FLUX PUMPS AND AC SUPERCONDUCTING COMPONENTS*

R. B. Britton, F. J. Abbatiello, and K. E. Robins
Brookhaven National Laboratory
Upton, New York

Abstract

In connection with the construction of ac to dc converters or flux pumps for powering dc beam magnets, several techniques were developed that improve the performance of the ac inductance coils, transformers, and magnetic switches used in the pump. Details of the construction of these components will be discussed along with performance data on a 500 A pump built for a beam splitter magnet.

1. Flux Pumps vs an External Current Source

In the operation of a dc superconducting magnet, provision must be made for a dc current within the low temperature environment to energize it. This can be readily provided now with a conventional current supply (but with a negligible 1 to 2 V potential requirement) connected to the magnet with commercially available lead-ins.[1] This straightforward approach which can, of course, be guaranteed to work, turns out to be very inefficient for refrigerated (closed cycle) systems even when compared with a poor flux pump. This comes as a surprise since with an open cycle dewar system (where helium gas is allowed to boil off) one can operate at 1000 A conducted through two leads for a loss of only 2 W,[2] or approximately 3 liters of liquid per hour. The same system but with a refrigerator recooling the gas as it escapes hot from the leads will show 12 to 15 W equivalent 4^{o}K loss per 1000 A.[3] A flux pump to produce 5 W at 1000 A might require 7 W total input for an efficiency of 71%. The direct losses to the dewar, therefore, would be 2 W or a factor of 7 lower than a closed system using an external supply and conventional leads. It may be seen that even a poor pump of quite useful power level can power a magnet at a refrigerator load far below that created by the most efficient leads.

2. Pump Requirements

The present pump development at BNL was inspired by a need in the Accelerator Department for two similar low power units.

a) A 900 A, 5 W pump to power a pair of 3.5 in. bore x 42 in. long x 42 kG dipole - beam bending magnets.

b) A 250 A, 1 W pump to drive a double 1 in. x 2 in. bore x 48 in. long x 16 kG beam splitter magnet.[4]

The magnets were to be energized in about 1 hour. Since the magnets were to be used in the AGS external beam lines under large amounts of concrete shielding and continuous duty for periods of months to years, the design was approached with some caution and the incorporation of several types of redundancy. In brief, a prototype of the large pump was built and tested to the 700 A level, at which point work was stopped when the magnet itself was shelved. In the second case, a pump has been well developed and extensively tested in the laboratory to the 500 A level, but not yet completely tested in combination with the splitter.

3. Development Process

The author's approach to flux pump designs[5] has been to pursue 60 Hz ac operation, thereby exploring a new (in 1966) research area that was relatively untouched by others and in addition, avoiding the complexities of either a rotating input shaft as in the electromechanical pumps or of a low frequency pulse generator as in the GE - Buchold designs.[6] Ac pump development has subsequently occurred in several stages:

a) 1966 proved that a flux pump could be made to convert 60 Hz ac to dc.

b) 1968 developed the transformer-rectifier pump circuit.[7]

c) 1971 improved switch materials and switch coil design.[8]

d) 1972 developed pumps having lowered losses, magnetic shielding, and filtered, high current outputs suitable for driving beam magnets.

To satisfy the smaller pump requirements, a factor of two in current was needed over our previous best and also something had to be done about vibration which emanated from the pump during operation, a characteristic that did not seem compatible with either low helium losses or long life.

4. Component Development

Each part of the pump, Fig. 1, was isolated and developed as a unit when it was realized that analysis of total pump operation was too difficult. The development of the individual components will therefore be discussed first.

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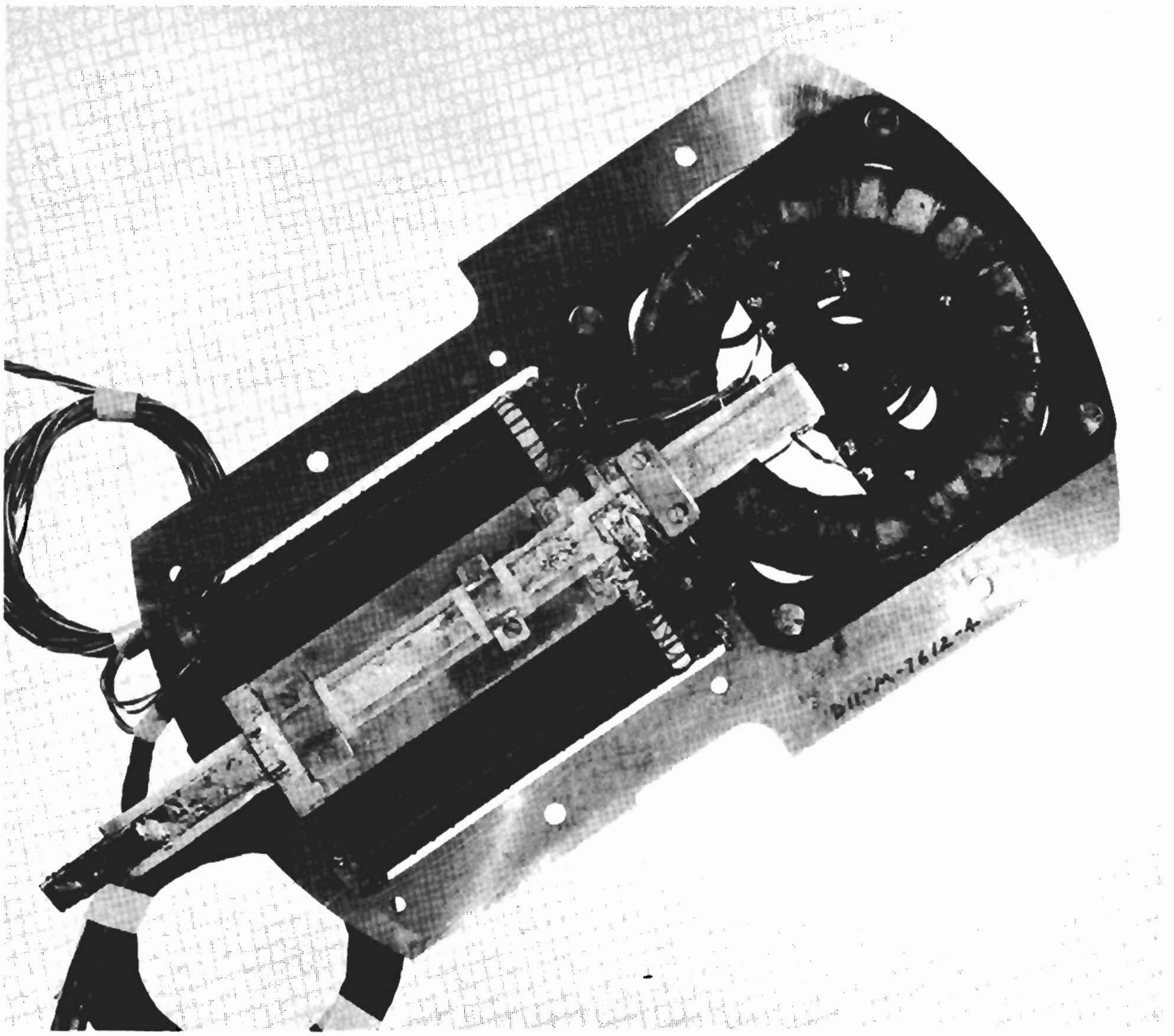

Fig. 1. 500 A Flux Pump

Switch Alloys

The first item of study was the superconductive element of the magnetic switches. The previous pump used Pb70-Sn30 solder wires 1/16 in. diam, and doubled or tripled to carry the current. A review of the Periodic Table disclosed that the soft, low melting point, heavy metals in columns IIB, IIIA, IVA, and VA - namely Al, Zn, Ga, Ge, Cd, In, Sn, Sb, Hg, Ti, Pb, and Bi has characteristics close to those desired in a switch element. Therefore, an alloy of them might prove even better and to this end, about 50 mixtures were prepared as wires 0.011 in. x 0.034 in. x 4 in. long and tested in background fields up to 50 kG. It finally appeared that from this metal group, all mixtures have a fixed relationship between critical field, normal state resistivity and melting point such that for a given H_c, to raise ρ_n one must reduce the melting point and the hardness. Therefore, a compromise was taken with Pb 50 - Sn 44.7 - In 5 - Ga 0.3 which has H_c = 1700 G at 4.2°K, $\rho_n = 4.4 \times 10^{-6}\ \Omega\cdot$cm at $B > H_c$ and a melting point of about 130°C.

There may also be good switch alloy combinations between hard, high melting point, heavy metals such as Ti, V, Zr, Nb, Hf, Ta, W, Re, etc. These were discounted in this study due to the difficulties of manufacturing them and of soldering to them.

Magnetic Coils

The next area studied was ac-SC coil design. A "standard" size coil was used having 1.75 in. o.d. and 5 in. length. About 1500 turns were needed on this form to provide a proper impedance match with the ac line. The goal was to minimize the losses in this coil volume at a field sweep of ± 2 kG about zero. The parameters studied included:

- Wire diameters - 0.0033 in., 0.0045, 0.0065, 0.008, 0.013 in.
- Wire materials - Nb-Ti single and multi cores in copper matrix
- Wire insulation - Formvar vs Polybondex
- Coolant channels - From none to maximum possible
- Single, double, and triple layers and random wound
- SS, glass and various plastic forms
- Glues, varnishes, etc. for bonding wire in place.

The lowest losses were achieved with single core wire having 0.67:1 Cu to SC ratio, "random wound" on a winding machine, baked after winding to "cure" a Polybondex-type coating on the wire and with a form having approximately 50% slotting around its circumference as well as radial perforations in the bottom of the slots. The form material was 1/8 in. wall glass fiber reinforced epoxy tubing which has a thermal contraction very close to that of the winding. The smallest wire gave the lowest losses but it was also the quickest to burn out if driven normal and, of course, carried less current. The next lowest losses were obtained with double layer smooth windings having 0.050 in. spaces every 0.25 in. along the coil axis. This latter winding was much more prone to burn out from overload. Single core 0.008 in. wire gave about half the losses of 0.008 in., 167 core wire, when measured at peak power but it is now felt that a wide variety of multicore materials must be tested before conclusions can be drawn.

Due to the high Q's obtainable in these coils, typically from 5000 to 500,000, it has not been thought that the addition of ferromagnetic cores to the magnetic circuits could hardly make an improvement. For this reason, we have not yet tested iron in any flux pump coils.

Typical losses as measured by calorimetric method are given in Fig. 2 for a coil having 1000 turns in a single layer of T48B wire with 0.0027 in. diam core, 0.0033 in. diam over copper and 0.0043 in. diam over the Formvar. At a peak current of ± 19 A (38 A p-p) it carried 600 W power, produced a central field of ± 1.86 kG, and had 0.08 W loss.

In all coils made for the pumps, a wire with 0.0065 in. o.d., single core, and Polybondex coating was used.

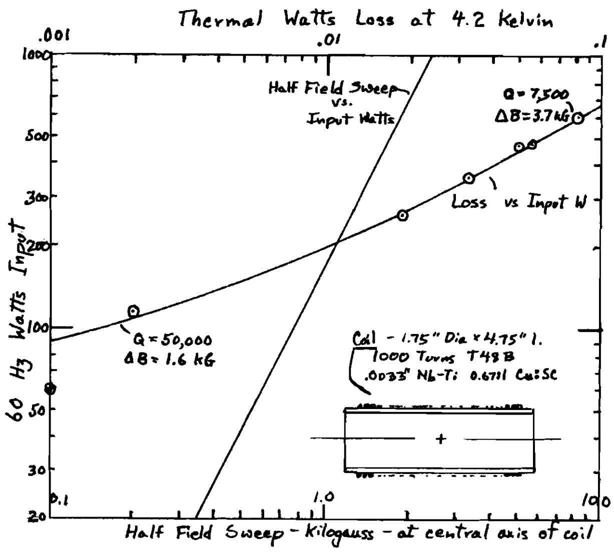

Fig. 2. Coil Losses vs Input Power

Inductors

Inductor design was quite simple for the flux pump since only 30 to 40 ft of conductor ($L \sim 0.3$ mH) was needed. For laboratory tests, small pie-wound coils were made from ½ in. wide by 0.006 in. thick Nb_3Sn ribbon made with 0.002 in. Cu cladding on each side. Insulation was either ½ in. mylar tape 0.005 in. thick or ½ in. masking tape. These coils with about 2.5 in. o.d. will readily carry 500 A dc with a high ripple content. Losses were not measured.

Permanent inductors for filtering were made in a toroidal shape to avoid stray fields. Forms were hollowed out, perforated, and grooved micarta.

They had a major outer diameter of 5 in. and a minor diameter of 2 in. A layer of glass fiber tape was applied with a heat curing resin[9] under and between all layers of ½ in. Nb_3Sn ribbon. Terminals were made with 0.030 in. copper sheet. Curing was done at about 175°C. Holes through the glass tape are necessary to allow coolant flow. No cold electrical or loss tests were made but room temperature Q tests disclosed shorts that had to be remedied. Cryogenic operation has been flawless.

Transformers

Air core transformer development was begun with a solid toroidal form of micarta. The major diameter was 8 in. by a minor diameter of 1.5 in. Fifty feet of ½ in. x 0.006 in. Nb_3Sn were doubled and used for the secondary which was wound first. Dry glass fiber tape was used for insulation between all layers. The primary was made of ¼ in. x 0.004 in. Nb_3Sn and the turns ratio was 4:1. Cooldown was very difficult because of the thick solid plastic. Tests, however, showed that up to 1950 W could be transformed with less than 1 W of loss to the helium and without driving the coils normal. Since these windings were not bonded in place, it is felt that the residual loss might still be considerably reduced. This transformer was obviously far too powerful so a series of transformers were wound on the smaller forms (5 in. x 2 in.) as described for the inductors. With considerable difficulty, a turns ratio of 100:1 was finally obtained (Nb_3Sn secondary, Nb-Ti wire primary) but power capacity was still approximately 1 kW and construction was tedious. For these reasons, the design was changed to concentric coils with a third shorted coil on the outside as a magnetic shield. Typically, the secondary has four turns of ½ in. x 0.006 in. Nb_3Sn wound on a 1.4 in. diam with a center tap, the primary is wound over it and contains 250 turns of Nb-Ti in a 1 in. length, the shield winding has 400 turns, an i.d. of 2 in. and a 1.5 in. length. The shield coil is shorted with a 10^{-4} Ω resistor that shunts ac while preventing accumulation of any large dc flow.

Magnetic Switches

The design of the superconductive magnetic switch requires the combination of an ac magnetic field, a steady or dc bias magnetic field, a rigid support for the superconductive element, good coolant flow, a close balance between the inductance of paralleled switch elements to maintain current sharing, and shielding of its own ac field from adjacent metals. These are not yet achieved in a complete pump but single switches have been tested that will carry 1300 A dc steady, 700 A rms ac (120° resistive - 60° cooldown - 180° superconductive per cycle) or closed with ~ 200 A dc current flowing through them. At present, performance is limited most by current imbalance, followed by insufficient cooling and last by inadequacies in the properties of the element alloy. The present topology of an element is shown in Fig. 3.

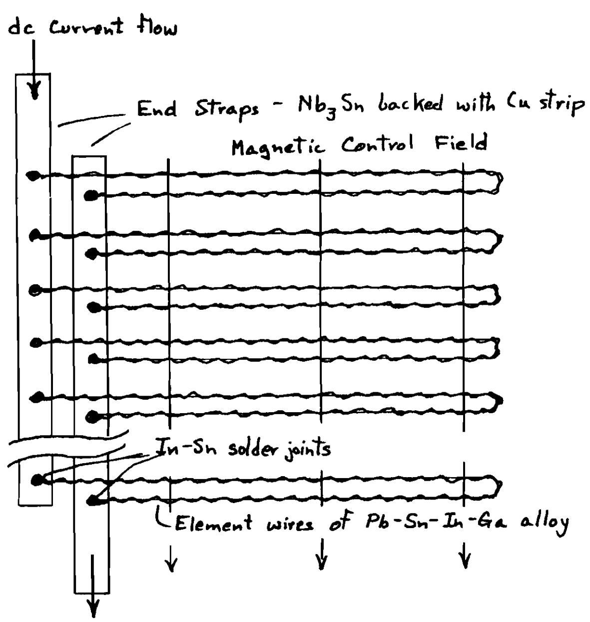

Fig. 3. Schematic Layout of Switch Element

The switch alloy described previously is first extruded as 0.020 in. wire, then drawn to 0.012 diam and finally twisted into a "cable" of three strands. This "cable" is glued into shallow grooves cut axially in the surface of a 1.75 in. o.d. x 6 in. long tube. Each cable makes a run down the tube and back in the adjacent groove. There are 24 cables 10 in. long each lying in 24 grooves. The cable ends are soldered with In-Sn eutectic solder to two C-shaped bands that encircle one end of the tube. The design is intended to minimize the total inductance of the switch as well as match the inductances of individual cables to encourage current sharing. A combination magnetic shield and magnet bias winding with 1000 turns is wound over the switch element and aids in holding the cables in place. This uniform winding is doubled-layered - the maximum number of close wound layers that can be adequately cooled - and wound in 0.25 in. sections spaced 0.05 in. to allow radial coolant flow to the element. The ac drive coil of the switch contains 1500 turns and is mounted on a 1.5 in. diam x 6 in. long perforated tube that slides inside the element. This double coil-switch design serves several purposes. First, it segregates ac and dc currents so that the dc bias field may be adjusted independently of ac sweep field. Second, the bias coil provides magnetic shielding for the ac fields, so long as it is shunted by an external capacitor or a resistor mounted at the coil as shown in Fig.4. Third, the coil combination produces high ac fields only in the radial space where they are useful, thereby reducing the switch drive power requirements.

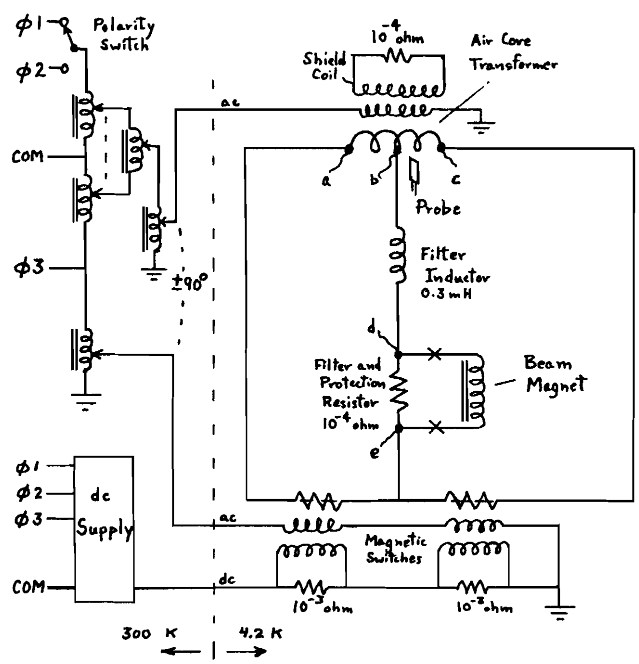

Fig. 4. Flux Pump and Control Circuit

Resistors

Resistors used in the pump for coil shunting and where a very low resistance but nonsuperconducting path is required are made from yellow brass sheet of various thicknesses. The low resistance ratio between 300°K and 4°K (about 3) means that the low temperature resistance is relatively stable and easy to calculate.

High Current Leads

Interconnections between high current components are made of ½ in. x 0.040 in. copper strip clad with Nb_3Sn. To keep vibration and noise down, these must be clamped well. Also, to keep stray inductances down, opposing current leads may be clamped together with thin insulation[10] in between the leads.

Drive Circuit

The control circuit for the present pumps, Fig. 4, operates from a three-phase line in place of the single-phase control used previously. This gives two advantages. First, it is easier to produce the ± 90° phase shift (by the combination of several autotransformers) that is required between transformer and switch current. Second, it is easier to generate low ripple dc for switch biasing.

5. Pump Operation

Briefly, the pump operates very much like a transformer-rectifier circuit. Ac current is applied to the transformer. Dc is applied to the two switch bias coils to produce about 1 kG of field on the elements. Ac is supplied to the other coil of the switches but in a sense such that one switch is raised in field to above 2 kG while the other is lowered to approximately zero. Therefore, one switch, Fig. 4, is driven about H_c (into the normal state) while the other switch is driven below H_c (superconducting). The rest of the operation is self-explanatory except that maximum output current is usually attained for a switch-on time of 120° which means the off or cooling time is 60° before the element must carry full load current. In an ideal circuit, the on time would be 180° and the cooling time needed would be 0°. An output curve (emf and power vs current) for the 500 A pump is shown in Fig. 5. It can be seen that peak power output occurs at approximately one-half of peak current.

Filtering of pump output is accomplished by the L-R combination shown in the circuit diagram, Fig. 4. The resistor is a brass plate of 0.040 in. thick x 2 in. wide x 6 in. long and has a value of 10^{-4} Ω while the inductor is about 0.3 mH. The resultant output voltage ripple is thereby reduced from approximately 100% to less than 5% at 250 A. In addition the resistor serves as a shunt across the magnet or load. The R value was determined by trial and error so that it protects the flux pump from excess energy absorption if both switches are magnetically opened and normalized for a long period of time.

Typical operating voltages for the pump when producing 250 A at 4 mV are 8 A - 10 V to the transformer, 7 A - 30 V to the ac switch coil, and 8 A - 0.1 V to the dc switch coil.

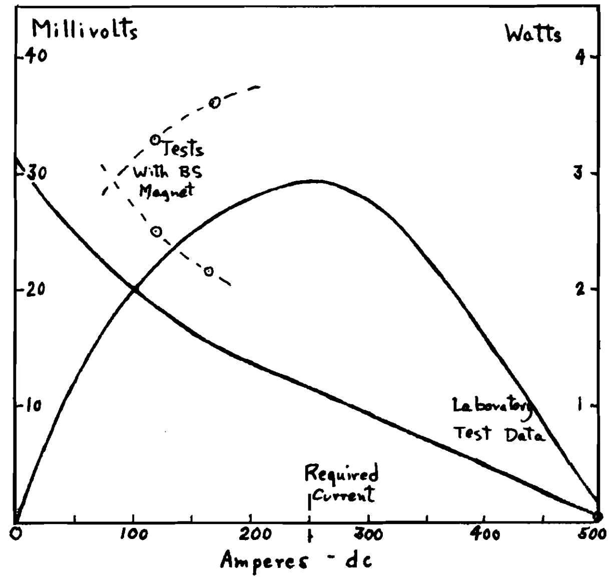

Fig. 5. 500 A Pump Output Curves

Pump output voltage is monitored by a millivoltmeter with center zero. This is connected directly across the splitter magnet to emf leads d and e.

Pump output voltage, if operated without either the inductor or the shunt resistor, was about ± 2 mV when producing 4 mV at 250 A. By adding the resistor, this was reduced to ± 0.8 mV and with the L-R combination, ± 0.2 mV.

A magnetic Hall probe is mounted inside the transformer to measure output current. The probe is operated by turning the pump off and then applying a dc bias of 12 A to one switch. A calibration curve which was made by applying external current to the pump is used to compare Hall voltage with pump current. In future designs, the probe will be designed to read current continuously by being inserted in a coil in series with one output lead.

6. DC to AC Power Conversion

It has been noted that by operating the switches as in ac to dc conversion but with the ac drive to the transformer removed, that 60 Hz ac power is produced at the terminals of the transformer. In other words, the pump can also operate as a dc to ac power inverter and convert magnet stored energy to high voltage ac available at room temperature.

7. Future Possibilities

The main holdback on power and efficiency of the ac to dc converter at present is the switch element. However, improvements can be made in the current sharing between individual elements in the geometry of the element (e.g., by the use of thin films in place of solid wires) and in the characteristics of the switch material used in the element.

All other components of the pump can be made virtually lossless. There also appears to be no theory to deny the possibility of inventing a perfect switch element or junction which could be switched from conducting supercurrents to a state of nearly infinite resistance.

Turning to more mundane sources of dc for driving superconducting magnets, it has been shown[11] that a thermoelectric couple (e.g., Ni vs Cu), if properly proportioned, can energize a 1.25 in. bore magnet to 47 kG (31 A) in approximately 1 hour. A "thermoelectric" effect has also been observed at superconducting junctions[12] which may indicate the possibility of lossless thermal to electrical energy conversion.

8. Acknowledgements

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