015	<50.7
5SF	255	2730	465	8000	<1362	<68.1
6SF	510	3920	8000	12833	<26,189	<131

Table 1. Specified performance of several Lucas Ledex solenoids with warm Cu coils (< 15 sec pulse operation) and extrapolated cold performance limit with the superconducting coil assuming no saturation.

In order to design optimized heat switches, therefore, it is necessary to either calculate saturation effects and/or measure them by measuring the forces actually achieved at low temperatures with the strong fields from superconducting coil. However, relatively simple room temperature measurements can be used to guide solenoid design, because the properties of metallic magnetic materials are not very sensitive to temperature. The permeability of the mild steel flux return is known to be relatively independent of temperature. The vendor of the NbFeB permanent magnets used for the latching solenoid had no information on their magnetic properties at low temperatures. It can be guessed from the theory of magnetic metals that they would not show the strong temperature dependence characteristic of some ferrite magnets. A pull test to separate two such magnets showed the same force to 10% accuracy at 4.2K as at 300K

Test Procedures

It was decided to instrument for force measurements and to test solenoid performance, both at room temperature and at 4.2K, A piezoelectric quartz crystal load cell Type 9212 and charge-integrating amplifier Type 5010 were purchased from Kistler Inc. to measure forces. This cell is rated for operation down to 77K. Apparatus was constructed to provide known forces to the load cell immersed in LHe at 4.2K, by means of weights and a push rod. The calibration provided by Kistler was verified. The load cell output was shown to be reproducible and linear at 4.2K, with a small change in sensitivity. This change was ascribed to the temperature dependence of the piezoelectric coefficient of the crystalline quartz used in the Kistler cell. Using this apparatus, the dependence of force on gap and current given in the specification sheets for the 5SF solenoid at room temperature was verified to 10% accuracy.

Latching Solenoid

The solenoid current and power dissipation over a cycle of operation can be reduced by the use of a latching solenoid. There is some mass penalty due to the permanent magnet and the larger size of the flux return. A search was made for commercial latching solenoids in hopes that the requirements could be supplied by an existing design. Such solenoids are typically used for electronic switching and do not have enough force for most heat switch applications. The most promising device located was the SH1LF 1240 permanent Magnet Solenoid from Densitron Corporation, which has a magnet-only holding force of ~20 N with a 0.1 mm opening. A group at Cardiff in the UK replaced the ferrite magnet in a similar device with a much stronger NdFeB magnet to produce a low capacity heat switch. The force is probably then limited by saturation in the ferromagnetic flux return. Commercial latching relays typically have strong holding force at both ends of the travel. This is not required for heat switch applications and there is a mass penalty associated with the extra flux return.

We have designed and fabricated a one-way latching solenoid based on a modification of the Lucas Ledex 5SF. Figure 2 shows a drawing of the device, which uses a toroidal NdFeB magnet from Magnequench Inc. This magnetic material was chosen for its large coercive force. The performance of a heat switch based on this latching solenoid depends on the precision of the jaw assembly, which sets the throw required for reliable operation. We assume a conservative throw of 1 mm. The cold solenoid coil must then produce enough force to open the switch when starting from a 1 mm gap in the solenoid magnetic circuit. The gap in the latching magnetic circuit is adjustable with the minimum useful value of 0.1 mm. Larger values can be used to adjust the effective strength in the permanent magnet.

Design of Switch Contacts

An important feature of latching solenoids, such as the one described above is that the force available for a given design decreases rapidly with the throw. The throw required to reliably open and close a heat switch depends on the precision of the mechanism and of the suspension of the vane. Lack of precision can lead to inadvertent contact. The minimum throw that can be safely used depends on how well the positions of the supports for the solenoid and the vane are known. For numerical estimates, we have adopted the conservative assumption that the relative positions are known to better than 0.5 mm, so that a throw of 1 mm is adequate. The heat switch designed by the P. I. for the SIRTF ADR used a symmetrical mechanism to provide jaws that clamp symmetrically on each side of an Au plated Cu vane. This switch has worked very well, but it is larger and more complicated than necessary. There is only one critical degree of freedom in the location of the vane relative to the Jaws. That is the position of the vane along the line joining the two jaws. We are now using the central rod of the solenoid as a single moving "jaw", to push a flexible bar into a fixed jaw attached to the solenoid body. In this design, the flexible bar is held away from the fixed jaw by a spring, and the separation is set by a Kevlar string under tension. The spring is extended and the string buckles when the switch is closed. We have produced a prototype switch with this design and gained considerable experience by using it in laboratory apparatus designed for another purpose.

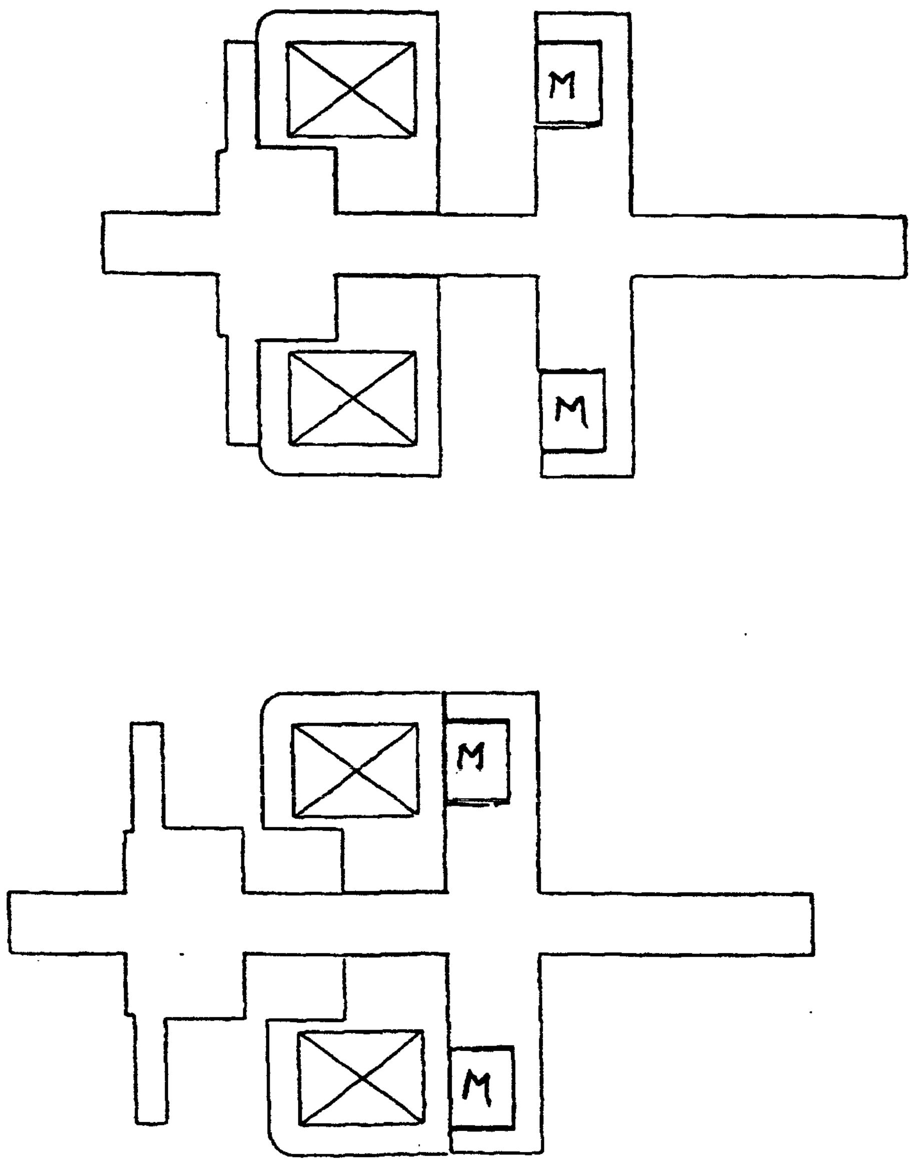

Figure 2. Functional cross-section of the one-way latching solenoid. All parts are symmetrical around the horizontal axis. The 5SF is at the left with the coil marked X. The permanent magnet marked M and its flux return are at the right. All other parts are of mild steel or other soft magnetic material. In the top drawing, the coil is excited and the shaft has moved to the right. In

the bottom drawing, the coil is not excited and the shaft is shown moved to the left. The throw is greatly exaggerated to show all parts clearly.

Design of Switch Contacts

Computer Simulations

Several computer codes are available which can provide a detailed analysis of the prototype solenoid. Given knowledge of the performance of the magnetic materials, the effects of saturation of the flux return can be calculated. The project employed an undergraduate with well developed computer skills to do a finite element analysis with the Poisson program developed at the Lawrence Berkeley National Laboratory. We had previously used this program to design the magnetic shield for the SIRTF ADR. After studying the program and doing some practice problems he produced the expected result that the design of the 5SF solenoid was reasonably efficient in the sense that the fringing fields were small at the rated current and showed significant saturation for the field values obtained with the superconducting coil. He then developed personal problems and left the University.

Third Grant Year

The tasks planned for the final grant year included using the apparatus developed to measure the force from the 5sf solenoid with superconducting coil at 4.2K as a function of current and compare the results with the existing simulations of saturation in the flux return. The measurements and simulations would also be done on the prototype latching solenoid. Based on this information, a paper would be written for Cryogenics on what we had learned about the optimization of solenoid driven heat switches. To meet this goal we recruited a student to continue the simulations and carry out the cryogenic tests. However, early in this year the P. I. developed a serious health problem that interfered with his supervision of the project. The P. I.'s major research projects, which were carried out with trained staff and senior collaborators were able to continue without significant problems. However, this small project, which did not have trained personnel was seriously impacted. The new student was able to make useful progress on simulating the latching solenoid without close supervision. However, he was not able to carry out the cryogenic measurements successfully. He was eventually transferred onto another project to make progress on his thesis research

The P I's health has finally returned to normal and plans to complete the project as outlined above. The timing will depend on locating a suitable person to carry out the limited number of cryogenic tests required. Institutional funds are available which could be used to cover the modest costs anticipated.