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Lunar Base
Applications of Superconductivity

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Lunar Base Applications of Superconductivity

National Aeronautics and Space Administration

Lyndon B. Johnson Space Center

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Lunar Base Systems Study Task 3.4

Prepared by:

Eagle Engineering, Inc.

Houston, Texas

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Foreword

The Lunar Base Applications of Superconductivity task was performed as a part of the Advanced Space Transportation Support Contract (ASTS), which is part of a NASA study to address planning for a Lunar Base near the year 2000. This report describes how superconductor technology may be applied to several key aspects of an advanced-stage Lunar Base. Applications in magnetic energy storage, electromagnetic launching, and radiation shielding are discussed.

Dr. John Alred was the NASA technical monitor for this contract. The NASA task manager was Mr. Mike Roberts.

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LIST OF ABBREVIATIONS

A	Amps
BeV	Billion electron volts
cm	centimeter
EML	Electromagnetic launcher
G	Gravity
GeV	Giga-electron-volt
GWH	Giga-watt-hour
H_c	Critical magnetic field strength
HTSC	High temperature superconductor
J	Joule
J_c	Critical current density
kA	kilo-amps
kg	kilogram
kHz	kilo-hertz
kV	kilo-volt
kW	kilo-watt
KWH	Kilo-watt-hour
m	meter
MeV	Mega-electron-volts
MJ	Mega-Joule
mmol	milli-mole
MW	Mega-watt
MWH	Mega-watt-hour
REM	Roentgen equivalent man
s	second
SMES	Superconducting magnetic energy storage
T	Tesla
T_c	Critical temperature
WH	Watt-hour

1.0 Executive Summary

Superconductors are materials that exhibit zero electrical resistance when cooled to temperatures below a critical value characteristic of the material. Until recently, these temperatures have been in the 1-40°K range, which requires that the materials be cooled using expensive liquid helium. In the past two years, advances in the development of high-temperature superconductors have led to a resurgent interest in their potential applications. Materials are being discovered that achieve superconducting characteristics at temperatures over 100°K, allowing cooling with relatively inexpensive liquid nitrogen. Research is continuing to find a room-temperature superconductor that will require no refrigeration.

Magnets constructed of superconducting materials are finding many applications because of their ability to store large amounts of energy in their coils in the form of electrical current with virtually no energy loss. They have the added advantage of being dischargeable in durations ranging from a fraction of a second to many hours or days. Three applications of superconductor magnet technology at a lunar base are discussed in this report: magnetic energy storage during the lunar day for usage during the night; electromagnetic rail launchers to propel lunar-derived oxygen or raw materials into lunar orbit; and magnetic shielding to protect lunar inhabitants from radiation.

The practical usage of superconducting magnetic energy storage (SMES) devices to store large amounts of energy has been proven through the development of prototypes by several research institutes and utility companies. Current technology makes them competitive with capacitor storage but not yet with fuel cells. SMES devices are practical as energy storage units only at stored levels above 500 MWH, which corresponds to lunar energy storage requirements at the early settlement phase (100-1000 persons).

Several geometries are considered for the coil, and a toroid shape is recommended to eliminate fringe fields. Such a device would be about 200 meters in diameter and 30 meters high to store 500 MWH.

Current terrestrial designs require cooling of the coil with liquid helium or liquid nitrogen in order for the devices to achieve their superconducting characteristics. Low temperatures on the moon may eliminate this need, though, making SMES even more competitive. Devices situated above the surface can be shaded with artificial shadows, producing operating temperatures of about 110°K. Superconducting materials already exist that work at this temperature, but higher current densities than those experimentally achieved are necessary before these can be used for practical energy storage. An above-ground SMES device would require strong containment, probably with steel, to withstand the large hoop stresses generated by the coil. The device could be buried in lunar bedrock to contain these forces, but a subsurface temperature of 230°K would require the discovery of a new superconductor material with a critical temperature higher than this.

Some advantages of SMES over other technologies include high efficiency, high reliability, and high energy density.

Superconductor technology has made possible the development of electromagnetic launchers (EML), which require the delivery of high energy in short bursts of power. EML designs have been proposed that are capable of accelerating 1000 kgs at 1000 gravities (G's) to 12.3 km/s. These devices offer several advantages for continuous cargo launch over rocket launch systems, including a higher payload fraction, greater launch rate, lower launch unit cost, and greater reliability. On the negative side, the electric launchers require heavy and complicated surface installations; and the payloads require catchers or small rockets to circularize, and must be able to withstand high G loadings.

Two families of EML are discussed: railgun and coaxial. Railgun devices consist of two parallel rails connected to a direct current with a projectile propelled between the rails by Lorentz forces generated in the projectile's armature. Coaxial devices use a linear synchronous motor to accelerate payload buckets containing energized coils along an assembly of fixed coaxial coils several kilometers in length. Coaxial EML's offer several advantages over railguns, including larger bore diameters for the projectiles, greater efficiency, longer life span, and the ability to operate well at moderate accelerations. A problem with coaxial EML's is the generation of large internal voltages that could cause arcing.

The development of high temperature superconductors has led to the application of quenching methods to a lunar electromagnetic launcher. This method uses successive switching on and off (quenching) of adjacent coils to propel the projectile. Problems with this approach that need further attention include the requirement to withstand high magnetic induction, high current densities, and large stresses. The advantage over other coaxial designs is the elimination of the need for superconducting switches. Quenchguns are able to accelerate 1000 kg payloads to 1.7 km/s.

Further study is needed to determine the tradeoffs of electromagnetic launchers versus reusable landers for oxygen and raw material transport.

A major concern of lunar mission planners is the exposure of astronauts to high levels of cosmic radiation, and occasional high-radiation dosages from solar flares. To safeguard the astronauts, radiation shielding must be considered for lunar habitats. The large magnetic fields generated in superconducting magnets may be beneficial for trapping charged particles away from the habitats. Three approaches are considered here: passive shielding, toroidal magnetic shielding, and plasma core shielding.

The cosmic ray spectrum must be cut off at 10-15 GeV/nucleon to achieve an acceptable dosage rate of 5 rem/year. It is estimated that 785 grams/cm^2 of passive regolith shielding is required to provide this protection. If active magnetic shielding is used, current densities of 10^9 A/m^2 are required to achieve this cutoff, a value approachable only with the use of superconducting coil materials.

Three configurations are considered for magnetic shielding:

- An unconfined field dipole, which is toroidal in shape producing a shield outside the torus,

- A confined field double torus, which places one toroid inside another and traps the particles between them, and
- A hybrid of the two in which a deformed toroidal winding is used to produce a spherical shape.

The hybrid magnetic shield is the most attractive configuration because it leads to the lowest dosage rate and has the lowest system mass.

An elaborate technique called plasma core shielding was also investigated. A plasma core shield creates a huge electric field around the habitat that deflects positively charged cosmic rays back into space. The attraction of surrounding electrons could neutralize the device, but superconducting magnets are arranged to create an electron well that traps these electrons. The advantage of a plasma core shield over a magnetic shield is that no electrons occur near the exterior surfaces of the habitat. However, there may be several obstacles to be safely overcome in operating within a 15 billion volt lunar base environment.

2.0 Background

A superconductor is an element or compound that changes its thermodynamic state when it is cooled to extremely low temperatures, causing it to exhibit zero electrical resistance. The temperature at which this state change occurs is known as the critical temperature, or T_c. Superconductivity was first observed in Mercury by Kamerlingh Onnes in 1911 at Leiden, Holland.[1] The critical temperature of Mercury is 4°K. A bath of liquid helium, which is relatively expensive, is required to maintain this material at such low temperatures.

Subsequent research has led to the discovery of other materials that exhibit superconductor characteristics at higher temperatures. In 1973, niobium-germanium (Nb_3Ge) was found to have a T_c of 23°K. The first of what is considered to be a high-temperature superconductor (HTSC) was discovered in 1986 by J. Georg Bednorz and K. Alex Müller of IBM's Zurich Research Laboratory, for which they were awarded the Nobel Prize in Physics. This material, lanthanum-barium-copper-oxide ($(LaBa)_2CuO_4$), has a T_c of 30-40°K. The search continued for a material that exhibits superconductivity at temperatures above 77°K. This is the boiling point of liquid nitrogen, which is a much cheaper cooling medium than liquid helium.

In 1987, Ching-Wu (Paul) Chu and his colleagues at the University of Houston broke the liquid nitrogen barrier with yttrium-barium-copper-oxide ($YBa_2Cu_3O_7$), which has a T_c of 95°K. In 1988, H. Maeda et al. of NRIM in Tsukuba, Japan, achieved a T_c of 107°K in bismuth-strontium-calcium-copper-oxide (BiSrCaCuO), and Zhengzhi Sheng and Allen Hermann of the University of Arkansas achieved 125°K in thallium-barium-calcium-copper-oxide

($Tl_2Ba_2Ca_2Cu_3O_x$). There have been claims of higher critical temperatures, but these have not been verified as repeatable (ref.). Dr. Chu has noted signs of superconductivity in materials with critical temperatures as high as 240°K.[2]

A property of superconductors known as the Meissner effect was discovered in 1933. When a magnet is placed near a material in a non-superconducting state, the magnetic lines of flux will pass through the material. If the superconductor is cooled to below its critical temperature, and if the magnetic field is below a critical value (denoted H_c), the material will repel these externally-applied fields.[3] As a result, the magnet will levitate above the superconductor. If the externally-applied field is increased above H_c, the magnetic flux lines will again penetrate the material and the material will no longer be superconducting. This transition is reversible by decreasing the magnetic field to below H_c.

Superconductors also become resistive when a critical current density J_c (induced, or impressed by transport currents) is exceeded.[4]

3.0 Superconducting Magnetic Energy Storage

Energy storage is one of the most attractive near-term applications of superconductor technology. A lunar superconducting magnetic energy storage (SMES) device could accumulate energy from solar power plants during the lunar day, and discharge it during the night when the power plant is inoperable. The concept has been proven through the development of prototype SMES devices by Brookhaven National Laboratory[5] and Bonneville Power Authority[6], and recent advances in producing higher-temperature superconductors has made this approach economically competitive with other energy storage technologies[6]. SMES technology is at an advanced enough stage that it does not depend on the development of other technologies, and in fact does not demand significant advances in superconductor or cryogenic technology.

A SMES device is essentially a coil made of superconducting material wrapped around a structural core and contained in a cryostat that thermally isolates it from its surroundings.[7] (Figure 3-1). Electrical energy is injected into the coil and the two leads are shorted. The current will continue to flow through the coil with virtually no energy loss until it is tapped for release.[*] The lifetime of an untapped current is on the order of 100,000 years.[8]

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[*] Like an electromagnet, when a superconducting coil is energized it will generate a magnetic field, whence the name Superconducting Magnetic Energy Storage.

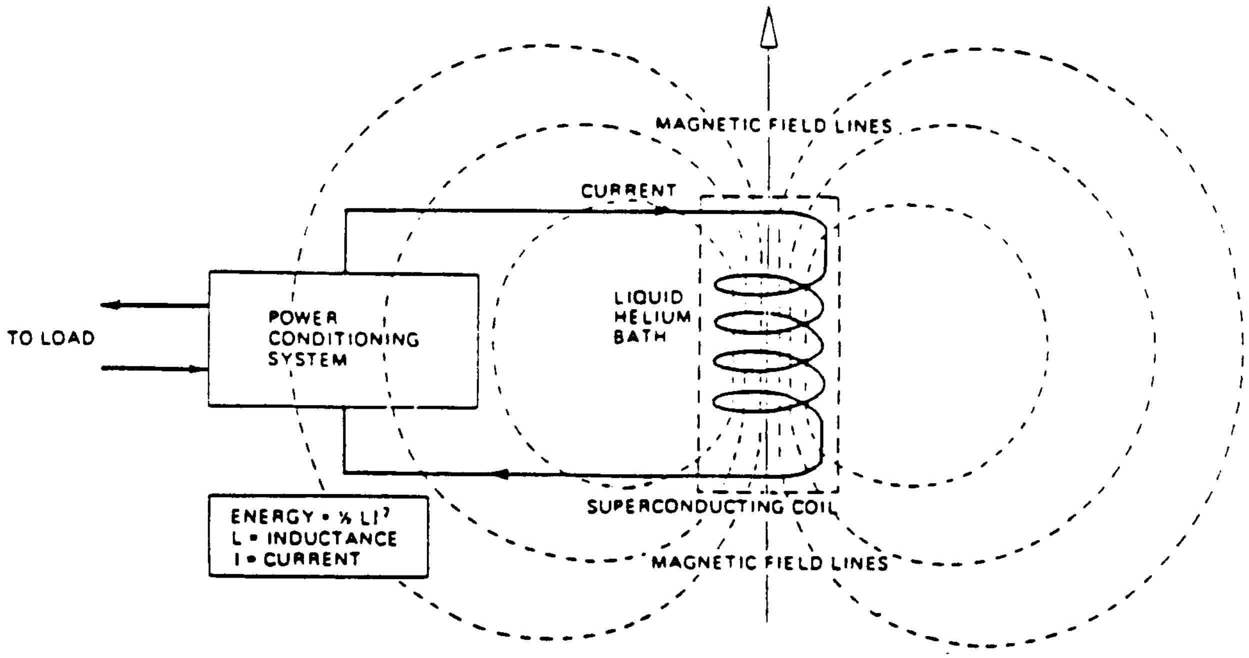

Figure 3-1, SMES Principles of Operation

3.1 Requirements

Burden and Angelo[9] have estimated that an initial lunar base (6-12 persons) would require about 100 kW of power, or about 40 MWH of energy storage capacity for the 394 hours that are effectively lunar night[10]. Early lunar settlements (100-1000 persons) would require about 1 MWe of power, or about 400 MWH of energy storage. A mature lunar settlement (10,000 persons) would require about 100 MWe of power, or about 40,000 MWH of energy storage. Capital costs for fuel cells is approximately $150-250/KWH. In order for SMES to be economically competitive, its energy storage must be in the 500-1000 MWH (1.3-2.5 MW) range (refer to Figure 3-2)[11,6]. Therefore, superconductor technology would not be a candidate for

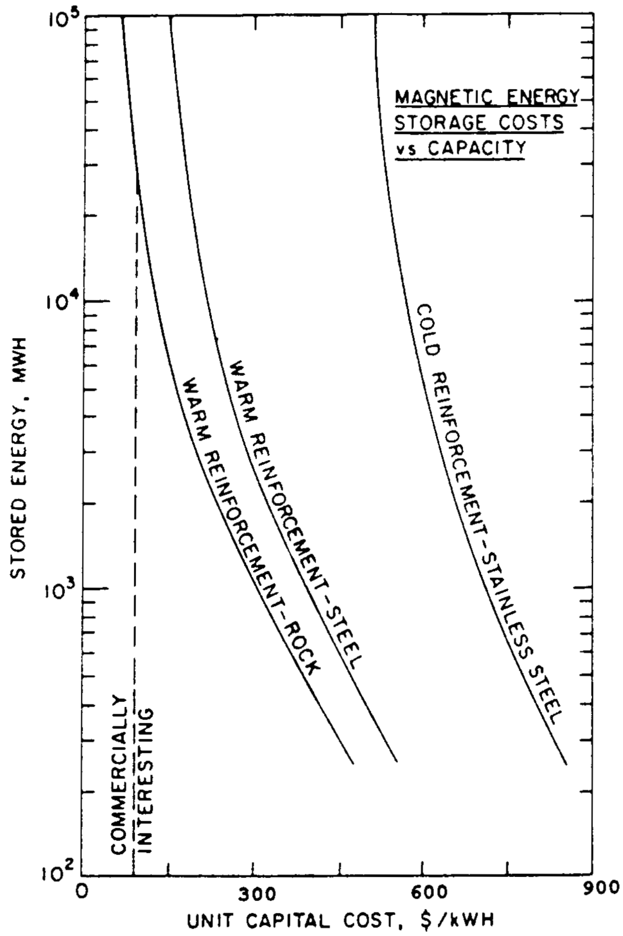

Figure 3-2, Cost of Magnetic Storage Versus Capacity

energy storage until the early lunar settlement phase. Conceptual designs have been performed on SMES devices with energy storage capacities of 1,000-10,000 MWH.

3.2 Configuration

Various coil shapes may be employed in the SMES device. A cylindrical solenoid is the simplest to construct, but exhibits large fringe fields that require extremely large exclusion areas[11]. A toroid or a series of alternating solenoids (Figures 3-3a and 3-3b) would eliminate the fringe fields. Four solenoids joined at the ends, a toroid/solenoid hybrid (Figure 3-3c), has several advantages, including relative ease of construction and assembly, and a uniform field around the coil (except at the ends, which are a small part of the coil volume).

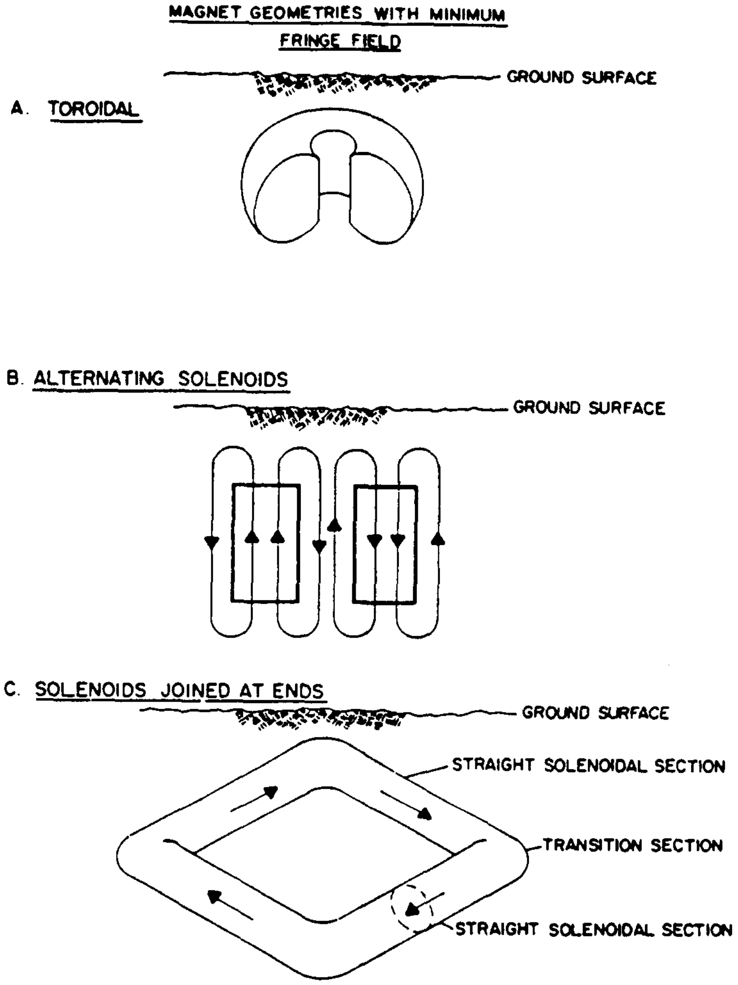

Figure 3-3, Magnetic Storage Coil Geometries

To maintain the magnet at the desired level of energy storage, it is short-circuited with a superconducting switch[12] (see Figure 3-4). The current supply to the magnet is then shut off and the magnet is energized with a persistent current flow through the switch. The advantage of using a superconducting switch is that no outside current needs to be applied to the coil so there is no joule heating in the leads connecting it to ambient temperature. (Joule heating is the phenomenon associated with heat loss to the surroundings due to the loss of electrical energy across a coil). To de-energize the magnet, the switch is driven normal by heating it to its critical temperature with a special heating coil.

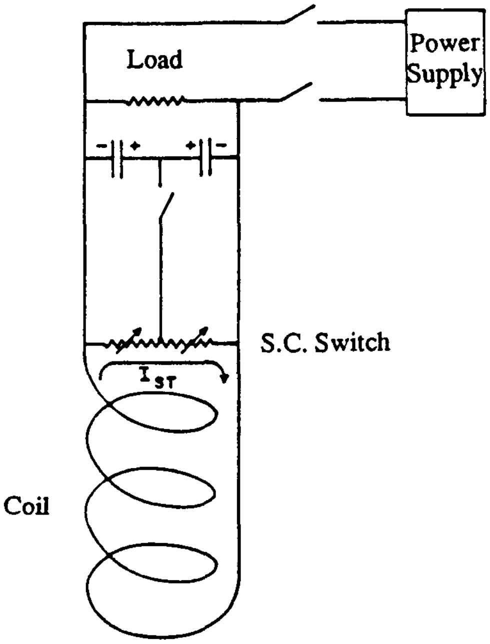

Figure 3-4, Energy Transfer Circuit

Recent studies of terrestrial SMES devices recommend the use of NbTi as the superconductor[6], whose critical temperature is 1.8°K, magnetic field is 3T, and current density is 7×10^5 A/cm^2. This can be formed into a hollow conductor, through which supercritical helium could be pumped for direct cooling. This type of construction would probably lead to lower cryostat and assembly costs[11].

A toroidal shape is used to calculate the magnitude of an NbTi SMES device (Figure 3-5). The flux density is given by

$$B = \mu_o(\lambda J_o)R_o(\beta-\alpha)/(1-\alpha). \quad (1)$$

So

$$(\lambda J_o) = B(1-\alpha)/[\mu_o R_o(\beta-\alpha)] \quad (2)$$

where

(λJ_o) is the current density in amps/meter^2

B is the flux density in tesla

$\alpha = R_1/R_o$, the ratio of inside coil radius to toroid radius

$\beta = R_2/R_o$, the ratio of outside coil radius to toroid radius

μ_o is the permeability constant (1.26×10^{-6} henrys/meter).

The energy stored in a toroid is given by

$$W = 2\mu_o\pi^2 R_o^5(\lambda J_o)^2 f(\alpha,\beta) \quad (3)$$

where

W is the energy stored in joules

R_o is the toroid radius

$f(\alpha,\beta)$ is the geometry factor.

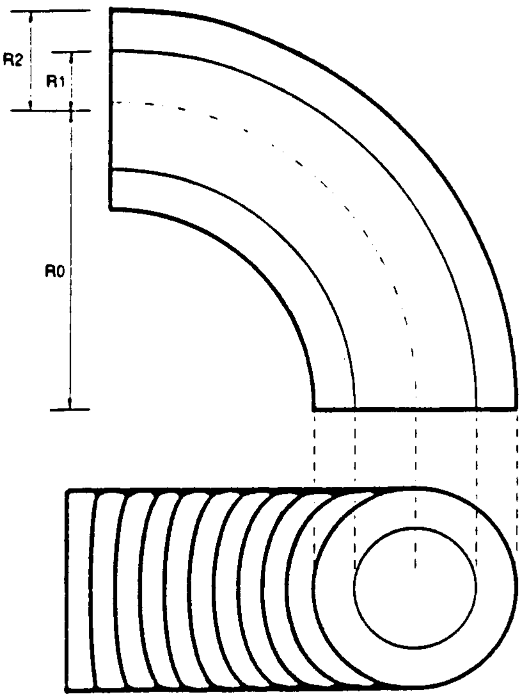

Figure 3-5, SMES Coil Dimensions

Substituting (2) into (3) above, it is shown that

$$W = [2\pi^2 R_o^3 B^2 (1-\alpha)^2 f(\alpha,\beta)]/[\mu_o(\beta-\alpha)^2] \tag{4}$$

or

$$R_o^3 = [W\mu_o(\beta-\alpha)^2]/[2\pi^2 B^2(1-\alpha)^2 f(\alpha,\beta)]. \tag{5}$$

We use 500 MWH or 1.8×10^{12} joules as the storage requirement; and select the two parameters $\alpha=0.2$, $\beta=0.3$ to obtain $f(\alpha,\beta)=2.468 \times 10^{-4}$. This results in a toroid radius $R_o = 93.1$ meters, an inside coil diameter $R_1 = 18.6$ meters, and an outside coil diameter $R_2 = 27.9$ meters.

The hoop stress is given by

$$\sigma_{\theta,max} = [R_1B(\lambda J_o)(2\beta-\beta^2)]/[(\beta-\alpha)2(1-\beta)] \text{ or } 1.4 \times 10^8 \text{ N/m}^2$$

and the radial stress is given by

$$\sigma_{r,max} = R_1B(\lambda J_o)\beta/2(\beta-\alpha) \text{ or } 5.8 \times 10^7 \text{ N/m}^2.$$

3.3 Environmental Considerations

The drawback to NbTi for lunar applications is the requirement for large amounts of liquid helium to cool the coil. The need for liquid gases as a cooling agent could be eliminated if superconductors were employed whose critical temperatures were below the lunar temperature. Since the cryostat and refrigerators account for approximately 30% of the total system cost, this would lead to considerable cost reduction. The sub-surface temperature below a depth of about one meter is considered to be uniformly about 230°K[13]. Temperatures as low as 110°K can be achieved artificially above the surface by producing shading[14].

Recently discovered HTSC's have critical temperatures that are entering this lower range. The problem with these materials is their relatively low current densities, too small to make them effective for high levels of energy storage. Should higher current densities be achieved, and above-surface devices designed, then special consideration would have to be given to developing strong structural shells to contain the huge hoop stresses generated by these magnets.

The discovery of higher critical temperature materials, provided they have sufficient current density, would allow the development of SMES devices that could be stored underground. This would have the advantage of eliminating the need for special structures, since the surrounding lunar material would act as the container. Unfortunately, little is currently known about the compressive strength of lunar material at the depths necessary for the SMES device (up to several hundred meters, depending on the tensile strength of the rock). Compressive strength of about 30,000 psi or greater is required. Some sort of adjustable volume fluid chamber may be needed between the coil and the rock to accommodate movement of the rock as it is stressed[11]. Much geotechnical research must be performed to design these underground support structures with a high degree of mechanical stability[15].

Coils that become damaged can suffer from thermal runaway. This can be caused by coil burnout due to over-dissipation, or by insulation breakdown due to excessive voltages produced by sudden current quenching. If one of these occurs, there needs to be a way to dump the stored energy[1]; otherwise the energy will dissipate as joule heating in quantities large enough to fuse the wire and destroy the coil locally. Dumping can be achieved by either switching a resistance much larger than the coil in series with it, or by attaching a low-resistance transformer in parallel with it.

3.4 Concluding Remarks

The usage of SMES devices for energy storage carries many advantages over other technologies. The energy stored in a superconducting magnet is stored as electricity, so it is immediately available. There is no penalty for energy conversion to or from mechanical, thermal, or chemical energy[6]. This gives SMES the highest round-trip efficiency, at 98%. (The 2% loss comes from transmitting the current into and out of the coil over ordinary copper wires[16]). In addition to being efficient, SMES coils have no moving parts, which contributes to its reliability. Finally, current SMES system designs have a storage density of about 10^5 joules or 27.7 WH per kilogram, which is ten times better than capacitor storage, but about 15-30 times worse than hydrogen-oxygen fuel cells (at 400-850 WH/kg)[12]. SMES density will improve if refrigerator requirements are eliminated, since the dewar structure is approximately 25% of the total mass[17].

4.0 Electromagnetic Launcher

The direct use of electromagnetic energy for accelerating macroscopic rather than sub-atomic matter is an old concept that inspired many premature and dramatically unsuccessful attempts over the years. An electromagnetic cannon built in Germany during World War II, based on a linear induction motor, tended to melt its projectiles, and an aircraft launcher built in the U.S. during the forties, the "Westinghouse Electropult," failed to come even close to the performance of steam and compressed air devices[18].

Recent research in superconductivity has brought electromagnetic launch closer to practical reality. One type of electromagnetic launcher (EML) accelerates a payload to near orbital velocity using electromagnetic forces induced by superconducting magnets. Although several Earth-based EML/superconductivity applications have been proposed, from magnetic levitating trains to first-stage boosters for space launch, the most attractive and original application is for lunar material transport. The basic function of the lunar EML would be the launching of lunar-derived oxygen or raw materials (regolith) into low lunar orbit or to L2 for transfer to low Earth orbit. The oxygen would support advanced space transportation systems while the raw lunar regolith could be utilized for shielding or on-orbit processing.

4.1 Historical Perspective

Technological progress in the development of a lunar-based EML system began in the mid 1970's when Dr. Gerard O'Neill proposed the Transport Linear Accelerator, more commonly referred to as the mass driver, as a means of launching lunar materials to a predetermined point in space[19]. This original concept led to the development of Mass Driver I which achieved accelerations of approximately 35 gravities in 1977. By 1979 work had begun on Mass Driver II which used superconducting coils and eventually achieved accelerations of about 800 gravities[20].

O'Neill's mass driver systems used payload canisters accelerated on recirculating buckets with the payloads collected by an on-orbit "catcher." This method required a number of launches on the order of 10^7 per year (due to small payload canister capacity), an on-orbit materials processing facility, plus the complex and poorly defined "catcher" system[21]. Snow et al. modified the O'Neill proposal by eliminating the recirculating bucket, simplifying the accelerator, and launching a larger payload in a "smart" projectile, eliminating the requirement for the on-orbit "catcher." This method reduced the number of launches per year to the order of 10^3.[22]

Dr. Kolm furthered the latest mass driver design in 1980 by proposing an Earth-based EML capable of accelerating a 1000 kg payload at 1,000 gravities to 12.3 km/s.[20] Interested in Earth-to-orbit electromagnetic launch, NASA commissioned Batelle Columbus Laboratories in 1981 to investigate the feasibility of using an EML to launch nuclear waste out of the solar system[20]. The recent discovery of high temperature superconductors has renewed the research efforts in the field of electromagnetic launch technology as applied to Earth-based launch, particularly by NASA and the Defense Advanced Research Projects Agency[23]. Fully developed EML systems offer many potential advantages and some disadvantages over current rocket launchers. Some of the comparisons are summarized in Table 4-1.[24] Note that certain figures are projections since EML technology does not have a verified history like rocket propulsion. Development costs will also be substantial for the EML option.

Table **4-1**, Comparison of Rocket Launch to Potential EML[24]

Rocket Launch	Electromagnetic Launch
1-5% Payload fraction	10-80% Payload fraction
Large payloads (5-50 ton)	Small payloads (.1-5 ton)
Low accelerations (5-20 G's)	High accelerations (2,000-20,000 G's)
1 Launch per month	10,000 Launches per month
1 Ton/day launched	50 Tons/day launched
\$4,000-\$40,000 per kg	\$20-\$1000 per kg
High launch hazards	Low launch hazards
Expendable or short lifetime	Long lifetime
Launch delays of months to years	Launch delays of minutes to hours
90%-98% Reliability	99.8%-99.999% Reliability

Conventional rocket technology is quite mature and only incremental advances can be expected in the future. Conversely, electromagnetic launch technology is relatively immature, with extensive developments expected as advances in superconductivity are made.

4.2 EML Configurations

Basically there exist two broad families of launchers: railguns and coaxial EMLs.

A railgun consists of two parallel rails connected to a source of direct current with the projectile propelled between the rails by the Lorentz force generated in the projectile's armature. As shown in Figure 4-1, the primary currents in railguns flow parallel to the direction of motion. At high velocities, the conducting armature must be a plasma rather than a solid conductor. Coaxial or coil launchers operate via the repulsive or attractive forces, due to the Meissner effect, generated between antiparallel or parallel currents flowing in coils perpendicular to the direction of motion, as shown in Figure 4-1.

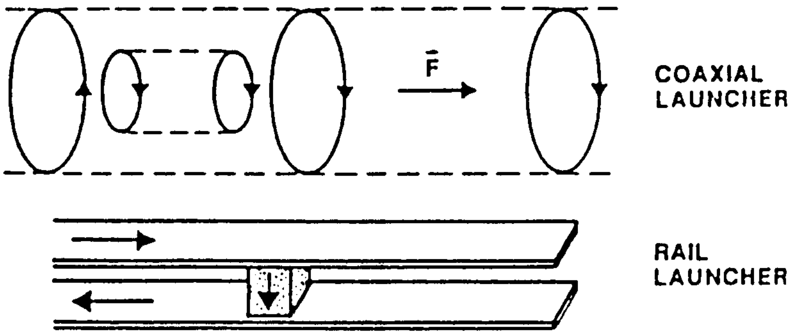

Figure 4-1, Two General Classes of Electromagnetic Accelerators[24]

Railguns have received considerable attention lately due to possible SDI applications; however, coaxial EML's offer considerable advantages for lunar launch systems. With respect to the scaling of the launcher tunnel, railguns are best suited to fairly small bore sizes (tens of centimeters), while coaxial accelerators have the potential for bore diameters of up to several meters[20].

Coaxial EML's are inherently more efficient than railguns, on the order of 80-90%. The low efficiency of railguns (1-10%) leads to problems with building very large power supplies and removing launcher heat[24]. Distributed energy-store railguns offer higher theoretical efficiencies but are complex. While railguns apply a force only to the base of the payload, coaxial systems can be designed to distribute the force along its entire length. This allows for lower current densities and a long slender payload vehicle, important for structural and aerodynamic considerations. Finally, coaxial EML's perform well at moderate accelerations, on the order of 1,000 gravities, and thus are suitable for a wide variety of payloads. Furthermore, coil launchers have a long lifetime in comparison to the railgun's short span of 1-10 launches[24].

Coaxial accelerators have potential for lower costs than the railgun systems for several reasons. The projectile stresses are lower because multiple projectile coils distribute the acceleration loads throughout the projectile, thus reducing the structural mass. The launcher guideway hoop stresses are also lower which correlates to reduced guideway structural mass. Based on these comparisons, the coaxial configuration has been recommended for lunar base applications.

4.3 The Coaxial EML

The basic coaxial EML uses a linear synchronous motor to accelerate small payload buckets. These buckets contain superconducting coils energized with persistent current while travelling along an assembly of coaxial coils several kilometers in length. The induced magnetic field in the guideway coils magnetically levitates the bucket for non-contact suspension. Each bucket is propelled linearly as the guideway coils are energized in a timed sequence, generating a moving magnetic wave. The bucket is first attracted and then repelled by each drive coil. Attraction has a centering effect, while repulsion has a destabilizing effect. The net stability is therefore neutral under completely symmetric timing conditions. However, if the wave form is made asymmetric so that the attractive pulse has a larger amplitude than the repulsive pulse, then the net effect will be stabilization of lateral motion[25].

Figure 4-2 outlines the essential coaxial EML system components in their ordered sequence. The launcher portion of the process involves charging the superconducting coils of the bucket or armature, injecting the payload into the armature, accelerating the projectile along the guideway, releasing the payload from the bucket, and decelerating the bucket for final retrieval and reuse.

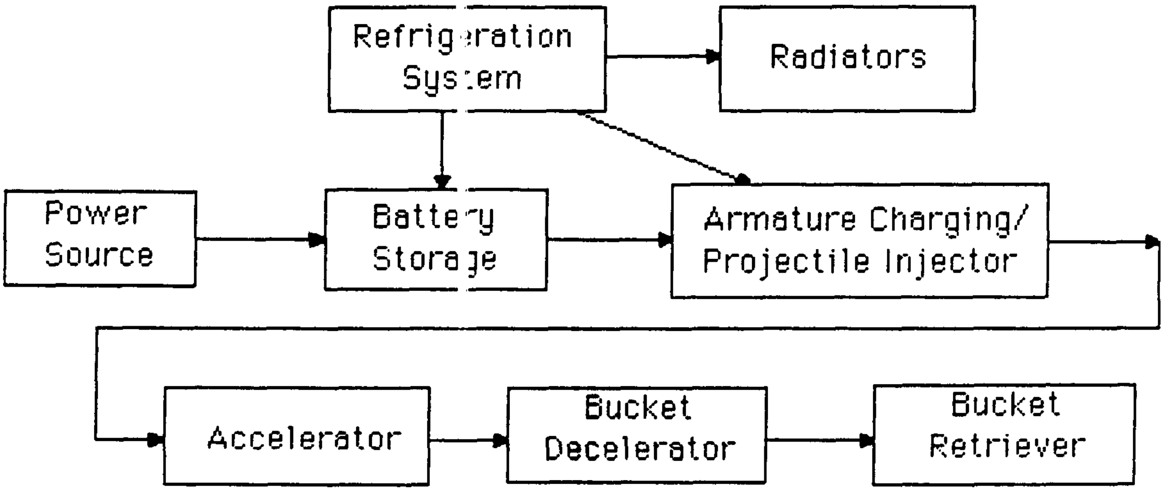

Figure 4-2, Coaxial EML System Components

4.4 Applications of High Temperature Superconductors (HTSC)

Many of the EML components would benefit from advances in superconductivity and thus make the concept viable for a lunar scenario. Applications of high temperature superconductors are prevalent for many of the EML components, including prime power generation, bus work, inductive energy storage, opening switches, launcher coils, and payloads. Of particular interest is the state of the art challenges for energy storage, switching, and coils. In addition to improving components, HTSC's generate stronger magnetic fields and reduce the stringent refrigeration requirements.

Power requirements for an Earth-based EML have been estimated as high as 10 MWH per metric ton, with a recommended delivery time of approximately one second[20]. While storage devices capable of meeting these demands are possible with conventional technologies, the costs are significant. Superconducting coils are theoretically capable of storing electromagnetic energy indefinitely, the only storage related losses being those associated with refrigerating the conductors. Researchers at the University of Wisconsin have performed studies on Superconducting Magnetic Energy Storage systems for load leveling applications[20]. These systems would absorb energy during periods of low demand and feed it back into the system during peak requirements, thus reducing the need for excess generating capacity. Recently, Bechtel has proposed an SMES sized for a 5,000 MWH capacity to the Department of Energy; furthermore, SMES systems as large as 10 GWH have been proposed elsewhere[20]. These systems have not been designed to operate in the pulse mode required for the EML. The pulse mode might pose significant problems since it requires large currents and substantial forces for very short periods of time.

Perhaps the most promising application of HTSC's is in high current opening switches. Within the launcher system circuit, it is desirable to have a solid state, reusable switch that releases the necessary current to the launcher coils as close to instantaneously as possible. The switching requirements for a lunar launcher have yet to be defined quantitatively. Although the lunar application would be less demanding than an Earth-based system, an Earth-based EML requires switches capable of standing off over 100 kV and of carrying mega-amp currents over submicro-second rise times of 10^{12} A/s.[20] Table 4-2 provides an overview of currently available switching technology. (The listed parameters represent available hardware rather than performance limits). Considering the EML switch requirements, the extant switching systems are not sufficient to sustain mega-amp currents. Explosive switches provide the best capabilities so far; however, because they are expendable they are not practical for continuous launch scenarios.

Table 4-2 Available Switching Technology[26]

	Current (kA)	Voltage (kV)	Frequency (kHz)	Interruption Time (s)
Gas Gap	10^3	10^3	1	10^{-3}
Vacuum Gap	10^2	10^2	10	10^{-5}
Thyratron	10	10	10	10^{-6}
Ignitron	10^3	10^2	0.1	10^{-2}
Solid State	10	10	10^5	10^{-6}
Explosives	10^3	10^3	0	10^{-6}
Mechanical	10^3	10^3	0.01	10^{-2}

The actual performance of a switch depends on two characteristics of the superconductor: the current density and the normal state resistivity. Current densities as low as a few hundred amps per square centimeter coupled with normal state resistivities of over 0.1 ohm-cm could make HTSC's effective for this application[24]. Low current densities are preferred in order to reduce switch heating; however, high current densities are more probable in launchers to sustain the large magnetic fields.

To properly latch the switch in the open position, the HTSC must be raised to its critical temperature, thus achieving the high resistivity in the normal state. This method of inducing superconductivity loss through slight heating is referred to as quenching. Magnetic quenching applied to a switch is advantageous for rapid switch reclosure, possible by just turning off the quenching field. Such rapid reclosure is necessary if an armature is not present in the launcher to accept the current from the switch.

Although low temperature superconductors have proven capable for launcher coil technology, HTSC materials appear more promising, particularly if quenching techniques are applied. A superconducting quench coil launcher, or quenchgun, operates by successively quenching the line of adjacent coaxial coils along the launcher guideway. Each coil in turn is quenched - turned "on" and "off" - so that only the magnets in front of the payload are attracting the payload. Thus, the payload rides an electromagnetic wave accelerating rapidly to high velocities. Like the linear synchronous motor previously described for coaxial EML's, the quenchgun provides propulsive energy stored directly in the drive coils and transferred to the payload bucket without contact leads[27].

Various potential problems exist with the quenchgun application, particularly with regard to the coils which must withstand high fields (20 Teslas), current densities (>50 kA/cm^2), and stresses (>3x10^8 Pascals). Further critical areas include synchronization and payload alignment due to the high velocities as well as sensitive quench timing on the order of five microseconds[24].

4.5 A Lunar EML Design Using Superconductor Quenching

Kolm recently applied the superconducting quench methods to a lunar electromagnetic launcher[28]. Kolm's design specifies that the required energy is stored directly in the superconducting coils, thus eliminating the need for external storage or power conditioning. The exemplary quenchgun also exhibits mechanical simplicity by removing the need for switches. Rather than a switch inducing the current in the coils, the projectile generates the superconducting phase change in the coil windings. Figure 4-3 shows the solenoid configuration of the quenchgun. Both the guideway and the projectile are solenoids with currents operating in the same direction. Kolm projects a high level of efficiency for this system, approximately 90%.

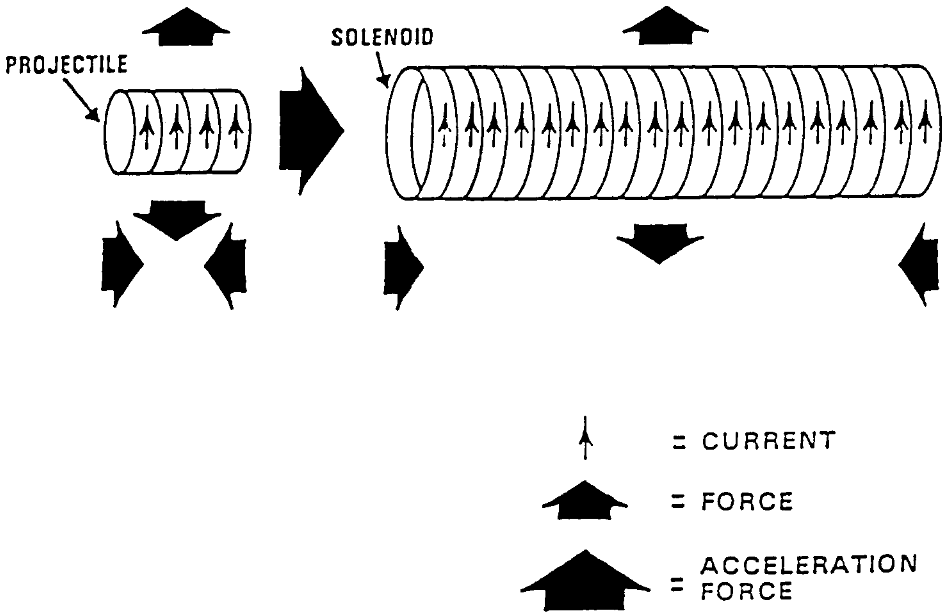

Figure 4-3, Quenchgun Concept - Solenoid Acceleration[28]

Figure 4-4 further clarifies the operational process of the quenchgun. Initially, the superconducting guideway coils are fully charged with the payload coil neutral. Once the payload coil is injected and a persistent current established, the process of attraction between the guideway and payload begins. The payload accelerates along the "gun barrel" as each preceding coil is quenched.

Kolm's quenchgun study is specifically designated for payloads of lunar-derived liquid oxygen, 1000 kg per payload. The payload canister of oxygen is contained in an armature, with the whole system accelerating along the launcher to 983 gravities. The payload canister, released by the armature, achieves an exit velocity of 1.7 km/s and continues to low lunar orbit as an inertially guided "smart" projectile. Meanwhile, the armature decelerates via an eddy current brake along a required length of 25 m for recovery and reuse. Table 4-3 summarizes pertinent quenchgun characteristics associated with Kolm's design.

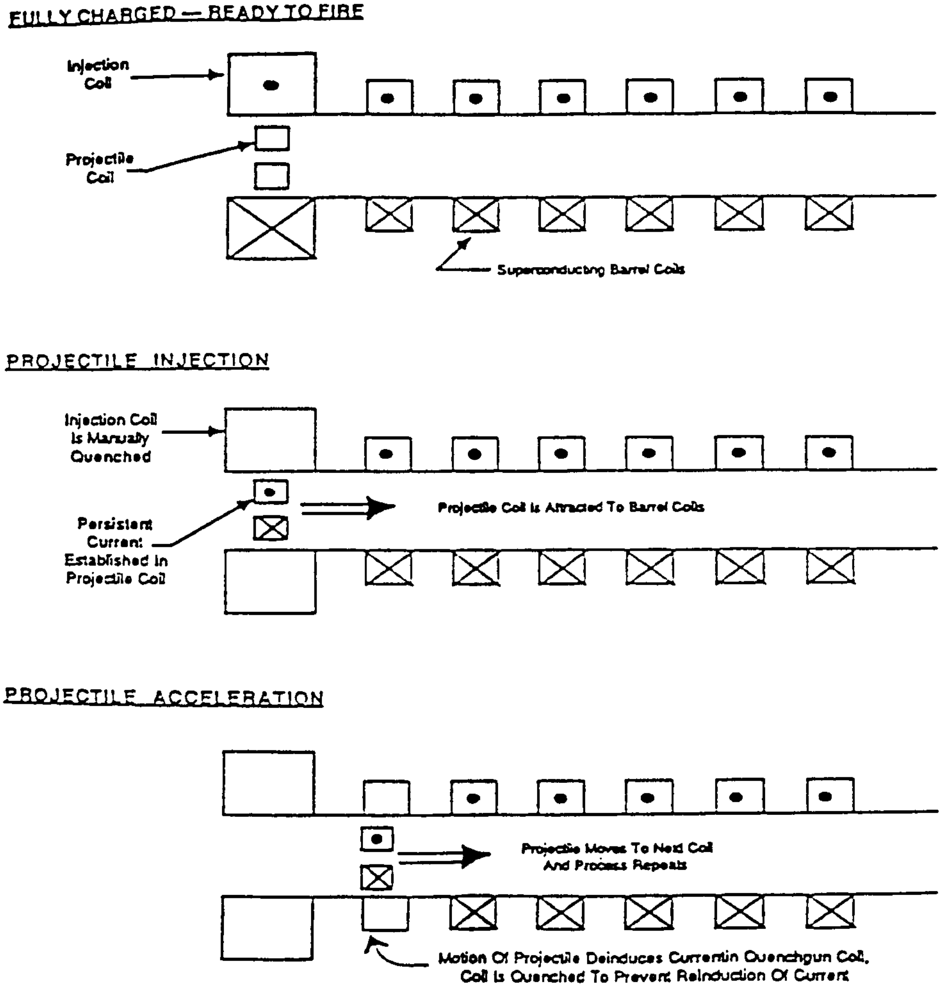

Figure 4-4, Quenchgun Operations[28]

Table 4-3, Quenchgun Characteristics

Projectile Mass	1500 kg	Current Densities:	
Exit Velocity	1700 m/s	- Solenoid	14 kA/cm^2
Launcher Length	150 m	- Payload	30 kA/cm^2
System Mass	256 MT	Maximum Hoop Internal Stress:	
Acceleration	983 g	- Solenoid	-12,000 psi
Energy Required	2170 MJ	- Payload	-150,000 psi
Power Required	350 kWe	Maximum Axial Internal Stress:	
Launch Duration	0.18 sec	- Solenoid	9,000 psi
Acceleration Force	14.5 MN	- Payload	20,000 psi

Note that the system mass does not include the mass of the power source. Data on the mechanical stresses are contained in the table to emphasize that containment of the pulsed magnetic pressures involved in an electromagnetic launch is a very complex issue.

4.6 Lunar Environmental Considerations

The lunar environment will pose serious constraints on the construction and operation of an EML. The most significant environmental factor is the surface temperature, ranging from 384°K during lunar day to 102°K during lunar night[29]. As previously discussed, superconductors currently require cooling temperatures on the order of the liquid nitrogen boiling point. In addition to active refrigeration, recommendations have been made to activate the EML and launch payloads only during lunar night[21]. Since temperatures below approximately one meter remain constant at about 230°K, burial of the launcher might provide additional thermal control[13]. Furthermore, burial would protect the system from possible micrometeorite damage.

Burial might also prove advantageous for anchoring the launcher assembly. Kolm's recent design projects an acceleration force of 14.5 MN along 150 meters of guideway (Table 4-2). Such an intense axial force will incur strong radial forces throughout the launcher, in addition to the gravitational and recoil forces experienced during each launch. Burial supplemented by anchor supports, possibly constructed from lunar concrete, will be necessary to stabilize the launcher. Complete burial might create problems with respect to the angular positioning of the launcher. A 2 degree launch angle with respect to the lunar surface at an equatorial launch site was recommended as a safety factor to assure clearance of distant lunar obstacles[21]. However, a larger launch angle might be preferred depending on the projectile orbital requirements.

With extremely high launch rates expected for robust lunar base scenarios, EML reliability becomes a paramount concern. Bucket snap out, payload breakup, large dynamic excursions, and the consequence of superconducting magnet normalization become serious challenges due to the extensive use rate. Lunar dust might also present EML operational complications, particularly if particles penetrate the superconducting coil regions.

4.7 Concluding Remarks

Various laboratory prototype EML's have been developed by Kolm, O'Neill, and others using low temperature superconductors. With the current advances in superconductor technology, the viability of electromagnetic launchers appears promising. Strides toward less stringent temperature requirements and more malleable candidate materials will instigate the development of Earth-based as well as lunar-based EML's. Of course, the moon offers advantages over the Earth, by providing a lower escape velocity and no atmosphere.

Although technical studies continue to evaluate EML designs and usage, the actual benefits to a lunar base have yet to be determined. The lunar EML, more likely than not, would be designated to launch payloads of lunar-derived liquid oxygen. However, is it more cost effective to use an electromagnetic launch system rather than a reusable lunar lander to deliver the payload to low lunar orbit? In order to answer that question, the costs to construct, set-up, and operate the EML need to be evaluated.

Certain technical factors also need to be considered for practical EML utilization on the lunar surface. The effect of the strong magnetic field on the crew and instrumentation functioning at the base has yet to be studied. Possible risk could be avoided by autonomous launcher operations placed a considerable distance from the main base. Other concerns include coil reliability, failure of the projectile guidance system, rotational instability of the payload, and overheating of the guideway.

5.0 Magnetic Shielding

Shielding against cosmic rays may be required for the longer extraterrestrial human expeditions due to the serious physical danger of radiation. Without help of extensive protection for long duration missions, radiation will shorten life expectancies and interfere with electronic support systems. The obvious solution considered has been mass shielding, but there may be a more effective protection technique. This section of the study will examine the different options that are available for active (magnetic) shielding. The applications of superconductivity in magnetic shielding will be investigated, including unconfined magnetic fields, confined magnetic fields and an elaborate technique called plasma core shielding.

5.1 Background

Destruction of tissue by radiation is of vital concern. As radioactive charged particles pass through tissue, chemical bonds are broken. This damaging result is closely related to the particle's "ionizing power" and can be measured in terms of the number of chemical bonds per unit mass of body that are broken. A charged particle's ionizing power is proportional to the charge squared over its velocity squared. Thus, highly charged, slow moving particles create the most damage. The current bone level radiation dose limit (5cm depth) for astronauts is 5 rem/year. Average dose rates for humans on Earth range from 0.1 rem/year to 0.8 rem/year. A sudden dose of 50 to 100 rem is fatal. The two sources of extraterrestrial radiation are Galactic Cosmic Rays and Solar Cosmic Rays. Galactic Cosmic Rays are low intensity, high energy particles which are comprised of 85% protons (H^+), 13% alpha particles (He^{++}) and 2% heavier nuclei. These particles originate from outside the solar system. Solar Cosmic Rays are also mostly protons and alpha particles, but originate during solar flares from disturbed regions of the sun.

A simple method to protect against this radiation is to use mass shielding. As the charged particle enters the mass shield, it excites electrons for many hundreds of angstroms about its trajectory. This excitation extracts kinetic energy at roughly a constant rate for relativistic particles and thus acts as a braking mechanism. Also, if a charged particle travels far enough into the shield it will collide with the nucleus of another atom and lose energy by inelastic collision. Thus, if the thickness of the mass shield is great enough, the charged particle will be stopped. It was estimated that to provide protection for an astronaut with a average dose level of 0.5 rem/year at the bone (similar to Earth), regolith mass shielding of 785 grams/cm^2 is required (for regolith densities of approximately 1 gm/cm^3 to 3 gm/cm^3).

The magnetic force on a constant velocity particle that is moving at right angles to a uniform magnetic field tends to push it into a circular path (as shown in Figure 5-1). The diameter (Δ) of this path is:

$$\Delta = 2mv/qB \tag{6}$$

where m is the mass of the particle, v is velocity, q is the particle charge and B is the magnetic field strength. It is important to note the dependency of the particle energy on Δ. Particles with higher energy require thicker magnetic shields (e.g. larger Δ's) given a constant magnetic strength field.

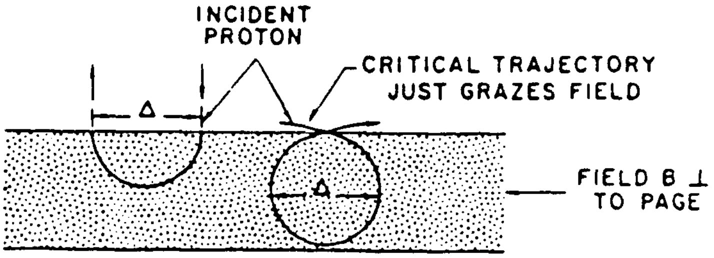

Figure 5-1, Effect of Magnetic Field on Charged Particle Path[30].

A particle on the critical trajectory that is barely contained by the magnetic field has what is called the cutoff energy. In other words, particles with higher than cutoff energy can escape through the other side of the magnetic field (Δ is larger than the thickness of the field). A particle, with less energy than the cutoff cannot penetrate past such a field since its direction is reversed by these forces (see Figure 5-1). This behavior by particles is what protects the Earth from some of the radiation. It has been shown that within a specific solid angle, particles of a certain energy are excluded from reaching the Earth by this redirection process. This type of motion can be applied to spacecraft/space colonies to exclude certain particles from reaching a shielded "safe haven". One way to create uniform fields is to use the poles of a magnet, however, for spacecraft applications it is more convenient to use the field of a torus.

To shield large volumes from high particle energies, the use of superconducting magnets can prove beneficial over normal coil magnets since normal magnet power requirements are substantially higher. Designs vary from a simple circular coil creating dipole fields to a convoluted torus containing no magnetic fields external or internal to the magnet. The coil system basically protects against monodirectional radiation by providing a magnetic field of about 0.1 T[7].

An early NASA study showed that a "safe haven" of 30 m^3 could be protected by a 4 T magnet having a stored energy of approximately 50 to 100 MJ. Production of such magnets was deemed viable within existing capabilities. The report also stated that a larger volume of 144 m^3 could be protected from energetic particles below 1 BeV by a system weighing 150 tons[7]. Most of the weight of this system is support structure. In comparison, Lockheed has constructed a prototype superconductive shielding magnet. The circular magnet has an inner diameter of 1.8 m with a 0.1 T central field (1.5 T at the winding). The magnet could protect several cubic meters from particles with an energy less than 100 MeV, and has an operation period of 5 to 10 days. The entire superconducting magnetic shield system weighs 85 kg, including the cooling system[7].

The effects of high magnetic fields on humans are not known, but initial research into magnetic fields suggests caution since testing on lower-level life forms has caused undesirable effects. Possible human risk suggests that the magnetic fields be arranged such that the field strength inside approaches zero for the volume to remain habitable.

5.2 Magnetic Shielding

Magnetic shielding takes advantage of the fact that charged particles follow curved trajectories when in a magnetic field. Thus, the proper configuration of magnetic field lines creates a region where hazardous particles cannot enter, i.e. a "safe haven". Since the radius of curvature of a charged particle's path through a magnetic field is proportional to that particle's momentum (cutoff energy), a magnetic shield only filters particles less than this cutoff energy. However, particles of higher energy that penetrate through the magnetic field do not degrade their level of energy. This filtering process prevents the generation of secondary radiation beyond the magnetic field, particularly for the blocked particles below cutoff. Radioactive particles that only contact a magnetic field can not create secondary radiation.

The cosmic ray spectrum must be cutoff any where between 10 and 15 GeV/nucleon to achieve a dose rate of 0.5 rem/year[30]. To achieve a field with this cutoff energy, it was determined that current densities in the coil of 10^9 amperes/m^2 are required[31]. The pressure between the coils is proportional to the current and the length of the conductor. Tremendous amounts of structural mass are required because these large currents place the structure supporting the inner coil in compression and the outer coil support structure in tension (due to Lorentz forces). Another detrimental point is that the structural mass (required to resist the created magnetic pressure) creates many secondary particles when struck by those particles that penetrate through the magnetic field. Thus, so much of the cosmic ray spectrum must be cutoff using very large magnetic fields that virtually no particles ever penetrate far enough to hit the support structure. The fatal flaw in magnetic shielding is that the structural mass required to support these huge magnetic fields makes quite a mass shield in itself.

To maintain the current level with a minimum expenditure of power, superconductor coils must be used. Superconducting coils should be constrained to materials that can operate superconductively above 70°K. This will allow the utilization of liquid nitrogen or oxygen for the refrigeration system. These two refrigerants are more abundant and have lower operating costs compared to liquid helium (the latter is used for applications that require operation close to zero degree kelvin). The radiant heat load from the sun determines the amount of cooling required to kelvin). The radiant heat load from the sun determines the amount of cooling required to maintain the superconductor temperature. Both insulation and refrigeration should be used to minimize the amount of energy required to maintain this temperature. The refrigeration-insulation components usually make up about 1/3 of the total weight of the magnetic shielding system. The cryogenic equipment consists of insulation, refrigeration machinery, power supply, and a waste heat radiator.

There are two confined and one unconfined field configurations for magnetic shielding that have been investigated and warrant consideration. The unconfined field dipole is toroidal in shape, similar to a ring-shaped hollow conductor. Placing the coil windings at the outer limit of the shielded region formed by the dipole field produces a desirable region of relatively low field strength. The resulting shielded region blocks particles below the design energy. The configuration is shown at the top of Figure 5-2.

The confined field double torus consists of two toroidal windings, one inside the other. The general arrangement is shown on the bottom left of Figure 5-2. Current direction on the inner winding is opposite to that on the outer winding, confining the magnetic field in the annular space formed between the windings and providing a field free shielded region within the inner torus.

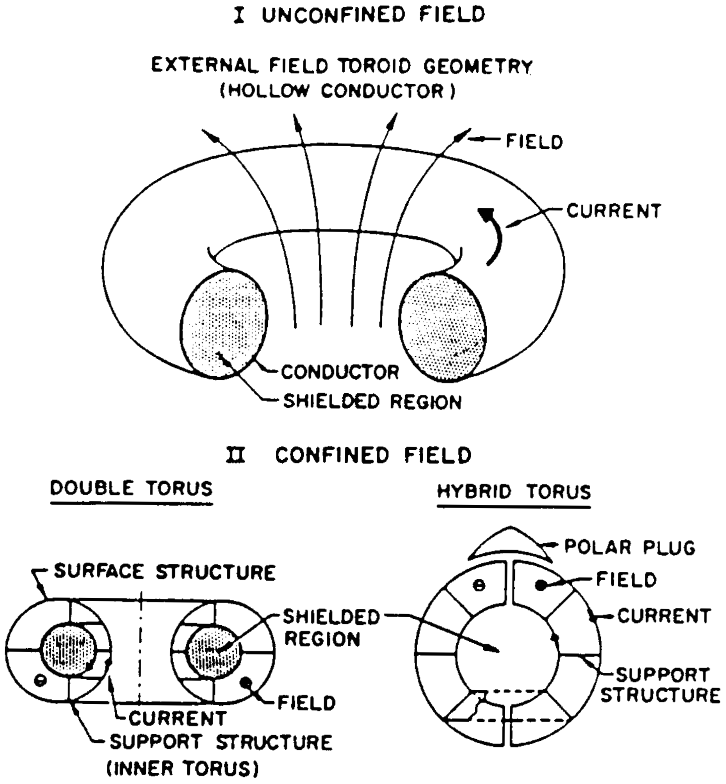

Figure 5-2, Magnetic Field Configurations[31].

The hybrid torus has a confined field geometry that can be generated by deforming a toroidal winding, as shown on the bottom right of Figure 5-2. The shielded region is spherical in shape and is located in the center of the geometry. For this configuration, it is necessary to add a polar plug of passive shielding material to prevent proton leakage at the field interface. The field is generated by a single toroidal winding and remains confined within the winding to provide a field-free shielded region.

Analysis has shown that, of the field geometries studied, the hybrid geometry not only yields the lowest dose rate for a given magnetic cutoff energy but also has the lowest system mass (see figures 5-3 & 5-4 on following page)[32].

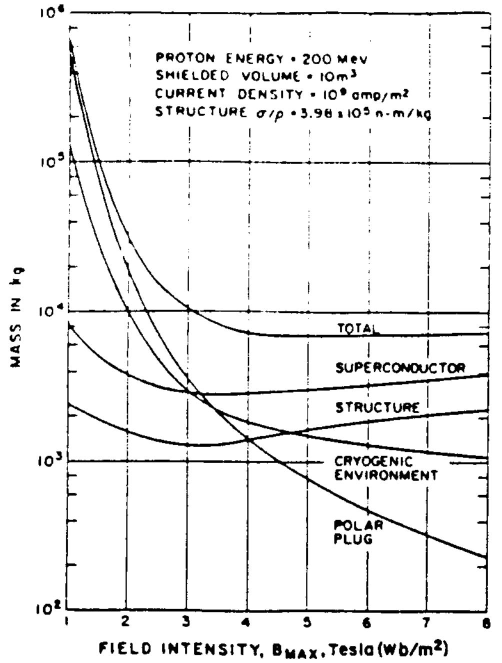

Figure 5-3, Component Weights of Hybrid Torus Magnetic Shields[27]

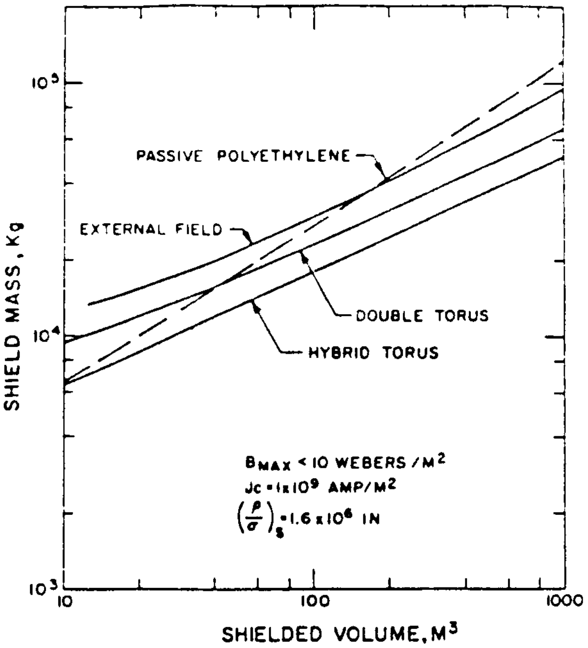

Figure 5-4, Passive & Magnetic Shield Weights Comparisons[27].

5.3 Plasma Core Shield

Plasma core shielding is used to create a huge electric field around a habitat that will deflect the predominately positively-charged, cosmic rays back into space. As a result, this strong positive charge on the habitat will attract surrounding electrons thus neutralizing the system. Such a neutralizing effect can be avoided if a magnetic field is erected around the habitat in such a way as to keep bending the electrons around and away from the structure. The center of the plasma core shield contains an "electron well" which holds about 1000 coulombs of electrons. A moderate magnetic field of approximately 0.3 T can contain these electrons by constraining the motion to be along the lines of magnetic force[30]. In addition, an "electric mirror" effect, referred to as the Meissner effect, at the end of the electron well pulls straying electrons back into the well by using the strong electric fields from the positively-charged well surface. This is shown in Figure 5-5.

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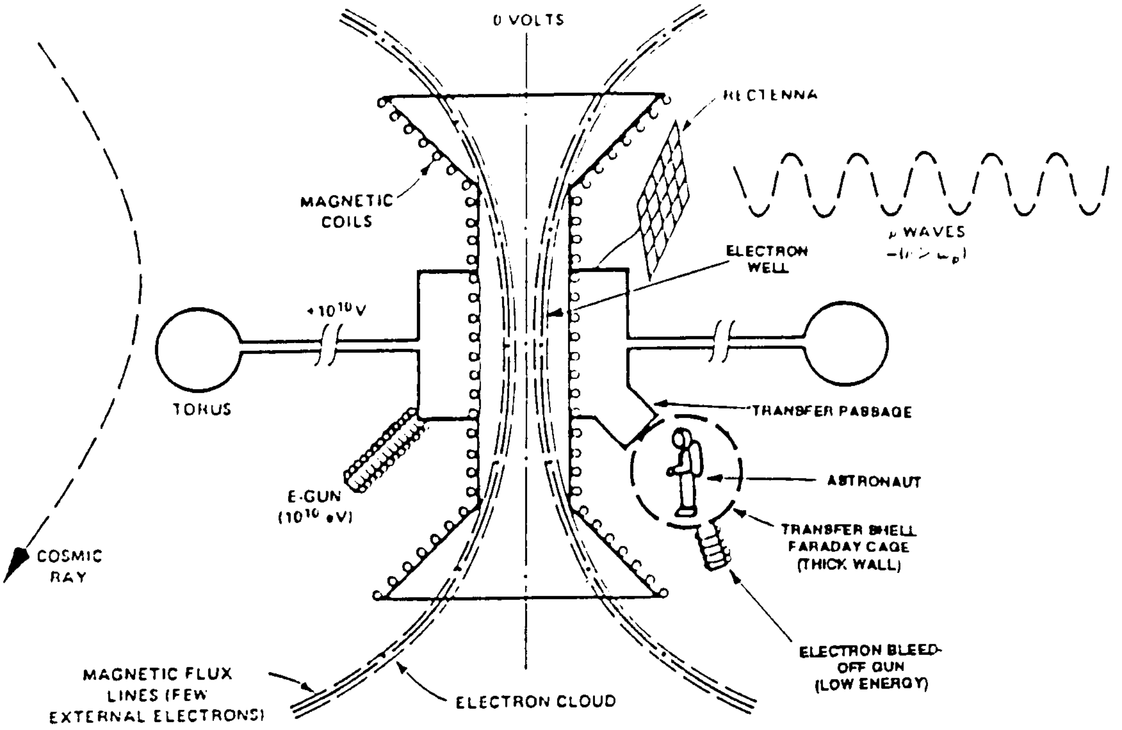

Figure 5-5, Solenoid Core Plasma Shield[32].

The critical advantage of the plasma core shield over previously discussed shields is that the fringing fields at the lips of the electron well keep the electrons electrostatically confined to the well's interior. Thus there are no electrons near the exterior surfaces of the habitat. This feature enormously simplifies construction and operation while improving safety.

The plasma core shield system is activated by ejecting electrons at high energy from the well's surface into far space using a 10 GeV electron accelerator[33]. As the habitat becomes more positive, neighboring electrons are attracted and move inward along the magnetic lines. Due to the magnetic field, however, they are pulled into the well avoiding the inhabited areas. Thus the electron plasma is safely contained in the shielded volume not adjacent to living quarters. The system energy requires about 10^{13} joules (equivalent to one day use of a 100MW power plant) to supply the electron accelerator with drive energy[30]. After start-up, the main power requirements exist for the refrigeration systems. The electron accelerator also sustains the shield from leakage currents.

All metal surfaces bolted onto the electron well will acquire an electric potential of approximately 15 billion volts. At this potential, the positively charged cosmic rays will be deflected away from all volumes contained inside any metal surface bolted to the electron well. The overall system is electronically neutral because the electron cloud inside the well is intensely negative in electric potential. This device is referred to as a bolt-on shield, because any metallic structure in electrostatic contact with the electron well is protected. Provided that the structure stays well within the last magnetic flux line which passes through the electron well (any line that touches is "shorted out"). The enormous electrostatic potential created by the system repels the protons and other cosmic ray nuclei from the shielded "safe haven", and cuts off the cosmic ray spectrum for energies below 7.5 GeV/nucleon (15 GeV for protons). This net radiation dose cutoff, including secondary production, is well below the acceptable dose of 5 rem/year.[33]

The electron well contains 10^{13} J of electrostatic energy which could easily be transformed into penetrating high energy radiation should a subsystem failure occur (i.e. the magnetic cryogenic system). One procedure of safely disposing of this energy is to accelerate positive ions away from the habitat, thus making all metal structures electrically neutral. The procedure can be easily accomplished, since an electron cloud charge of 1000 coulombs is only about 10 mmol of easily accomplished, since an electron cloud charge of 1000 coulombs is only about 10 mmol of particles. Thus, 1 percent of a mole of hydrogen ionized outside the metal structure would be enough to neutralize the habitat once the habitat's electric field had accelerated the ions away. In effect, the "charge" account is balanced by absorbing the electrons contributed by the ions, receding from the habitat at great speed. As the fringing electric fields die away, the electric mirror effect would cease and the well's electrons would repel themselves along the lines of magnetic flux - arranged not to touch the lunar habitat. Since the abort action would act more quickly than the magnetic field could decay, the magnetic flux would still exist. Thus, in perhaps a millisecond, 10^{13} joules and 1000 coulombs of electrons are safely neutralized.

If the shield requires operation 100 percent of the time, it must be possible to gain entrance or exit from the habitat without turning off the shield. Since there are essentially no electrons external to the well this is not difficult. Varying levels of charge on objects must be achieved in order to transfer them from the habitat to the unshielded zone and back again. Such a transfer is accomplished by using a Faraday cage equipped with electron/ion guns to neutralize the transfer item (i.e. astronaut or cargo vehicle). After the transfer item enters the transfer cage, the electron gun bleeds off enough electrons (which go into the well) to equalize the potential between its cargo and the habitat. Once this equi-potential is achieved, the transfer item can safely enter the habitat through the transfer passage. Note that for this procedure to work safely, the Faraday cage cannot be in electrostatic contact with the rest of the habitat and must be heavily insulated. In reversing the operation the transfer item with supporting systems emits positive ions (directed to infinity) to neutralize its cargo.

The plasma magnetic shielding scheme was originally designed for space station applications. There may be several obstacles that will have to be overcome before it can be safely applied to a lunar surface habitat. The required potential of 15 billion volts may cause severe problems. If this large habitat potential arcs to ground, the destructive stored energy will explosively discharge. In the absence of an insulator, arcing on the order of 100 meters may occur. However, a properly shaped, extensive insulation system (perhaps using lunar-derived ceramics) may be able to prevent this occurrence. The impact of this insulation system on the overall mass will have to be evaluated. If a combined system of mass and magnetic shielding is used, a 15 billion volt potential may not be required. Thus, the insulation requirements may be more reasonable. The feasibility of this shielding method can not be assessed until analysis is performed on a configuration specifically designed for the lunar surface.

5.4 Concluding Remarks

Several concerns were raised during study evaluation. For example, will the 15 billion volt potential of the habitat in the plasma core shield have any adverse effects on the crew or onboard electronic systems? Can arcing due to this high voltage potential be eliminated? Would secondary production of charged particles in the magnetic structure by the unshielded primary flux above the cutoff energy require additional mass shielding? The effect of these large magnetic fields on humans is not understood and further research is required. The energy stored in the magnetic field is in thousands of foot pounds. Interruption of the current flow will impose a substantial shock load to the structure. Structural and electrical effects and safeguards will require attention. Also, effects of the magnetic field on outside equipment and communications will have to be determined. These and other concerns will have to be answered in future work.

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