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Electromagnetic Launch of Lunar Material

William R. Snow and Henry H. Kolm

Introduction

Lunar soil can become a source of relatively inexpensive oxygen propellant for vehicles going from low Earth orbit (LEO) to geosynchronous Earth orbit (GEO) and beyond. This lunar oxygen could replace the oxygen propellant that, in the current plans for these missions, is launched from the Earth's surface and amounts to approximately 75 percent of the total mass. Besides the LEO-to-GEO missions, a manned Mars mission could benefit from this more economical oxygen. The use of such oxygen in a chemical rocket would eliminate the need to develop an advanced nonchemical propulsion technology for this mission. And the shorter trip time afforded by a chemical rocket would also reduce life support requirements.

The reason for considering the use of oxygen produced on the Moon is that the cost for the energy needed to transport things from the lunar surface to LEO is approximately 5 percent the cost from the surface of the Earth to LEO. This small percentage is due to the reduced escape velocity of the Moon compared with that of the Earth. Therefore, lunar derived oxygen would be more economical to use even if its production cost was considerably higher than the cost of producing it on Earth.

Electromagnetic launchers, in particular the superconducting quenchgun, provide a method of getting this lunar oxygen off the lunar surface at minimal cost. This cost savings comes from the fact that the superconducting quenchgun gets its launch energy from locally supplied, solar- or nuclear-generated electrical power. By comparison, unless hydrogen can be found in usable quantities on the Moon, the delivery of oxygen from the Moon to LEO by chemical rocket would cost much more, primarily because of the cost of bringing hydrogen for the rocket from Earth.

Lunar Oxygen Supply Concept

Various methods by which lunar oxygen could be delivered from the surface of the Moon to lunar orbit and on to LEO have been studied by a number of investigators (Clarke 1950; Salkeld 1966; Andrews and Snow 1981; Snow, Kubby, and Dunbar 1982; Davis 1983; Bilby et al. 1987; Snow et al. 1988; LSPI 1988). A diagram of the Earth-Moon system showing the orbits and missions for the lunar oxygen delivery concept that we recommend is shown in figure 12.

The mission scenario starts with the launching of tanks containing 1 metric ton or more of liquid oxygen from an electromagnetic launcher (superconducting quenchgun) on the lunar surface into low lunar orbit (100-km altitude), as shown in figures 13 and 14. When the tank reaches apolune (maximum altitude), a small thruster is fired to circularize its orbit and keep it from crashing back into the lunar surface. With a launch rate of one every 2 hours, the liquid oxygen tanks collect at one spot in lunar orbit. After a number of these tanks accumulate

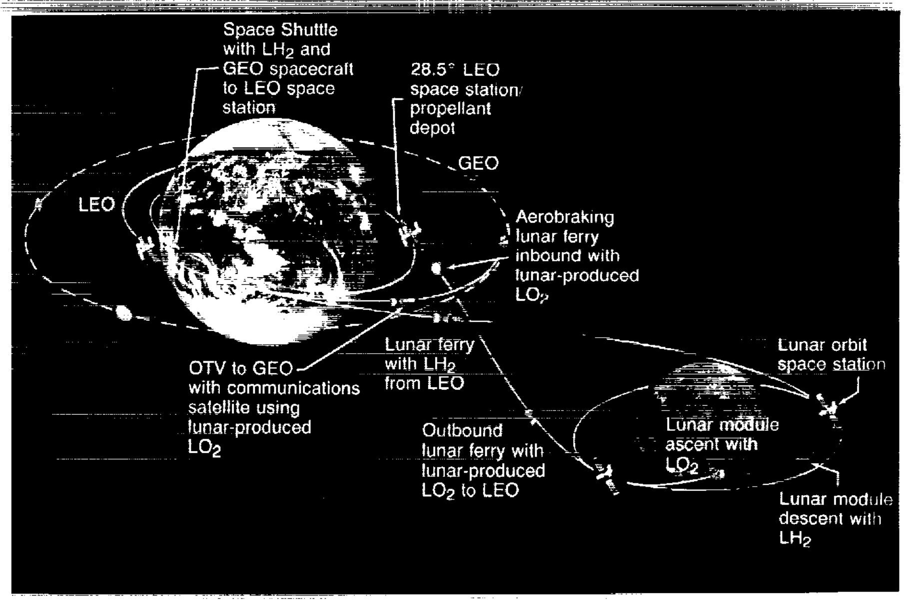


Figure 12

Lunar Oxygen Delivery Orbits and Missions

in orbit, they are recovered and the liquid oxygen is transferred to an aerobraked lunar ferry (shown in figure 15), which delivers it to low Earth orbit. This lunar ferry returns to lunar orbit, bringing back with it some liquid hydrogen. A lunar module returns the empty tanks to the lunar surface so that they can be reused. This lunar module as well as the lunar ferry is fueled by the liquid oxygen coming from the lunar surface and the liquid hydrogen brought back by the lunar ferry. With the empty tanks now back at the electromagnetic launcher site, the process repeats itself.

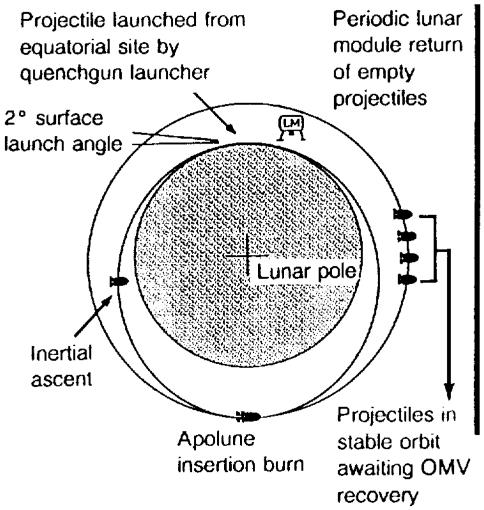


Figure 13

Lunar Launcher Mission

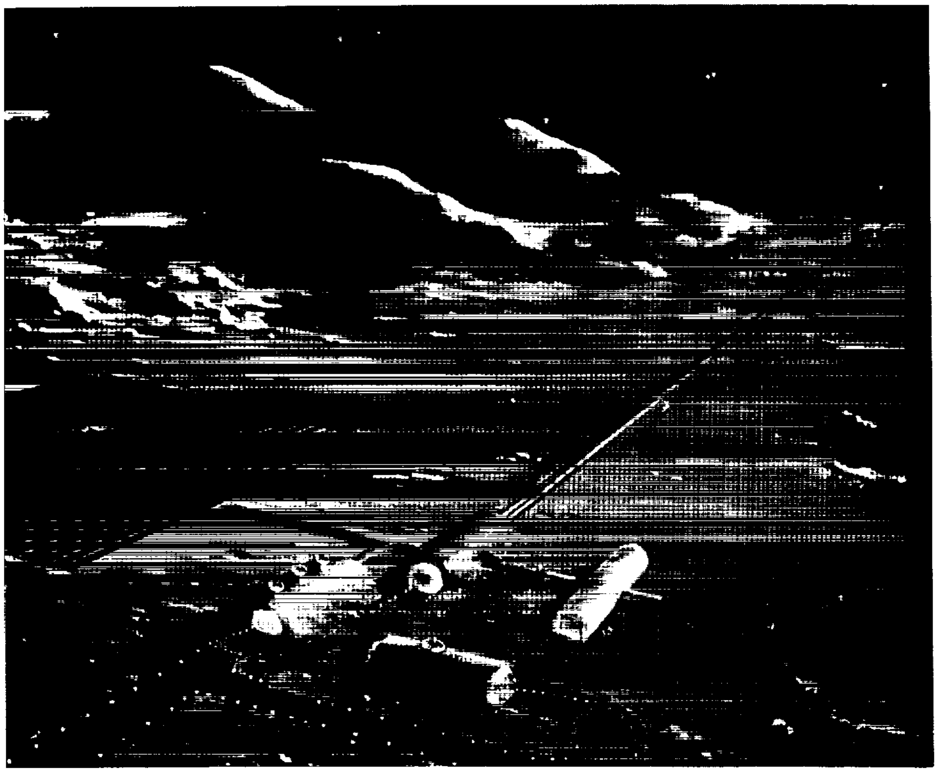


Figure 14

Lunar-Based Superconducting Quenchgun

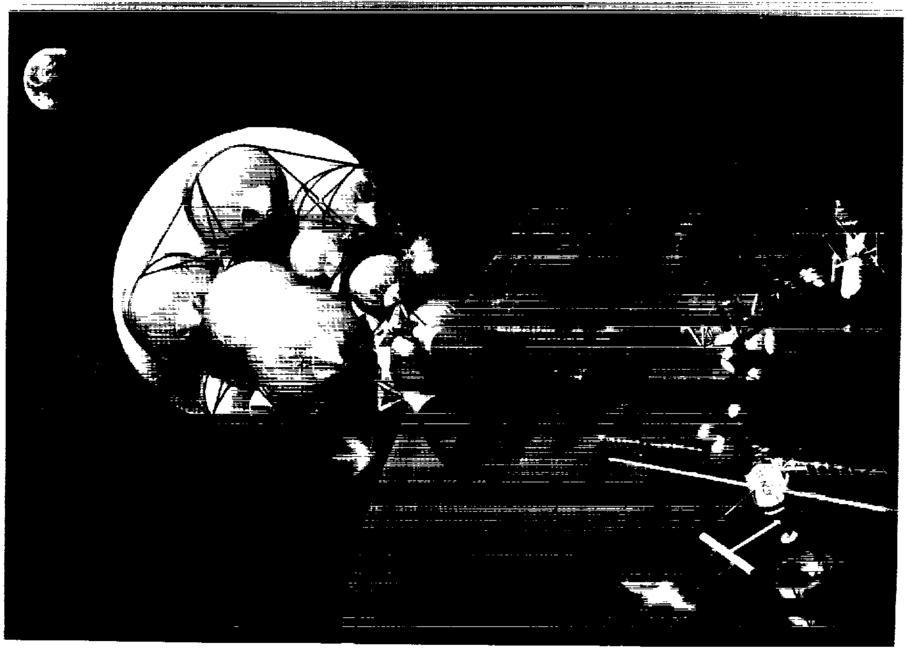


Figure 15

Aerobraked Lunar Ferry
Artist: Pat Rawlings

Electromagnetic Launcher History

The first reported effort to construct and test an electromagnetic launcher was that of Professor Kristian Birkeland at the University of Oslo in 1901 (Egeland and Leer 1986). He received the first world patent for an electromagnetic gun and formed a company, "Birkeland's Firearms," to research and produce them. His largest gun, constructed in 1902, launched 10-kg iron projectiles. The barrel was 10 meters long with a bore of 6.5 centimeters and achieved projectile velocities of 80 to 100 meters per second. He envisioned building guns that would have ranges of 100 to 1000 km. He abandoned his efforts due to a lack of funds and his realization that there were no available pulsed power sources to operate his guns. This would continue to be the case for the next 70 years.

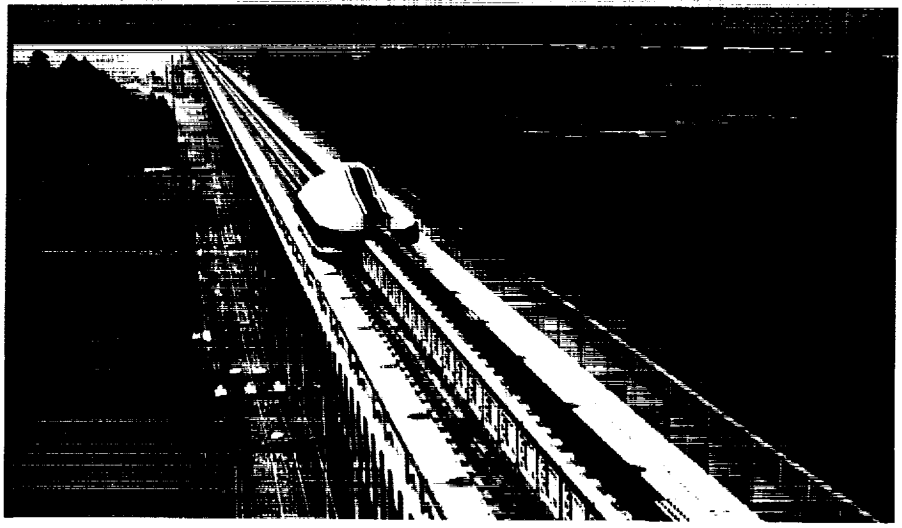
The next reported efforts were made by Professor Edwin F. Northrup at Princeton University in the 1930s (Northrup 1937). He constructed a number of electromagnetic launchers in the early 1930s. His launchers were linear three-phase induction motors (like their rotary counterparts), the same type as Birkeland's guns. He envisioned an ideal electromagnetic launcher in which only a small part of the barrel would be energized at any one time and the energized part would be synchronized with the passage of the projectile, thus minimizing heat losses and being more efficient. This idea required fast high-power opening and closing switches, which did not exist at that time. But the idea would later be used in the mass driver and other launcher designs (coilguns) of the 1970s. He also recognized the effect of magnetic levitation on the projectile; this magnetic force capable of centering the projectile would eliminate friction between the projectile and the barrel. This effect would also be used in the 1970s, with modifications, in the magnetically levitated (maglev) high-speed ground transportation vehicles.

As a variation on Jules Verne's approach, Northrup proposed using an electromagnetic launcher on the Earth to send a capsule with two people onboard on a trip around the Moon. In his book this was to have taken place in the early 1960s and under the condition of a race with Russia to get to the Moon first.

During World War II, several efforts were made to use electromagnetic launch technology. In Germany, at Peenemünde in 1943, an electric catapult for launching V-2 rockets was unsuccessfully tested. In Japan, electromagnetic launchers were studied for use as antiaircraft guns, but they were never constructed. In the United States, the Westinghouse Electric Corporation built a catapult (known as the Electropult) for the Navy to launch airplanes. The catapult wasn't completed until after the war, but it successfully launched airplanes such as the B-25. This catapult lost out to the steam catapult which was being developed at that time for use onboard aircraft carriers. In the late 1940s, electromagnetic launchers were still in their infancy and were still using the inefficient linear induction motor design instead of the more efficient linear synchronous motor design that would be used in the 1980s.

For the next 20 years, electromagnetic launcher technology lay dormant except for a few efforts in building railguns and a small coilgun built by Thom and Norwood at the NASA Langley Research Center in 1961. Their brush-commutated coilgun was a linear synchronous motor (unlike all previous electromagnetic launchers). It was proposed for use as a lunar launcher in support of a large base on the Moon. However, Thom and Norwood's work would lie unknown until after the concept of mass drivers emerged in the late 1970s.

In the late 1960s and early 1970s, electromagnetic launcher technology was being developed for high-speed ground transportation by the United States, Japan, and Germany (Kolm and Thornton 1973). The first repulsively levitated synchronous high-speed transportation system (known as the Magneplane) was developed and tested at 1/25 scale in the early 1970s as a joint effort by MIT's Francis Bitter National Magnet Laboratory and Raytheon. This concept has been adopted by both the German and the Japanese maglev group, who are continuing their efforts, but U.S. support for maglev research was terminated in 1975. A Japanese maglev system, which rides on a cushion of air, has reached test speeds of 520 kilometers per hour (325 mph).



Maglev Test Track In Japan

An offshoot of this maglev research resulted in the concept of the mass driver by Professor Gerard K. O'Neill of Princeton University in 1974. It was based on features of the Magneplane, like magnetic levitation and superconducting armature coils, but the drive circuit was based on the resonant transfer of energy from capacitors rather than on a three-phase power supply. The mass driver was proposed as a means for launching raw materials (payloads of 1-10 kg size at launch rates of 1-10 per second) from a lunar base to a construction site in space. The mass driver was studied extensively for missions of this type, during three NASA Ames summer studies in 1975, 1976, and 1977 (Billingham, Gilbreath, and O'Leary 1979) and subsequently at MIT and Princeton University (Snow 1982). The first lunar launcher proof-of-concept model was constructed in 1977 by a group of students at the MIT Francis Bitter National Magnet Laboratory; it is shown in figure 16.

The energy storage capacitors in the mass driver dominate its mass and cost. And, because capacitors have a low energy density, they are especially unsuitable for an electromagnetic launcher of lunar oxygen, facing the requirements of a larger payload mass at a lower launch rate.

Looking for an alternative way to launch nuclear waste from the surface of the Earth, Henry Kolm in 1978 developed the idea of the superconducting quenchgun (Kolm

Figure 16

Mass Driver I During Construction

While Gerard K. O'Neill, a Princeton physics professor, was on sabbatical as the Hunsaker Professor of Aeronautics at MIT in 1976-77, he and Henry Kolm, one of the cofounders of the Francis Bitter National Magnet Laboratory, led a team of students in building Mass Driver I. Shown here are Bill Snow, Kevin Fine, Jonah Garbus, O'Neill, Kolm, and Eric Drexler.

In 1977 it was widely believed that a highly advanced mass driver, using the most sophisticated materials and design, could achieve at best 50 gravities of acceleration. However, even this primitive model, built from about $3000 worth of scrounged equipment, demonstrated an acceleration of over 30 g's.

Courtesy of Space Studies Institute

ORIGINAL PAGE
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et al. 1979, Graneau 1980). The quenchgun is analogous to the Carnot engine in thermodynamics—the ideal launcher capable of achieving the maximum theoretically possible efficiency. It eliminates the need for energy storage capacitors. Quenchguns store the entire launch energy in the superconducting barrel coils and transfer it to the projectile almost without loss.

The quenchgun concept was not pursued in 1978 because it was considered impractical for any tactical terrestrial applications of interest at the time. High-temperature superconductors or better refrigerators would be required. However, the quenchgun is practical, even with existing low-temperature superconductors, on the cold lunar surface. A proof-of-concept model of the quenchgun was built and successfully tested in 1985 using normal conductors and silicon-controlled rectifier (SCR) switches (Snow and Mongeau 1985).

Electromagnetic Launcher Coilgun Principles

Coilguns achieve acceleration by the Lorentz force exerted by one or more current-carrying barrel coils on one or more current-carrying projectile coils. The barrel and projectile coils can be coaxial or coplanar, as long as they are inductively coupled to each other. The thrust generated is simply the product of the two coil currents times a proportionality constant. This constant is the mutual inductance gradient between the projectile coil and the barrel coil. The mutual inductance gradient for a coilgun is typically about 100 times as large as that for a railgun. As a result, the coilgun generates 100 times more thrust for a given heat loss.

This large thrust is generated only when the two coils are in close proximity to each other. Therefore, coilguns require that the barrel coil current must be synchronized with the passing projectile. When normal conductors are used, this current must be supplied by a pulsed power source to minimize energy loss due to conductor heating.

In the mass driver, the synchronization was accomplished by triggering the resonant capacitor discharge to coincide with the passage of the projectile. Capacitors unfortunately have too low an energy density to be practical, and it becomes necessary to use inductive energy storage when megajoules of launch energy are needed.

Unfortunately it is difficult to commutate (turn the current in a coil on or off) inductively stored energy. This can be accomplished by the use of brushes located on the projectile to synchronize the barrel current with that in the projectile. However, brushes are not suited to the large energies and vacuum environment of the lunar launcher mission, and the wear they would cause is unacceptable in such a mission. The only reasonable option for this mission is the superconducting quenchgun, which is capable of storing the entire launch energy in its barrel without loss and of commutating it synchronously without brushes.

Quenchgun Principles

The quenchgun consists of a superconducting solenoid barrel divided up into a number of short, current-carrying barrel coils. Each of the barrel coils is open-circuited (after the barrel coil current has been de-induced) at the instant the projectile coil passes through it. When the projectile reaches the muzzle, nearly all of the energy initially stored in the barrel will have been transferred to the projectile in the form of kinetic energy.

The unique feature of the quenchgun is the superconducting barrel coils. Ordinary conductors cannot store the entire launch energy in the barrel coils very efficiently for more than 1 second. Superconductors, on the other hand, can store this launch energy without loss for an indefinite period of time. Because of this feature, the superconducting quenchgun can be charged up between firings. Thus the superconducting barrel requires only 1/10 000 the power required by a non-superconducting barrel.

To provide the very high pulse power needed in a non-superconducting barrel, the source would have to be some sort of rotating machinery (with bearings that would wear), such as a flywheel/pulsed alternator. The power for a superconducting barrel can instead be derived from a much simpler and smaller solar or nuclear source. This is the key feature that makes the superconducting quenchgun a much more practical device for lunar launching than any other electromagnetic launcher.

The operation of a superconducting quenchgun is illustrated in figure 17. It consists simply of a row of short coaxial superconducting barrel coils, with an oversized injection coil at the breech. The projectile coil is at rest in the breech, as shown in the first of the three diagrams. It does not need to be superconducting, as long as its characteristic time constant is longer than the launch time. This time constant increases with size, and at the size proposed aluminum or beryllium alloys meet the requirement if they are precooled to about 80 K. To initiate the launch, it is necessary merely to quench the injection coil, as indicated in the second diagram. This induces a current in the projectile coil, which will persist for more than the duration of the launch. The projectile is now sucked into the quenchgun, as shown in the third diagram. As the projectile reaches the first barrel coil, it induces a current zero (by what is called motion-induced commutation), and the superconductivity of the first coil must be quenched so as to prevent current from being re-induced in the barrel coil as the projectile coil passes through it. If the superconductivity of the barrel coil is not quenched, the re-induced current in it will pull the projectile backward and reduce its acceleration force.

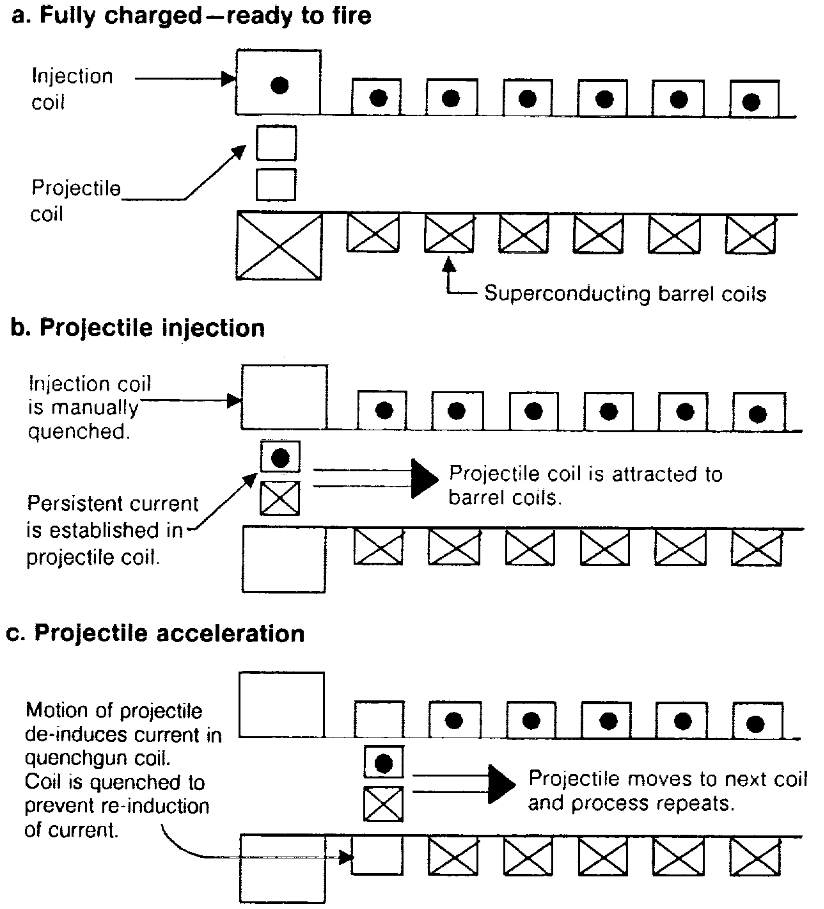

Figure 17

Principles of Quenchgun Operation

Quenching can be accomplished by simply exposing a small portion of the barrel coil winding to radial flux from the approaching projectile coil, making sure that the critical magnetic field in this portion is exceeded. An equally simple method of quenching would be to have the heat induced by the moving projectile coil exceed the critical temperature at the prevailing magnetic field. The important factor is the absence of current at the instant of quench, and therefore the absence of energy dissipation. Each barrel coil is quenched in succession as the projectile coil approaches, and the projectile thus acquires nearly all of the energy initially stored in the barrel.

As shown in figure 18, all of the barrel coils are charged in series to minimize the required charging current and the number of connecting leads. After the barrel is charged, the individual barrel coils are disconnected from this series connection just before launch. They can be disconnected simply by turning on the rhermally activated superconducting shunt switches across the barrel turns and turning off the switches connecting the turns in series.

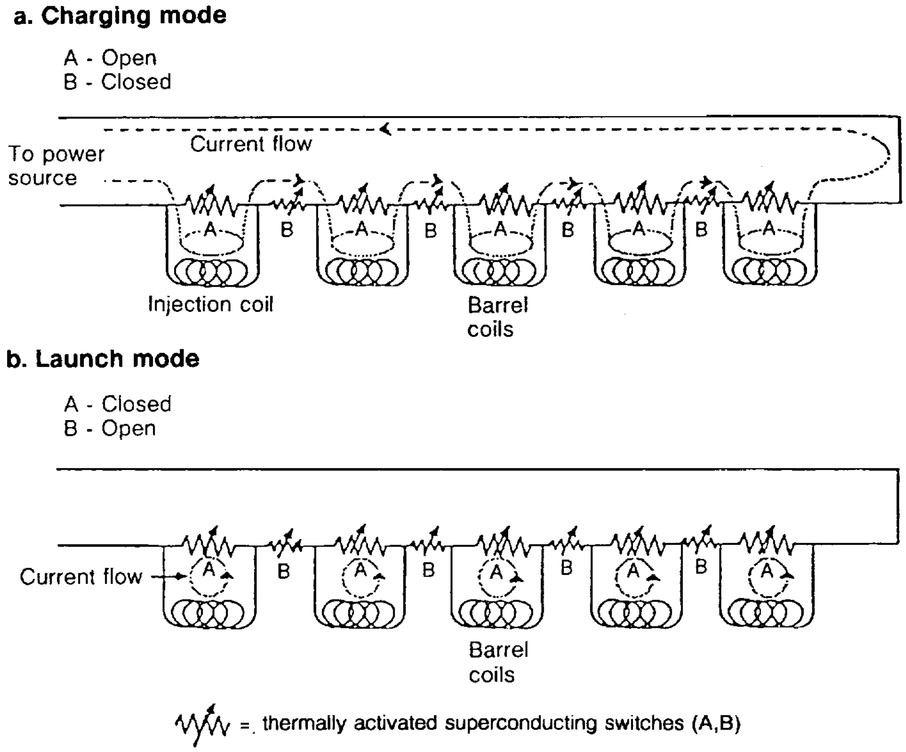

Figure 18

Quenchgun Charging and Launch Modes

A Lunar Superconducting Quenchgun Design

The Quenchgun Barrel

We now present a preliminary reference design to show the main features and components of a lunar-based superconducting quenchgun for use in launching 1-ton containers of liquid oxygen, one every 2 hours. At this rate nearly 4400 tons of liquid oxygen would be launched into low lunar orbit in a year. This is only one of several possible plans for launching lunar oxygen tanks from the lunar surface with a quenchgun. Figure 19 shows the basic features of the barrel.

The quenchgun consists of a cold inner section connected by slinky springs to a warm outer section. The cold inner section consists of the barrel coil modules, each about 1 meter in diameter and 0.5 m long, separated by flanges between

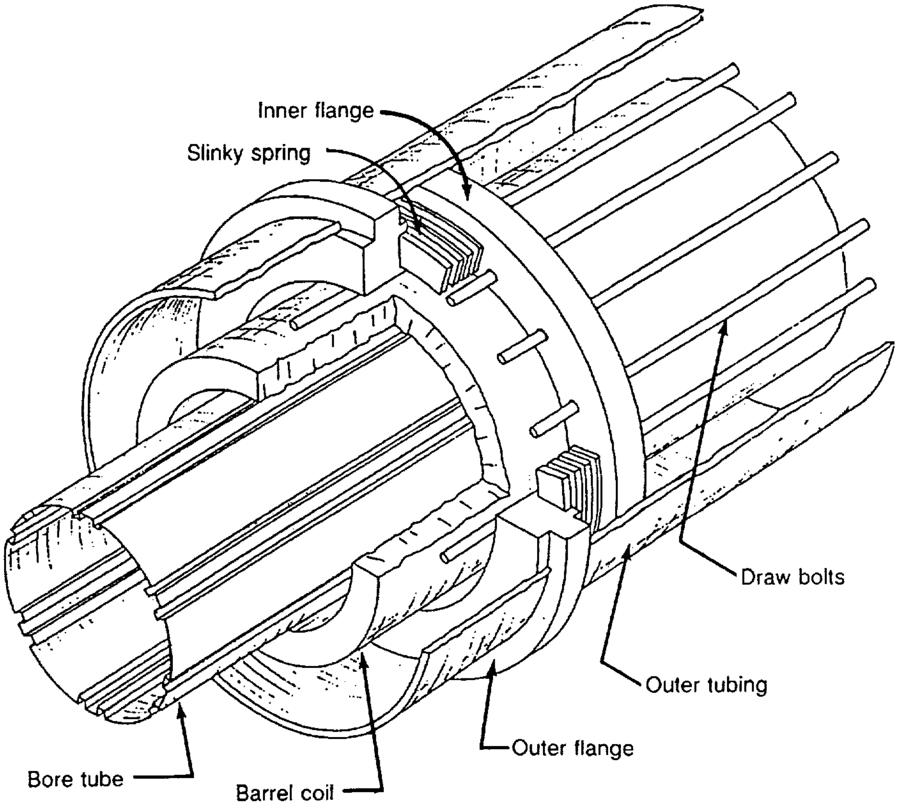

Figure 19

Quenchgun Barrel Module

neighboring coils and compressed by 16 draw bolts which pass through holes in the flanges. Cooling is provided by a forced flow system of supercritical helium using small-diameter stainless steel tubing, which is not shown.

Superinsulation is used as a radiation heat shield between the warm outer section and the cold inner section.

The cold inner section is connected to the warm outer section by slinky springs as shown; they are made of fiber-reinforced composite (to avoid high induced voltages). These springs provide a very long heat conduction path and at the same time permit the inner cold section to recoil. During the instant of recoil, the inner flanges thus transmit the very strong axial forces directly to the outer flanges through the completely compressed slinky springs, causing a temporarily high heat leak. When the barrel is not undergoing recoil, however, the heat leak through the slinky springs is very low, approximately 1 watt per ton of suspended cold system mass. Any rigid suspension system capable of withstanding the recoil force would involve about 100 times this heat leak.

The only metal components of the entire launcher are the superconducting coils, the draw bolts, and the stainless steel cooling tubes for the supercritical helium refrigeration system. Inner tube, outer tube, and all flanges are reinforced composite. Metal cannot be used too near the barrel coils because it would carry very high induced circumferential currents.

The Carriage and the Liquid Oxygen Tank

The projectile consists of two major components, as shown in figure 20. One is the tank that contains the liquid oxygen which is to be delivered to low lunar orbit. This tank has an apolune kick motor on one end which is used to circularize the orbit. Orientation of the tank for proper altitude control is accomplished by spin stabilization. Since this tank must be returned to the lunar surface for reuse, its mass must be minimized. It only needs to be strong enough to handle loads experienced after launch.

To withstand the high acceleration force placed on it during launch, it rests inside a carriage that can take this force. This carriage contains the projectile (armature) coil made from aluminum or beryllium, and stress containment is provided by a graphite-reinforced hoop. Since the carriage is decelerated at the launcher site, it never leaves the Moon and thereby improves the efficiency of delivering oxygen.

The Carriage Decelerating Barrel

For deceleration, the barrel coils are connected in series and no commutation is required. The decelerating barrel coils are energized with a suitable current level in the opposing direction. As the projectile coil enters the decelerator, both the barrel coil current and the projectile coil current increase progressively, until the carriage is brought to rest and clamped mechanically at its stopping position. If not clamped, it would simply rebound. The projectile coil current is then allowed to decay. The superconducting barrel coil in the decelerator can be connected to the accelerating barrel coils so that a fraction of the braking energy is reused for the next launch.

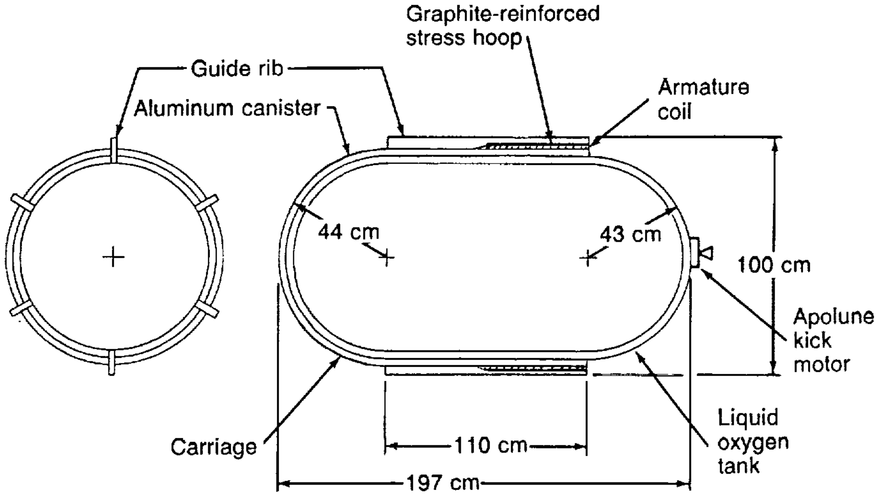

Figure 20

Quenchgun Carriage and Liquid Oxygen Tank

Carriage Retrieval

A mechanical retrieval mechanism is used to return the carriage to the breech after a launch. One possible retrieval mechanism is a self-propelled "mole" powered through an umbilical cable. It normally rests in a dead siding behind the carriage/tank insertion position at the breech. To retrieve the carriage, it propels itself to the decelerating section, connects mechanically to the carriage, and pulls the carriage back to the breech either by itself or by retracting a cable attached back at the breech.

System Description

The system design is based on launching a 1-ton payload of liquid oxygen every 2 hours into low lunar orbit. A block diagram of the components of a superconducting quenchgun is shown in figure 21. The overall use of the superconducting quenchgun in supplying liquid oxygen from the Moon is shown in figure 22. And a summary of the superconducting quenchgun specifications for this reference design is presented in table 10.

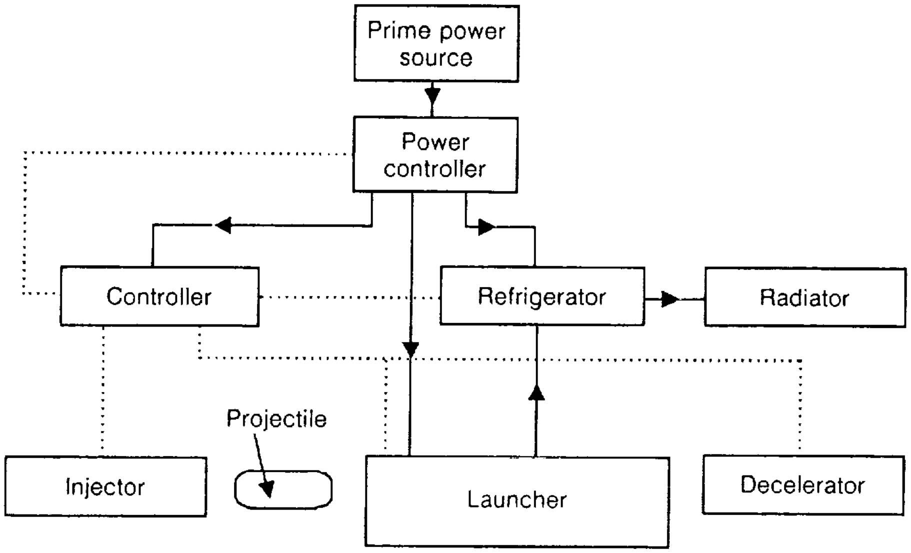

Figure 21

Quenchgun Components

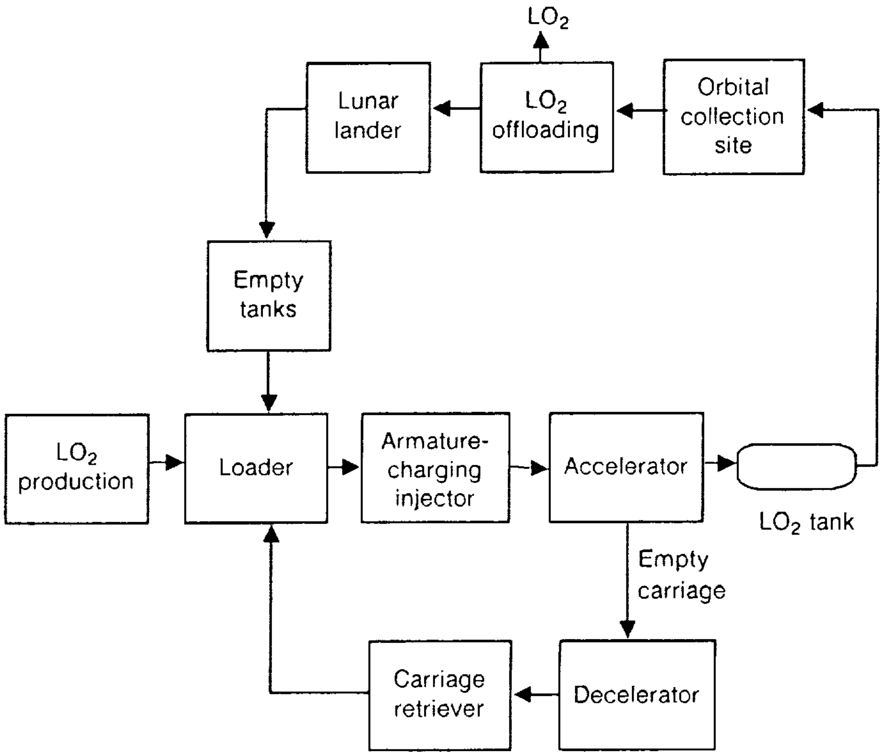

Figure 22

Quenchgun Operation

TABLE 10. *Superconducting Quenchgun Specifications*

Launch performance	
Projectile mass	1500 kg
Payload (oxygen) mass	1000 kg
Velocity	1700 m/sec
Length	150 m
Acceleration	983 *g*'s
Barrel energy	2170 MJ
Launch time	0.18 sec
Force	14.5 MN
Decelerator length	50 m

Projectile (armature coil)	
Coil inner radius	43 cm
Coil outer radius	47 cm
Width	48 cm
Current density	30 kA/cm^2

Quenchgun (barrel coil)	
Coil inner radius	52 cm
Coil outer radius	56 cm
Current density	14 kA/cm^2

System	
Launcher mass	250 metric tons
Decelerator mass	83 metric tons
Power required	350 kW for 1 launch/2 hr

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