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C. D. Schwebel
*Mechanical Systems Engineer, Martin Company - Canaveral Division, Cocoa Beach, Florida*

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# SOLAR ENERGY CONVERSION BY THERMAL DESTRUCTION OF SUPERCONDUCTIVITY

C. D. Schwebel
Mechanical Systems Engineer
Martin Company - Canaveral Division
Cocoa Beach, Florida

## Summary

A method is proposed for converting solar radiation directly to electrical energy in space by utilizing the change of state of a superconductor. Apparatus is described whereby intermittent exposure to a concentrated beam of solar radiation causes a magnetic shield to fluctuate between the superconductive state (zero permeability) and the normal state (unity permeability) with resultant flux changes converted to electrical energy by conventional induction methods.

A thermal embodiment of Lenz's law, akin to the back torque of a conventional generator or the counter current in the primary of a transformer, is postulated. Such a reaction is demanded by energy conservation principles, although in the present case it can be exerted only against an input of purely thermal energy.

In a heat engine working between heat quantities represented by intercepted solar flux at the upper limit and the black cold of space at the lower limit, a theoretical thermal efficiency in excess of 99% is possible. In order to realize this phenomenal efficiency in a heat engine with a radiator of practical size, a closed compound cycle is proposed in which a portion of the power output is used to drive a refrigerator. By compounding the cycle the net thermal efficiency is reduced but the effectiveness of the system remains unchanged, provided only that a part of the output of the converter be utilized in the cooling of other cryogenic devices such as superconductive delay lines, lasers, IR sensors etc., the balance being available for general purposes. The heat extracted from all cryogenic equipment, including the converter itself, can then be radiated away at a temperature high enough to benefit from the fourth power law.

A practical form of the converter is described, with particular reference to the problem of eddy-current losses, which are unusually severe at very low temperatures.

## Introduction

Superconductivity has many potential applications in space technology. Long regarded as remote and forbidden territory, the superconductive state is now being investigated routinely in many laboratories. From these investigations have come some remarkable devices: the cryotron, a tiny ultra-fast computer element; the superconductive electromagnet, capable of producing fields of hundreds of thousands of gauss in a magnet weighing pounds instead of tons; the superconductive delay line which operates without loss, and the frictionless gyro bearing spinning on a reflected magnetic field. In addition, many components such as IR sensors, lasers and masers benefit from the low temperatures associated with superconductivity.

In space, where intense heat and intense cold co-exist, we could now make good use of Maxwell's Demon in separating galactic radiation from solar radiation by degree of attenuation. Lacking such fanciful means we must resort to brute force engineering to effect a separation. The advantages of sustained cryogenic temperatures in space are nevertheless so compelling that efforts are presently being made to develop a flyable helium liquifier. Machinery of this kind, however, imposes an inordinate demand upon the already hard-pressed electrical generating systems now in use or in immediate prospect. A refrigerator is basically a heat engine run backward. If it is powered by another heat engine operating in the conventional 30% area, very little backfield is left. This is especially true if the generator is also expected to furnish electrical power for general purposes. But if it were possible to endow the primary system with a thermal efficiency in the neighborhood of 90%, the refrigerator could run back up the scale, pay dividends in the form of cooling, and leave the primary system at a point where conventional conversion methods expect to begin. It is the purpose of this presentation to outline one method by which an answer to this problem in cryogenics may be found within the realm of cryogenics itself.

## Magnetic Properties of a Superconductor

A superconductor posesses unique magneto-thermal properties which may be applied to the purposes of energy conversion. In fact, heat and magnetism are so closely related in the change of state of a superconductor that their interaction has been the subject of extensive treatment in the literature. For example, it has been found that a latent heat of transition accompanies the change of state of a superconductor in the presence of an external magnetic field; latent heat effects are totally lacking when the transition occurs in the absence of an applied field. Since magnetism is directly related to electricity, it follows that a triple play is theoretically possible: heat to magnetism to electricity, all within a solid state medium. It is true that classical experiments in superconductivity performed with free magnetic fields involve only minute quantities of energy. But we are not going to concern ourselves with magnetic fields linked to nothing more demanding than the quiet air of a laboratory. All that is needed to produce a highly reactive magnetic field is simply to put it to work. The energy involved in the manipulation of a working magnetic field is worthy of attention from the standpoint of energy conversion even though its rowdy behavior may have caused it to be banished from the laboratory.

The property of a superconductor which appears to lend itself most readily to the purpose of energy conversion is that of zero magnetic permeability. When a magnetic field is applied to a superconductor an electric current is induced at the surface of the metal. The induced current encounters no resistance and hence continues to flow even after a state of magnetic equilibrium is reached. Moreover, the magnetic field accompanying the induced current opposes the external field in both intensity and polarity. The applied field therefore cannot penetrate the metal, except to a depth of the order of millionths of a centimeter.

This phenomenon is illustrated in a striking way by the famous floating magnet experiment, as shown in Figure 1. If a bar magnet is placed above a superconductor, the persistent currents generated by its approach give rise to an opposing magnetic field which precisely matches that of the magnet. The magnet will then float forever upon its own reflected field. The lines of force cannot penetrate the superconductor, yet each must form a closed loop. Therefore, these magnetic lines of force will be parallel to the surface of the superconductor and must also be somewhat compressed because they occupy a smaller cross-sectional area than they would normally occupy in free space. This compression of the lines of force, or in other words, intensity of the incident field, cannot exceed a certain critical value without causing breakdown of the superconductive state. For each of the superconductive metals at a given temperature there exists a critical magnetic field.

Figure 2 shows the relationship between temperature and critical field ($H_c$) for niobium. The metal niobium was chosen for illustration because it will maintain the superconductive state in the presence of relatively intense fields. It will be seen, for example, that at a temperature of 5 degrees K, corresponding roughly to the boiling point of helium, niobium will resist penetration by a magnetic field of 1800 gauss. Certain alloys such as niobium-zirconium will remain superconductive in the presence of much higher fields but do not exhibit zero permeability over their entire surfaces due to the inclusion of normal areas. As conductors of supercurrents such alloys are useful since the superconductive portions are of filamentary form and therefore maintain continuity. To serve as a magnetic insulator, however, a metal must be of the highest purity.

Suppose now that we bend the bar magnet of Figure 1 into the form of a "C" with the superconductive sheet interposed in the gap as shown in Figure 3. This exercise in topology has caused no change in the magnetic circuit except for a variation in the leakage pattern. The flux lines are still repelled by the superconductive surface.[1] The magnet is now a folded bar magnet but the reluctance of the circuit remains practically the same. Each pole is reflected from an opposite side of the superconductor but the lines of force are still parallel to the surface and they must travel almost as far to get home.

If the superconductive barrier were to be removed, we would then have a true "C" magnet with the greatly reduced reluctance of that configuration. This can be done in effect simply by heating a central area of the barrier until it returns to the normal state. The source of heat could well be a concentrated beam of solar radiation. Or it could be a laser beam carrying power from one of a series of generating stations on earth. In any case, restoration of the normal gap length will reduce the reluctance of the magnetic circuit by a very considerable factor and increase the flux density within the magnet by the same factor. If a coil is linked with this change in flux as shown in Figure 4, an emf will be induced in the coil and a useful electric current will be generated. Moreover, Lenz's law insures that the input energy will be required to match the output energy as it does in every other member of the family of electro-magnetic generators.

In order to function as a useful energy conversion means, the process must be repeatable. A series of pulses or cycles must be generated, preferably at a fairly high frequency. In theory this does not entail any difficulty since the superconductive phase transition is thermodynamically reversible. If the metal is cooled through a very small threshold temperature range it will return to the superconductive state. Of course, no energy can be converted during this phase change because none is received. Any attempt to impose a load upon the transition from normal to superconductive would undoubtedly block the transition. Such an occurrence has in fact been reported by von Laue, although the effect was accidental and very little significance was attached to it.[2] In Figure 4 a diode is shown in series with the output coil to prevent the development of a back mmf during the reverse transition. Lenz's law can work both for and against us; if it can demand energy when energy is available and eager to be converted, it can oppose a flux change equally as vigorously when nothing more is forthcoming than the exceedingly feeble free energy difference between the two states of the medium itself. It should be noted, however, that no power on earth or in space can stop the transition from superconductive to normal. If this were not the case, the superconductive state could be carried up to room temperature simply by threatening it with a job.

Even a free magnetic field relieved of the burden of an inductive load can interfere with the transition from normal to superconductive to a certain extent. In 1933, Meissner and Ochsenfeld established the fact that a superconductor will not only resist penetration by a magnetic field but will actually expel a field that is present during the transition, provided that the field strength is less than critical.[3] But the expulsion of an existing field is subject to imperfections in the form of flux entrapment, the configuration shown in Figure 3 being particularly susceptible. To facilitate the return of the metal to the superconductive state the field in the gap should be reduced as much as possible immediately prior to the transition. Since the output coil has in effect been open-circuited by the blocking effect of the diode, the field in the gap can be reduced or even eliminated during this phase of the cycle by a suitable shunting means at no greater cost than that of hysteresis and eddy-current losses. This kind of trade-off is not uncommon in energy conversion devices. The four-cycle gasoline engine, for example, goes through a very elaborate and energy consuming mechanical routine before returning to its single power stroke.

## Design Concepts

It is apparent that the rudimentary form of the device as shown in Figure 4 does not lend itself readily to cyclic operation. Even with the output coil open-circuited it would be difficult to remove the field in the gap of a permanent magnet without having to contend with some rather violent reactions. These reactions could be nulled out by complicated energy-recovery machinery, but it is always advisable to avoid machinery, especially in the space environment. However, before proceding to the description of a more sophisticated design, it would be well to isolate and analyze what may be called the power stroke of the cycle.

To do this it will be necessary to assume certain dimensions. Let the pole diameter be 1" and the normal gap length 2" as shown at $G_1$ in Figure 4. Using niobium as a superconductor at a temperature of 5 degrees K, the field strength in the gap must not exceed 1800 gauss. If the magnet is of Alnico V and is properly designed to operate at a point on the demagnetization curve at which the energy product is a maximum, the flux density within the magnet will be 10,500 gauss when the barrier is in the normal state. With the barrier in the superconductive state there will be no gap at all, properly speaking, but merely a complex flux leakage pattern. For purposes of calculation the leakage path can be represented by a hypothetical gap $G_2$ having a length of 6 1/2" based upon a barrier diameter of 6". The relationship between gap length and reluctance is highly indeterminate in any magnetic circuit. Normally about 90% of the reluctance of the circuit resides in the gap and hence any change in gap length has a profound and disproportionate effect upon the reluctance. To be conservative in this case, we will assume that the reluctance varies linearly with respect to gap length. The change in flux density varies directly with reluctance; therefore, a change in gap length from 6 1/2" to 2" under the effect of thermal destruction of a superconductive barrier will result in a flux change of 10,500 x 2/6.5 or 3240 gauss.

If this flux change is not put to work it represents very little energy; no more, in fact, than the energy represented by the original distortion of the free field. The distinction between a working flux change and one that merely exercises its little domains is forcibly illustrated by the flux changes occurring in the core of a power transformer. With the secondary open-circuited the core can be saturated by an exciting current of only about 3% of the rated load current. With an output current flowing in the secondary, the same flux change will transport an enormously greater amount of energy from the source. This device is in effect a transformer with an exotic heat-actuated primary and a conventional secondary.

Now let us see how much energy can be transported by a working flux change of 3240 gauss. Assuming a uniform change in flux, the resultant emf can be calculated by Faraday's formula,

$$E = \frac{\Delta B A N}{t} \times 10^{-8}$$

in which $\Delta B$ is the flux change in gauss, A is the area of the core in square centimeters, N is the number of turns in the coil and t is the interval of time in which the flux change takes place. A coil consisting of 150 turns of #18 wire is arbitrarily assumed. The time required for the transition depends upon the incident heat energy, the strength of the applied field and the thermal mass of the medium. In this case, using a film 1/10000" thick, a pulse duration of .001 sec. does not appear to be unreasonable, considering the fact that in a cryotron the transition occurs in about 15 billionths of a second. Substituting these values, we have

$$E = \frac{3240\ (5.07)\ 150}{.001 \times 10^{8}} = 24.6 \text{ Volts}$$

Since heat is normally absorbed at a uniform rate, there is reason to believe that the flux change will be uniform with time and that the output will therefore be pure d-c. In this respect the device is comparable to a homopolar generator.

Taking full advantage of the cryogenic facilities which this converter will presumably make available, the coil can be maintained at an average temperature of 127 degrees K by means of a liquid nitrogen jacket, assuming a temperature rise of 50 degrees. At that temperature its resistance will be about .09 ohm. The short-circuit output will then be

$$P = \frac{24.6^2}{.09} = 6.6 \text{ KW}$$

An output of this order of magnitude in a converter weighing only a few pounds indicates the possibility of an interesting future. Upon such a premise we may be justified in giving some attention to a more practical form of the device.

Figure 5 shows an arrangement having two gaps, each with its own barrier, 1 and 2, together with a branching system of ferrite pole pieces connected to a permanent magnet 3. The barriers 1 and 2 are alternately irradiated by means of a rotating mirror not shown in the sketch. Thus the reluctance of one branch increases as that of the other decreases, the flux changes being confined to the pole pieces which serve as cores for output coils 4 and 5. In this way the total flux in the magnetic circuit remains the same, although in each branch it may fluctuate through a range that could not be tolerated in even the most highly stabilized permanent magnet. The magnet 3 furnishes what may be called magnetic potential and is not affected by the flux changes in the pole pieces except perhaps to a very limited extent. The barriers 1 and 2 are maintained at superconductive temperature by contact with liquid helium. Control windings, shown at 6 and 7, are wound in such direction as to buck the magnetic flux in each branch.

We now have the makings of a cycle. Let us start with barrier 1 in the superconducting state at the beginning of the irradiated phase. Barrier 2 is in the normal state. Control windings 6 and 7 are open-circuited. Coils 4 and 5 are connected to the load. As barrier 1 passes to the normal state the reluctance of the associated branch is reduced and a current is induced in coils 4 as a result of the expanding field. The flux density in the opposite branch is reduced as the flux tends to equalize and a current is then induced in coils 5 due to the collapsing field in that branch. Coils 4 and 5 are of course wound in series aiding fashion. When barrier 1 has completed its transition to the normal state, or perhaps slightly before, all coils are open-circuited by a suitable switching means. During the time that the energy beam is moving from barrier 1 to barrier 2, control winding 7 is energized, removing the field from barrier 2 which then snaps into the superconducting state. This transition requires no energy whatever in the absence of a magnetic field and occurs in practically zero time. It should be noted that the current in control winding 7 is not working against any load other than the resistance of the coil and the reaction of the core material. It is comparable to the exciting current of an unloaded transformer and, considering its transient nature, probably represents an even smaller fraction of the total output. With the de-energizing of control winding 7 coils 4 and 5 are reconnected to the load through a solid-state commutator and the cycle is then repeated.

Solar energy is supplied in space at the rate of about $10^3$ watts/m$^2$. Taking as a goal the 6. 6 kilowatts of the power impulse of the prototype design which the improved form should provide almost continuously, a collector about ten feet in diameter will be required, allowing a collector efficiency of 75%. A concentrated beam 2" in diameter (to conform to the dimensions of the magnet gap) will then provide an energy flux of 270 watts/cm$^2$. This corresponds to the temperature, $T_1$, of an equivalent black body close to the superconducting surface, where:

$$T_1 = \sqrt[4]{\frac{270}{5.8 \times 10^{-12}}} = 2600°K$$

Waste heat is rejected to the liquid helium coolant at a temperature, $T_2$, of about 5 degrees K. The thermodynamic efficiency of the converter is therefore

$$\eta = \frac{T_1 - T_2}{T_1} = 997$$

Thus, only 0. 3 of 1% of the input heat is unavailable for conversion and must be rejected to the coolant. In terms of electrical power this represents a loss of only 3 watts per kilowatt.

At first glance it seems highly improbable that a film of niobium 0001" thick mounted on a thin substrate and subjected to a temperature of 2600 degrees at one face and 5 degrees at the other would survive for even a small fraction of a second. Ordinarily it wouldn't. In a passive magnetic field the consequences would be catastrophic since the latent heat of transition in the presence of such a field is negligible. In the case of a working magnetic field there is a vital difference. The input of heat is reflected directly and immediately in an output of electrical energy. Over 99% of the incident heat energy is available for this purpose. Obviously, the same unit-of-radiant energy that contributes to a changing magnetic flux and is withdrawn by induction to do honest work elsewhere cannot at the same time remain behind for the purpose of heating up a metal film.

Ideally, an energy conversion medium serves only as a stepping-stone. In most heat engines the conversion process leaves behind it a trail of violence, stepping-stones that are melted down and recast for every erg that goes from one job to another. Yet there is no basic immutable reason for the working medium even to change temperature, except as required to dispose of unavailable heat. The intimate relationship between heat and magnetism in the phase change of a superconductor is such that an energy exchange can occur without any significant macroscopic change in the medium. Such an effect is rendered credible by the fact that the superconductive state of a metal does not differ physically from the normal state in any observable respect. The conversion of heat energy to electrical energy by means of the closely related magneto-thermal properties of a superconductor therefore does not require the molecular gyrations and consequent involvement of mass and volume that characterizes the alien working fluid of a conventional turbo-generator. This isolation and direct combination of properties contributing to thermo-electric conversion and only to thermo-electric conversion holds forth the promise of a compactness and power/weight ratio impossible even to approach by conventional means.

In any electromagnetic generator a reaction must exist which requires the input energy to match the output, except for the usual losses. The law of conservation of energy demands such a reaction. The back torque exerted by the shaft of a mechanically driven generator imposes a load upon the prime mover precisely proportional to the output of the generator. Similarly, the back emf in the secondary of a transformer induces a counter-current in the primary which opposes the input to the precise degree necessary to insure that conservation laws are satisfied. This requirement is encapsulated by Lenz's law, which states that any electric current initiated by a change in magnetic flux must react in such manner as to oppose the cause of the flux change. But in the present case the cause of the flux change is an input of thermal energy. The mechanism by which a back emf can react against a purely thermal input of radiant energy and require it to deliver full measure is at present unknown, at least to the writer. Certainly it could not be more complex than the series of energy exchanges by which the interaction between a coil and a magnetic field in a conventional steam driven generator is ultimately manifested in a cooling effect upon some distant flames which in turn gain their energy from a sun that set a million years ago. In the present case, a detailed analysis of the processes involved in the change of state of a superconductor under the effect of a reactive magnetic field is beyond the scope of this paper. Many of the writer's consultants have shown some interest in the theoretical aspects of the problem; eventually some light may be thrown upon the manner in which Lenz's law is manifested in this generator.

Ironically, one of the most obstructive roadblocks in the course of development of this idea arose from the high thermal efficiency of the device. Even though the amount of heat that must be rejected is very small the temperature difference between the coolant and the sink is also very small, which makes it difficult to get rid of the heat. In space it is much easier to radiate away kilowatts in the form of waste heat at the temperature of liquid mercury than it is to dispose of a fraction of a watt at the temperature of liquid helium. It is a case of Carnot vs. Stefan-Boltzmann. We can of course give the decision to Stefan-Boltzmann and commit ourselves for all time to the use of a high-temperature medium at a maximum thermal efficiency of about 35%. Or we can take the bolder course and try to invent our way around the problem.

If the temperature at which waste heat is rejected can be increased, the rate of radiation will increase as the ratio of the difference between the fourth powers of the temperatures of radiator and sink. This is in accordance with the Stefan-Boltzmann radiation law. On the other hand the expression for Carnot efficiency takes no heed of the use to which the work is put. Thus a heat engine can be caused to drive a refrigerator without losing a single percentage point of its original efficiency. The net efficiency of the compound system will be reduced, however, because the temperature, $T_2$, at which heat is ultimately rejected will be increased. But if one happens to need the services of a refrigerator (helium liquifier in this case) and also wishes to take advantage of the fourth power law, the combination is a particularly fortunate one. Moreover, when the primary system operates at a thermal efficiency in excess of 99% a considerable degree of freedom in the allocation of the output is permitted. For example, a cooler can be designed to draw 40% of the output of the converter, leaving 60% to be distributed as electrical power. If a smaller radiator is desired, together with the extraction of more heat from cryogenic devices, a proportion of 70% for cooling and 30% for electrical power may be chosen. Of course the efficiency of the cooler must be taken into account, but the overall loss is no greater when the cooler is compounded with the generator than when each goes its separate way.

With power in the kilowatt range available for closed-cycle cryogenic cooling, many superconductive devices now barely dreamed of will be possible. For example, an entire spacecraft can be shielded against dangerous radiation by sheathing it with an intense magnetic field, a field of the order of hundreds of thousands of gauss. Such an expedient would be impossible without the benefit of enormous currents running losslessly and eternally in threadlike wires. The space technology of the future will most certainly rely heavily upon supercurrents; devices unknown today will be conceived to meet problems of which we are not even aware. The ability to maintain superconductivity in space on a large scale will in itself give rise to many advances. The unique properties of the superfluid state may also find exploitation when the means for maintaining this state of matter is readily at hand.

Any approach to the objective of energy conversion in space must take into account the effects of the environment. The method proposed herein is no exception; at very low temperatures, materials behave quite differently than at room temperatures. For example, at cryogenic temperatures eddy current losses are very severe due to increased electrical conductivity of the core. The use of a ferrite material will help to alleviate this condition at the expense of increased bulk but with no increase in net weight. Further improvement may be possible by using a laminated ferrite. The core could be pressed in the green state with the ferrite contained between very thin strips of insulating material and the entire assembly then sintered. This improvement, if such it is, represents only one avenue of attack. There could be many.

## Concluding Remarks

At the present time this method of energy conversion exists only in the mind of its inventor and in the files of the Patent Office. As a system it has not been physically developed beyond the performance of some simple experiments using superconductive lead and undertaken only for the purpose of demonstrating the process from a scientific standpoint. The experiments were successful and are serving as a basis for further investigation of a highly theoretical nature. In a practical way nothing has yet been done to provide experimental evidence of the feasibility of the system as a whole. Lacking such evidence, the system concept of the idea must necessarily hang upon a rather tenuous thread of logic. At this precarious point in its history, however, it does have one benefit to offer. Almost every energy conversion method now under development has filtered through many minds and in most cases many generations of minds. Improvement becomes not only increasingly difficult but less rewarding. In the present case a totally new method of converting heat to electricity is offered. Every major improvement has yet to be conceived. Despite its lack of ancestry and the fact that the sum total of its literature is represented by this one paper, the proposed method may open a promising field of investigation to the few who are not afraid of being alone in the dark.

## Acknowledgments

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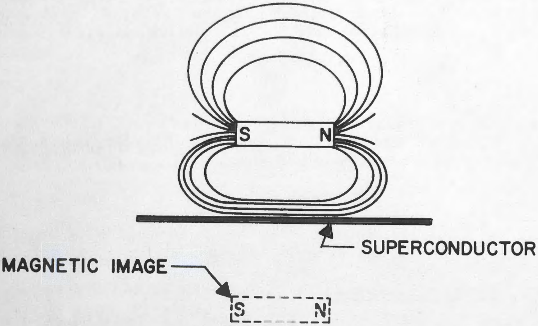

FIGURE 1

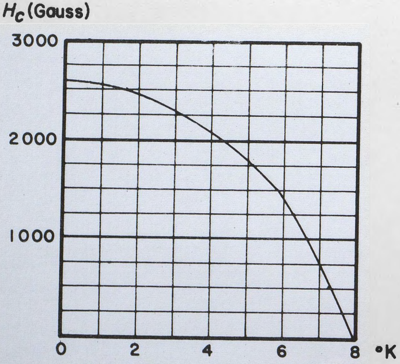

FIGURE 2

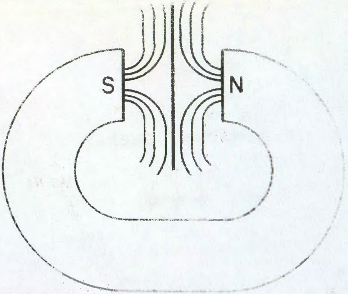

FIGURE 3

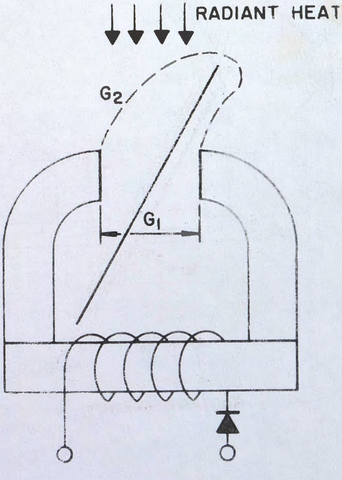

FIGURE 4

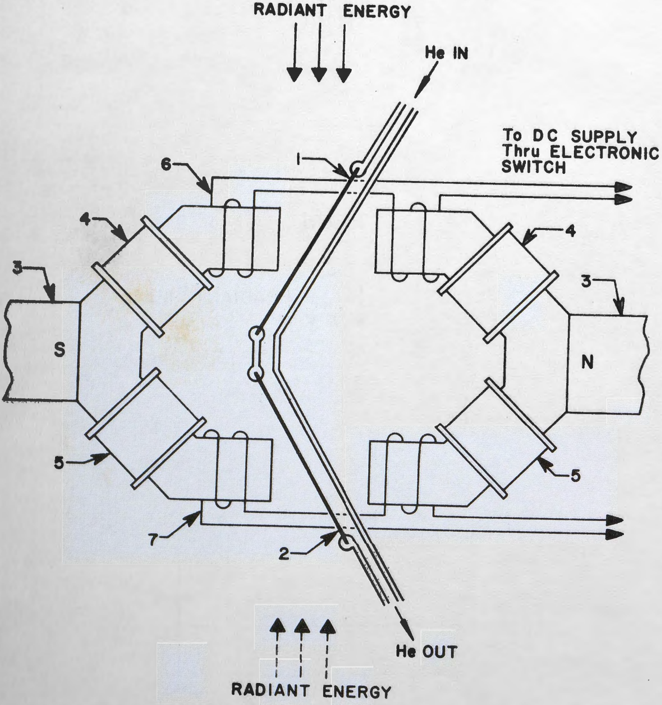
RADIANT ENERGY
He IN
To DC SUPPLY
Thru ELECTRONIC
SWITCH
1
6
4
4
3
3
S
N
5
5
7
2
He OUT
RADIANT ENERGY

FIGURE 5