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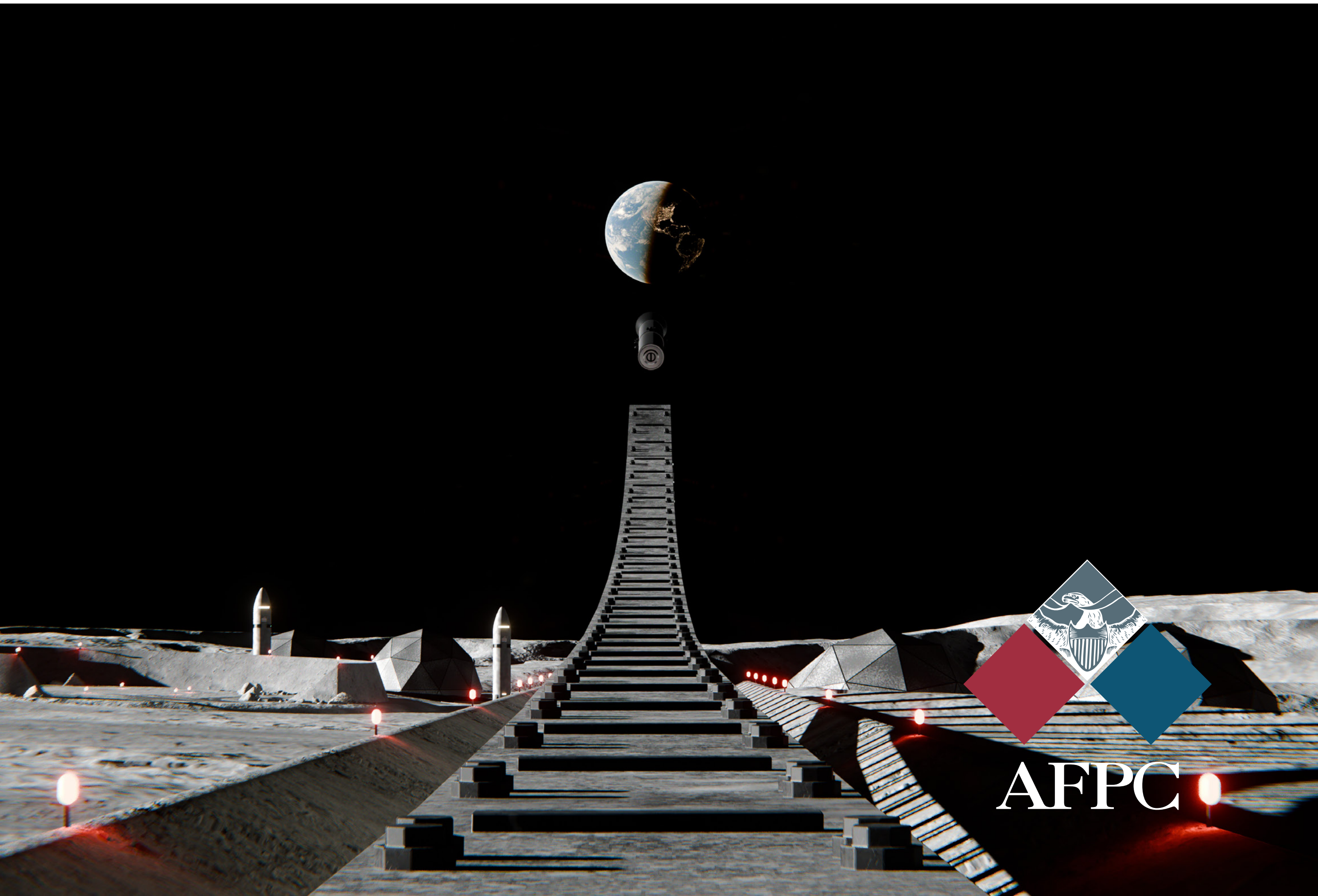

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AUTHOR'S NOTE

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ABOUT THE AUTHOR

ANDRE SONNTAG is an independent space power and policy analyst focused on cislunar security, strategy, and near-term space conflict. His work examines the intersection of emerging space capabilities with national security, public policy, and international competition. He has led multinational efforts analyzing Lunar development and its implications for cooperation and conflict. He has presented his analyses to U.S. Space Force and Air Force elements, the Naval Research Laboratory, and the Joint Staff J7, and has supported scenario design for the National Space Society and the Nonproliferation Education Center. In parallel with his research, he works as a defense acquisition professional and life cycle logistician. He is a 2023 political science graduate of Bowling Green State University. He can be reached via email at Tokyoandre@gmail.com.

EXECUTIVE SUMMARY

Strategic Stakes. The United States faces a narrowing window to shape the strategic environment of the High Frontier. As activity expands beyond Earth orbit, the ability to move mass at scale will become the defining measure of space power. Lunar mass driver infrastructure enables sustained, high throughput transport at a level traditional rocket systems cannot match.

If developed first by a competitor, this capability would confer more than economic advantage. It would allow control over logistics, influence access to key regions, and shape the operational norms that govern cislunar space. Once established, these advantages would be difficult to challenge.

Without early and deliberate investment, the United States risks ceding both the economic and strategic initiative. For these reasons, immediate and measurable steps toward the practical development and fielding must be taken.

What Mass Drivers Are. Mass drivers are launchers that accelerate payloads to high speed using electricity instead of using chemical propellant or explosives. Acceleration is instead provided via electromechanical or electromagnetic means. Designs and concepts of varying maturity have been in the works since the 1970s and have become a staple in science fiction. Operating from the Lunar surface, a mass driver could deliver thousands of tons of harvested material to Low Earth Orbit (LEO) or elsewhere in Cislunar space.

The Logistics Revolution in Cislunar Space. Due in part to the tyranny of the rocket equation, transporting Lunar propellant and harvested material with “traditional” ferry systems is incredibly wasteful. A ferry spacecraft must carry significant dry mass, including structure, engines, and support systems, regardless of payload. To enable reuse, it must also reserve propellant for the return trip, meaning a portion of every flight is dedicated to moving the vehicle itself rather than delivering cargo. This “double back” reduces the usable mass delivered and drives down overall transport efficiency.

In contrast, cargo launched via a Lunar mass driver requires little to no onboard propellant and does not require a return trip. Nearly all launched mass can be dedicated to payload, enabling far greater efficiency. As a result, mass drivers can provide sustained, high-volume transport of material that traditional systems cannot match.

Strategic and Military Implications. The economic advantages of mass drivers are inseparable from their security implications. As high throughput launch systems, they are inherently dual use. Mass drivers are in fact, just large electrically driven cannons.

What distinguishes a benign use from a hostile one is not the system itself, but the payload and its destination. Cargo delivered safely to orbit enables economic growth and sustained presence. That same capability, redirected, could deliver destructive payloads with minimal warning. Positioned on the Moon, mass drivers would operate largely outside existing early warning and attribution architectures, complicating detection and response.

This duality places mass drivers in a uniquely sensitive strategic position. They are not weapons by default, but their operation is indistinguishable from one until intent is revealed. As a result, their deployment introduces both significant opportunity and substantial risk into the emerging Cislunar environment.

Strategic Competition and U.S. Policy. Recent developments indicate that the People's Republic of China (PRC) view mass drivers and related technologies as central to Lunar industrialization and long-term space development. Integrated with the International Lunar Research Station and broader industrialization plans, these capabilities would enable a sustained, high throughput logistics chain between the Moon and Earth. If realized first, this would provide the PRC with a decisive advantage, allowing it not only to dominate resource extraction, but to set the operational and legal precedents that will govern Cislunar activity.

The risk is not limited to economic competition. Early control of key infrastructure and locations would allow the PRC to shape access, influence norms, and establish de facto control over critical regions of the Lunar surface and associated transport corridors. Once established, these advantages would be difficult to displace and could define the strategic environment for decades.

Recommendations

The United States must respond with a coordinated strategy:

1. **The United States, via the Artemis Program, should pursue an aggressive campaign to establish a distributed permanent presence at certain locations of the Lunar south pole and equatorial regions.** Perhaps the most limiting factor when it comes to mass driver development is that of location. Only certain regions on the Moon can launch payloads onto efficient Earth-intercept orbits, and there are only a few viable polar sites capable of sending material directly to low Earth orbit. These limited polar locations are arguably the most valuable real estate on the Moon—the adjacent permanently shadowed craters are expected to hold high concentrations of volatiles, and the terrain outside receives near-continuous sunlight, making solar power consistently available for mass driver operations. Due to the abundant continuous power, increased presence of volatiles, and very limited sites for mass driver development, the United States should pursue an aggressive campaign to establish presence at these polar sites. Having an established presence would give the United States de facto control of these strategic locations, allowing it to develop its own drivers, work

cooperatively with friendly nations, and prevent the use of these sites by hostile powers. Even if the United States fails to invest in mass drivers, having access to the largest reserve of volatiles in Cislunar space will give the United States significant leverage.

2. **The United States should collaborate with allied nations and commercial entities in investing in Lunar Mining Operations and ISRU efforts to maximize the capabilities of a Lunar mass driver.** Mass drivers are only as effective as the industrial ecosystem that feeds them. Without robust Lunar mining and In Situ Resource Utilization (ISRU) infrastructure, a mass driver becomes an underutilized asset rather than a transformative logistics system. To enable long term, high throughput operations, the United States should pursue joint mining and ISRU efforts at the same strategically valuable sites identified for permanent presence. Commercial operators within the Artemis coalition should be supported in fielding excavation systems, volatile extraction plants, and refining units capable of producing both propellant and bulk materials. Cooperation with allied nations distributes the financial and technical burden of establishing mining and processing hardware, and creates shared equity in the early stages of mass driver development. As actors process ISRU material on hand, they will become invested in developing and maintaining systems like mass drivers, allowing them to get their greatest return on investment. Through combined investment and clear interoperability standards, the United States can ensure that the industrial foundation for mass driver operations is in friendly hands, lowering costs and strengthening the position of the United States and its partners as leaders in the Lunar economy.

3. **The United States Space Force must develop a robust Cislunar sensor network in order to maintain Space Domain Awareness.** The need for robust Cislunar Space Domain Awareness (SDA) does not depend on whether the United States chooses to build a mass driver. At present, the Earth-Moon system remains largely unmonitored, with only limited and intermittent visibility beyond geostationary orbit. As activity expands outward, this region will transition from a benign frontier into a contested environment whose competing national, commercial, and scientific interests must be observed and understood in real time. Robust Cislunar awareness is essential for planetary defense, as future resource extraction or redirection missions by other spacefaring nations could alter the trajectories of potentially hazardous objects without detection. It is equally important for space traffic management, as more spacecraft, depots, and uncrewed platforms operating near the Moon will require new deconfliction procedures and shared situational awareness. Most critically, inadequate Cislunar SDA creates opportunities for adversaries to operate below the threshold of open conflict—a foreign actor could assemble infrastructure, shift assets, or launch small payloads without timely detection, inviting gray zone behavior that undermines stability. To close this gap, the Space Force should pursue high power radar platforms, on orbit imaging, and Electro-Optical/Infrared (EO/IR) systems optimized for tracking signatures in Cislunar space. Without a comprehensive and resilient SDA capability, the United States risks being

strategically blind in a region that will rapidly become central to security, commerce, and long-term space governance.

4. **The United States should establish a strategic Lunar ISRU propellant reserve through long term bulk procurement agreements.** The primary obstacle to mass driver development is not technical feasibility, but the absence of guaranteed demand. No private firm can justify the capital investment required to build high throughput Lunar transport infrastructure without confidence that a sustained market will exist. The United States government should establish a strategic reserve of Lunar derived propellant and bulk materials, analogous to terrestrial strategic reserves, sourced through long term procurement contracts committing to large quantities of oxygen, water, or other ISRU products delivered to specified orbits. These contracts should be structured around throughput rather than transport method, with baseline pricing for initial deliveries and higher unit prices or milestone-based awards triggered as delivery volumes increase. Under such a framework, mass drivers gain a natural advantage, as their ability to move large quantities of material with low marginal energy cost makes them well suited to meeting escalating volume thresholds, while contractors retain freedom to pursue alternative approaches provided they meet the same delivery benchmarks. Throughput based incentives also reduce risk for the government, as payments are tied directly to delivered material rather than promised capability. By rewarding volume, reliability, and sustained performance, the United States can shape the Lunar logistics market toward solutions that enable true industrial scale activity, ensuring that high throughput Lunar logistics develop under United States leadership rather than through externally imposed realities.

5. **The United States should advocate for a new Outer Space Treaty with guidelines for Lunar Resource Exploitation and Transport.** As industrialization and permanent presence on the Moon develop, territorial claims will occur in every practical sense except in name. Without clearly defined rules, overlapping safety zones and operational zones will lead to de facto claims and territorial disputes. For nearly a century, the Outer Space Treaty (OST) has preserved stability in space, but that condition is now changing as sustained presence and industrial scale activity become feasible. The Artemis Accords represent an attempt to address the realities of sustained Lunar activity, encouraging transparency, interoperability, and the establishment of safety zones, but they are deliberately framed as voluntary norms rather than binding rules. They do not specify objective criteria for the size or scope of safety zones, define how overlapping zones should be adjudicated, or provide mechanisms to challenge exclusionary behavior or resolve disputes. As Lunar activity scales from exploration to industrial competition, these gaps will become increasingly consequential. A new treaty should build on the principles of the OST and the Artemis Accords while addressing their limitations, defining acceptable uses for safety zones, establishing rules for coordination in high value regions, and setting clear expectations for mass drivers and other high energy transport systems. Transparency and verification should be core elements, with advance notification of

major operations and cooperative monitoring of trajectories to reduce ambiguity and prevent misinterpretation of industrial activity as hostile. By leading the creation of this framework, the United States can shape the rules of the Cislunar frontier before precedent is set by unilateral action, ensuring that Lunar development proceeds under norms that reflect strategic reality rather than legal fiction.

STRATEGIC IMPLICATIONS OF LUNAR MASS DRIVERS AS A DUAL-USE TECHNOLOGY

While mass drivers have long captured the imagination of science fiction authors, they are rapidly moving into the realm of practical engineering. Operational mass drivers would pose unique and profound implications to global economic and military strategy. By dramatically lowering the cost of moving mass in space, mass drivers could enable large-scale industrialization of the Moon, rapid deployment and repositioning of orbital infrastructure, and fundamentally new approaches to logistics in space. Their impact extends well beyond logistics.

Mass drivers are inherently dual-use systems. A driver capable of launching bulk material for industrial purposes is also capable of launching weaponized payloads. This places mass drivers in a unique strategic position: they can enable operations through logistical support, or they can act as a strategic weapon system themselves. Understanding this duality is essential as mass-driver development accelerates and their role in future spacepower becomes unavoidable.

Whoever first develops and fields an operational mass driver will fundamentally alter the character of space operations. A functioning mass-driver infrastructure would grant its owner enormous logistical leverage, industrial capacity, and strategic reach. As mass drivers can also be used for strike purposes, they pose more than just an economic risk. They must therefore be monitored, regulated, and transparently operated to ensure their peaceful use. Without clear norms and oversight, the same technology capable of enabling economic expansion in space could also destabilize it.

WHAT IS A MASS DRIVER?

A mass driver is an electromagnetic accelerator that uses magnetic fields to propel payloads at high velocity without chemical propellants. The system was originally proposed and demonstrated by Gerard K. O'Neill in the 1970s as a means of moving bulk quantities of Lunar material. While there are various ways to accelerate mass electromagnetically, a prime example in current use with the U.S. Navy, as well as the Chinese People's Liberation Army Navy (PLAN), is that of the Electromagnetic Aircraft Launch System (EMALS).

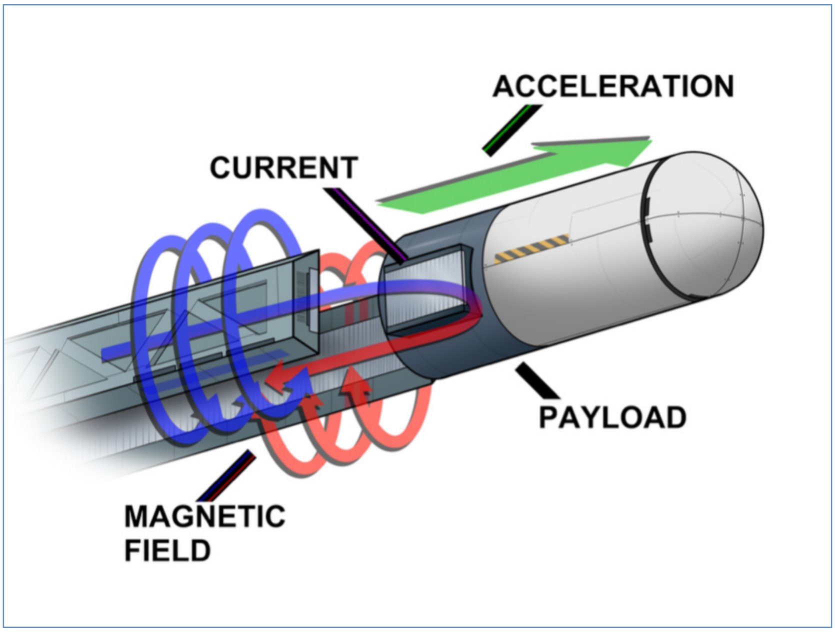
While mass driver architectures vary in technical characteristics, all mass drivers operate effectively the same, they impart velocity on a given payload without the use of propellant. Rocket engines generate their thrust and acceleration from expelling propellant, or remass, at high velocity. The resulting recoil provides the acceleration and the ending velocity. Comparatively, a mass driver accelerates its payload through electromechanical or electromagnetic means to its end velocity. In short, the key difference between the two is where the "engine" and "propellant" stays.

Apart from their payload, rockets and spacecraft must carry everything they need to accelerate. Every kilogram of propellant used to push the rocket also requires additional propellant to move that propellant, creating a compounding cycle. This is the tyranny of the rocket equation, which makes achieving high velocity high mass vehicles difficult. By contrast, mass drivers stay entirely on the ground, and only their end payload moves. The "engine" is the driver and the "propellant" is electricity. Electromagnetic mass drivers operate on the same physical principles as EMALS or a railgun. A payload, typically housed within a reusable launch bucket or carrier, is accelerated along a fixed track using a controlled sequence of electromagnetic pulses. These pulses create a moving magnetic field that pulls or pushes the payload forward, steadily building velocity.

In addition to purely electromagnetic systems, electromechanical mass drivers offer an alternative approach. These systems use physical mechanisms such as spinning arms to impart velocity to a payload. While potentially simpler in some respects and less demanding in peak electrical power, they introduce greater mechanical stress and wear, which limits precision, scalability, and payload throughput compared to electromagnetic designs.

Regardless of the means used, once the payload has reached its desired velocity it leaves the driver. From there, apart from course corrections, little to no onboard propellant is required. Depending on the specific architecture, payloads may still require a small amount of propellant for final orbital insertion, using simple ISRU-derived solid rocket motors, or they may rely on aerobraking to achieve capture. Regardless, the amount of propellant used is orders of magnitude less than relying on ferry systems.

FIGURE 1: REPRESENTATIVE CONFIGURATIONS OF MASS DRIVER LAUNCH SYSTEMS[1]



The main takeaway: rockets accelerate a payload <u>after</u> leaving the pad. Mass drivers accelerate a payload <u>before</u> it leaves the pad.

TYPES OF MASS DRIVERS

Mass drivers are available in numerous configurations. **Railguns** use electric current between two rails to accelerate a conductive armature at extreme speeds but suffer from rail erosion and high-power demands. **Coilguns** use sequential magnetic coils to pull a projectile forward with less wear and better control, making them suitable for reusable launchers. While various types of coilguns exist, special note should be taken of quenchguns due to many of their unique advantages. A quenchgun is a superconducting coilgun that releases stored magnetic energy by deliberately quenching its coils to produce a single powerful pulse. **Linear synchronous motor systems** use continuous electromagnetic levitation and drive fields to provide smooth acceleration along long tracks. Rotating or spin launchers accelerate their payloads via an electromechanical high-speed, rotating arm, in effect, like a shepherd's sling.

TABLE 1: COMPARISON OF MASS DRIVER CONCEPTS FOR LUNAR LAUNCH APPLICATIONS

MASS DRIVER TYPE	ACCELERATION METHOD	ADVANTAGES	LIMITATIONS	TECHNOLOGY STATUS
Railgun	Electric current flows through two parallel rails and a conductive armature, producing a Lorentz force that accelerates the payload.	Highest technology readiness level (TRL); relatively low system complexity; demonstrated prototypes and extensive testing.	Rail erosion from heat and electromagnetic stress; requires large fast power supplies; frequent rail and armature replacement; large facility footprint.	Highest TRL; tested by organizations including BAE Systems and General Atomics; active research globally.
Coilgun (generic)	Sequential magnetic coils are energized to pull the projectile forward using a traveling magnetic field.	No rail wear; non-contact acceleration; requires smaller facility footprint.	Lower practical efficiency; requires precise timing control; higher demands on energy storage, power generation, and cooling.	Lower TRL than railguns.
Coilgun* (Superconducting Quenchgun)	Superconducting coils store magnetic energy and intentionally quench to release a single powerful launch pulse.	Very high efficiency (often cited above 90%); reduced system mass; no rail erosion.	Requires cryogenics, quench detection, and protection circuits; uncontrolled quench can destroy the system; high build cost.	Low TRL; under development by groups such as Electromagnetic Launch.
Linear Synchronous Motor System	Accelerates a payload along a track using a traveling electromagnetic field generated by sequentially energized coils	Smooth but low acceleration; minimal mechanical wear; mature technology used in EMALS aircraft launch systems.	Extremely long track required to reach Lunar escape velocity; very high construction cost; highest mass system.	Mature and operational in naval aircraft launch systems.
Spin Launch System	Payload attached to a rotating arm or centrifuge and released at high tangential velocity.	Compact and lightweight launcher; relatively cheap and low mass; easy to deploy.	Extremely high g-forces (10,000–20,000 G); low throughput due to spin-up & down time; extreme mechanical stress on rotor and tether.	Early commercial development.

Railguns

Railguns have the highest technology readiness level of any proposed mass-driver concept. A railgun consists of two parallel conductive rails and a conductive armature that bridges them. A huge electric current flows from one rail, through the armature, and back down the other rail, creating a magnetic field. The interaction between the current and the magnetic field produces a Lorentz force, basically an electrical shove, that pushes the armature and payload along the rails at very high acceleration. This process generates extreme heat and electromagnetic stress, which drives erosion of the rails.

Additionally, railguns require large, fast power supplies. While the U.S. Navy railgun program demonstrated rail life of hundreds of firings,[2] a mass driver will require hundreds of thousands, if not millions, of firings per year. As continually shipping the armatures and rails to the Moon would be cost prohibitive, additional infrastructure would be required to manufacture armatures and replacement rails. Due to the additional facilities required for rail manufacturing, when compared to other mass driver systems, railguns would have the largest visible facilities footprint. The relatively low system complexity is offset by high maintenance requirements and potential downtime, which will ultimately affect payload delivery rates.

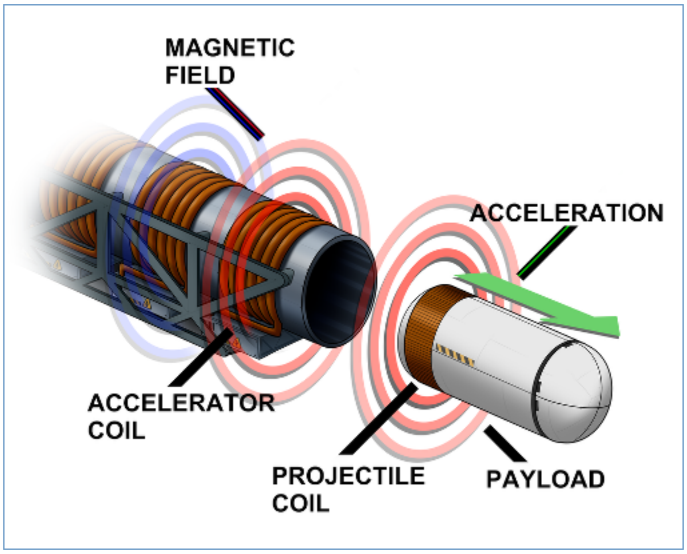
Global investment in railguns, while primarily for military application, is active and varied. China has continued steady government-backed research and development and sea trials of ship-mounted prototypes, with reports that Beijing is pushing to improve continuous-fire capability and solve erosion and power issues.[3] Japan has been one of the most visible investors, running at-sea tests (including work on the JS Asuka testbed), cooperating with European research institutes, and publicly showcasing higher-energy prototypes.[4] In the United States, the large defense primes and specialty firms (notably General Atomics and BAE Systems) have preserved railgun expertise and in 2025 began re-pitching renewed, more compact/mission-tailored concepts for air and missile defense applications.[5] European research centers such as the French-German ISL remain engaged on material, pulsed-power, and launcher-design work and are collaborating with partners including Japan.[6] Other countries including India have shown growing interest and investments with their Defence Research Development Organization (DRDO) exhibiting their “EMRG concept” at defense shows and signaling intent to continue development.

BAE Systems and General Atomics have both built and rigorously tested railguns for the Navy. After the Navy’s cancellation of the Railgun due to lack of ships able to support its power demands, General Atomics has maintained their ability to build railguns.

Coilguns

Coilguns can approach the efficiency of railguns while avoiding rail wear because the payload never contacts the barrel. They accelerate a payload using a series of solenoidal coils placed along

FIGURE 2. REPRESENTATIVE CONFIGURATION OF A COILGUN[7]

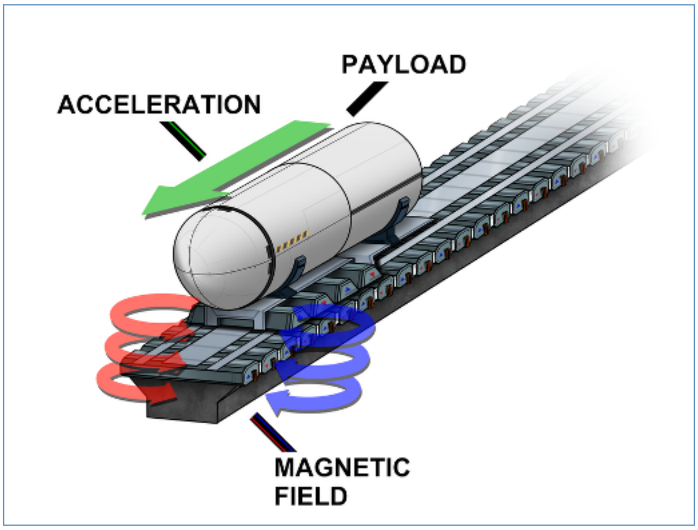


a barrel; each coil is energized in precise sequence as the projectile passes to create a traveling magnetic field that pulls the payload forward and hands it off to the next coil. Active sensing and timing control are required to switch coils at the correct moments, and energy recovery or staged capacitor systems are commonly used to shape pulses and improve overall efficiency. Coilguns lag railguns in technology readiness, and their lower practical efficiency increases demands on energy storage, power generation, and cooling. Their main advantage is simpler, lower-wear construction that is more amenable to using in situ Lunar resources.[8]

Superconducting Quenchgun

Quenchguns are a superconducting variant of coilgun mass drivers that store launch energy in the barrel's superconducting coils and then release it as a single, high-power pulse by intentionally quenching the coils. Quenching is the abrupt transition of a superconductor to a normal resistive state when a local region exceeds a critical temperature, current, or magnetic field, causing a rapid collapse of the magnetic field and a fast dump of stored energy into the launch pulse. If a quench is uncontrolled it can rapidly dump the barrel's stored energy, causing breakage or even explosion. As most energy is stored in the barrel, quenchguns can reach very high system efficiencies, commonly cited above 90 percent, while also achieving dramatically reduced overall system mass compared with non-superconducting designs.[9] They accelerate payloads without physical contact so they avoid rail erosion. Deliberate quenching requires cryogenics, fast quench detection, and robust protection circuits to prevent hot spots, mechanical damage, or coil loss. On the Moon, a quenchgun could also leverage oxygen extracted from regolith to support its cryogenic systems, reducing the need to import consumables from Earth. These requirements keep quenchguns

FIGURE 3. REPRESENTATIVE CONFIGURATION OF A LINEAR SYNCHRONOUS MOTOR SYSTEM[10]



at low technology readiness and high build cost today, though groups such as Electromagnetic Launch are pursuing development.

Linear Synchronous Motor Systems

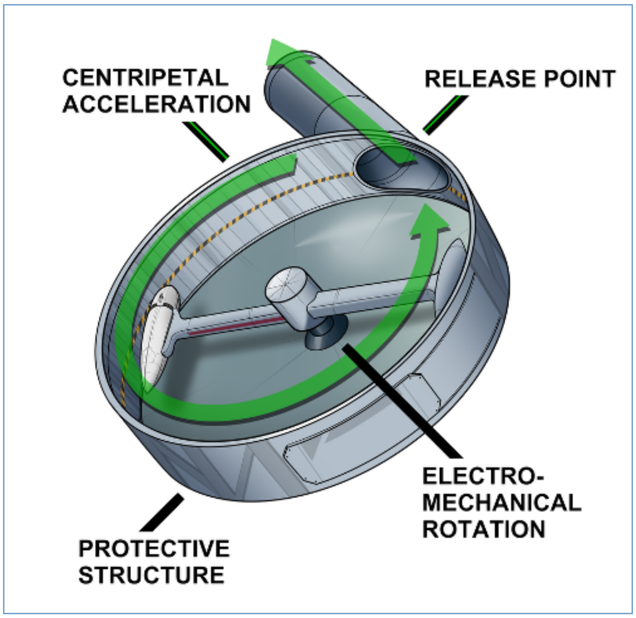
Linear Synchronous Motor Systems (LSM) accelerate payloads using a traveling magnetic field that propels a magnetically levitated or guided vehicle along a track, providing continuous, smooth acceleration with fine velocity control and minimal mechanical wear. Linear Synchronous Motor Systems are currently in use by the US Navy on the USS Gerald R. Ford class in the form of EMALS. The Chinese also have an EMALS system on their new Type 003 Aircraft carrier, the Fujian.[11] While fully mature and in active use, simply put, Linear Synchronous Motor Systems are not ideal for use as a Lunar mass driver.

Compared to all other systems they have the lowest acceleration. To reach Lunar escape velocity, many kilometers of track would be required. The material used for the track is also generally higher mass than the barrels of other mass drivers. The requirement for more, heavier track leads to significantly higher cost for construction.[12] On top of being cost prohibitive to deploy, they are maintenance heavy.

Spin Launch Systems

Spin launch systems accelerate payloads by attaching them to a rotating arm, tether, or centrifuge and releasing them at high tangential velocity. This approach allows for a very compact and

FIGURE 4. REPRESENTATIVE CONFIGURATION OF A SPIN LAUNCH SYSTEM[13]



lightweight launcher compared with railguns, coilguns, or LSM tracks, making the system cheaper and easier to deploy. While they are perhaps the easiest to construct, that is where their advantages end. Of all mass driver systems they have the smallest throughput. Spinning the system up and down between shots takes a significant amount of time. The payload experiences extremely high centripetal acceleration, between 10,000-20,000Gs.[14] This restricts them to durable or specially designed cargo. The extreme force also imparts very high mechanical stresses on the rotor, tether, and release mechanisms.

A CISLUNAR LOGISTICS PRIMER

Currently, every gram of propellant in space is sourced from Earth and must undergo a trip costing approximately 9-10 kilometers per second (km/s) before arriving in Low Earth Orbit (LEO). This change in velocity is known as Delta-V. As the amount of Delta-V a maneuver needs is proportional to the amount of propellant required, it can somewhat be thought of like fuel. Robert Heinlein's famous quote, "If you can get your ship into orbit, you are halfway to anywhere," applies. Apart from some maneuvers near the Jovians (Jupiter, Saturn, Uranus, and Neptune), the trip up from the Earth to LEO is one of the most Delta-V intensive maneuvers anywhere in the solar system.

Transferring material from LEO to Low Lunar Orbit (LLO), or vice versa, requires approximately 4.1 km/s of Delta-V. Moving between LLO and the Lunar surface adds another 1.7 km/s, bringing the total energy cost for a one-way trip to about 5.8 km/s. Each of these maneuvers consumes large amounts of propellant. This too must first travel the 10 km/s up the gravity well. This compounding fuel requirement dramatically increases the number of launches needed to enable, let alone sustain, Lunar operations. For example, SpaceXs Human Landing System (HLS) with a 100-ton payload is projected to require 10 Starship tanker launches to provide the 1,500 tons of propellant for its 11.6 km/s round trip.[15] While reusable launch vehicles have drastically lowered costs, sourcing propellant from Earth is incredibly wasteful.

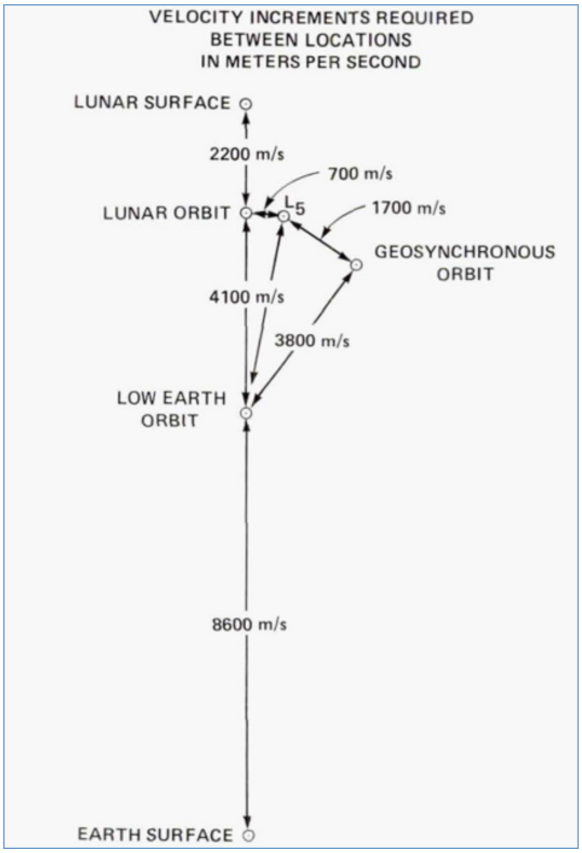
Spacecraft and payloads returning from deep space and the Moon can reduce the amount of propellant and Delta-V they need to expend through aerobraking. Aerobraking, in short, is when a spacecraft carefully skims the upper atmosphere and uses air resistance to bleed off speed instead of burning fuel to slow down. This technique can greatly reduce propellant needs. However, the spacecraft must be able to withstand the heat generated by atmospheric friction and follow a precise entry angle to avoid “bouncing” off or punching through the atmosphere.

Significant investment has gone into aerobrake technology, and it has already been proven in multiple mission contexts. For example, the U.S. Space Force’s X-37B Orbital Test Vehicle recently began performing a novel aerobraking maneuver to change its orbit while using minimal fuel.[16] Blue Origin recently unveiled a massive deployable aerobrake.[17] Aerobrakes need not be expensive deployable systems. Mass driver canisters made from ISRU Lunar steel could be easily insulated to survive the thermal load and take advantage to aerobrake and arrive in LEO.

In-Situ Resource Utilization (ISRU) offers a fundamental shift in how space operations are sustained by sourcing critical materials directly from space rather than having to send them up and out of Earth’s gravity well. On the Moon, ISRU efforts will likely focus on the extraction and processing of water ice. Once extracted, water can be split via electrolysis into hydrogen and oxygen, both of which can be used for spacecraft propellant. Oxygen can also be derived directly from Lunar regolith through reduction processes, providing an additional and abundant source of oxidizer.[19] In practical terms, this allows the most mass intensive components of space operations, particularly propellant, to be sourced locally rather than launched at extreme energy cost.

The importance of ISRU cannot be overstated. Because propellant represents the majority of mass required for most space missions, producing it on the Moon breaks the compounding logistics burden imposed by the rocket equation. Instead of launching propellant to enable missions, missions can be built around locally sourced resources, dramatically reducing launch demand from Earth. This transforms the Moon from a destination into a logistics hub, enabling sustained presence, scalable infrastructure, and continuous industrial activity in cislunar space.

FIGURE 5. DELTA-V MAP[18]



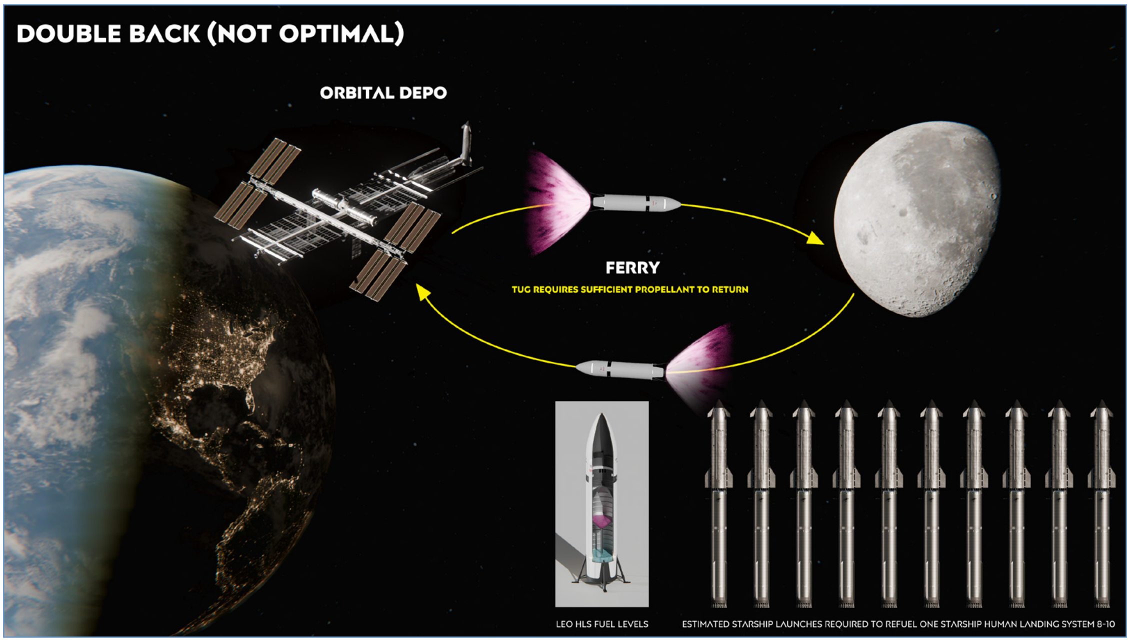
Mass Driver Impact on Cislunar Logistics

Space power is linked to the ability to move mass. Satellites and their payloads are ultimately constrained by how much mass they carry and how much propellant they can spare to maneuver. This mass can take many forms, larger, more capable spacecraft, or smaller, more distributed systems that trade individual capability for resilience and numbers. Regardless of scale or architecture, every system in space is bound by the same truth: to maneuver, you must spend propellant, and once that propellant is gone, so is your freedom of action.

Maneuver without regret is as central to space power as freedom of navigation is to naval power. A navy that cannot move freely loses the initiative and the battle. While system designers and logisticians have recognized the importance of space architectures that can refuel, every gram of fuel that is spent in maneuvers must first endure the costly trip up from the ground. The orbital propellant reserves abundant on earth are currently vital to supporting maneuver without regret.

While ISRU eliminates the expensive trip up from Earth’s gravity well, material still has to be moved to its final destination, i.e. from the Lunar surface to LEO. Delivering material from the

FIGURE 6. FERRY BASED LUNAR LOGISTICS[21]

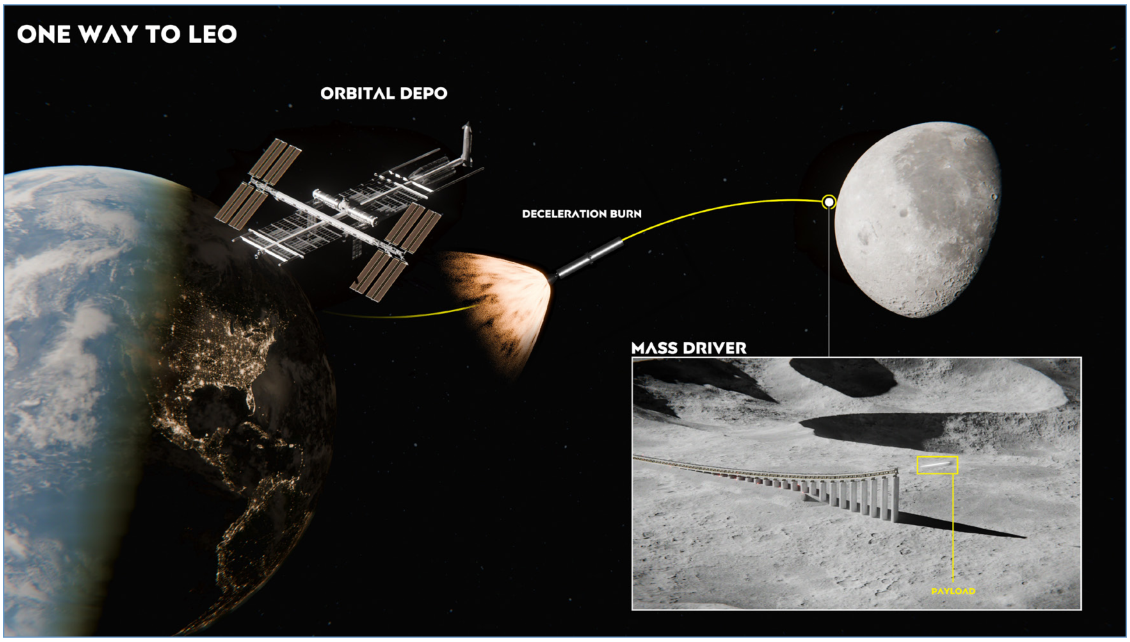


Lunar surface to LEO requires about 60% of the Delta-V that launching material up from Earth does. Moving propellant from the Lunar surface back to LEO, using rockets is only around 40% cheaper in Delta-V than bringing it up from Earth. While the velocity required for transit is effectively fixed, using higher-efficiency engines or advanced propulsion methods can reduce the overall cost of transporting Lunar material to usable orbits. Despite this, all rocket systems still must waste propellant to achieve orbital insertion. For frequent logistical trips this waste significantly adds up.

As of now, Starship serves as the practical gold-standard benchmark for low-cost, high-mass orbital delivery. In a fully reusable configuration, it is projected to place more than 150 tons into LEO for roughly $10 million per launch, including about $1 million in propellant and around $9 million in amortized refurbishment and operations costs. To deliver a 100-ton payload to the Lunar surface and return empty to LEO, the HLS variant is currently expected to require roughly ten full Starship tanker launches. Providing the ~1500 tons of propellant needed for such a mission would cost on the order of $100 million in tanker flights alone, before even accounting for the cost of the HLS vehicle itself.[20] While the amount of Earth side rocket launches can be reduced through ISRU, moving propellant back to LEO from the Lunar surface making use of rocket systems does not make economic sense.

While no public figures exist on exact propellant usage during different phases of the HLS mission, scaling from its descent profile gives a useful approximation. If delivering 100 tons to the Lunar surface consumes roughly half to two-thirds of HLS's ~1500-ton propellant load, then

FIGURE 7. MASS DRIVER BASED LUNAR LOGISTICS[22]



lifting a comparable payload back to LEO would demand a similar amount. Assuming a tanker-configured HLS could add roughly 50 tons of payload capacity compared to a human-rated version, a full round-trip logistics cycle still remains enormously propellant-intensive. Delivering approximately 150 tons of Lunar propellant to LEO and then returning to the Moon to repeat the mission would consume on the order of 1500 tons of propellant. To put it simply, the vast majority of the limited ISRU propellant would be consumed just moving material back to LEO.

Using rocket-based systems to ferry Lunar propellant means that only about 10% of any harvested mass is actually available for use in LEO.

By contrast, mass drivers can deliver nearly 100% of harvested material from the Lunar surface to LEO.

Mass-driver architectures differ dramatically in scale, performance, and complexity. For the purposes of this case study, quenchgun systems offer the clearest economic benchmark thanks to their high throughput potential, shorter barrels, and overall lower system mass.

A representative quenchgun architecture, derived from *Scaling Laws for a Superconducting Quenchgun: 1–10 Ton Payloads,* illustrates the core features of this mass-driver class. For a 1-ton payload, the launcher uses a 147-meter barrel with a 0.92-meter bore and a total barrel mass of roughly 212 tons. The payload carriage adds only 0.26 tons. Each shot requires ~1.82 GJ of stored energy and drives the payload to launch velocity at an acceleration of roughly 1,150 g—high, but

TABLE 2: SCALING LAWS[24]

Oxygen Mass (tons)	1.37	1.00	2.00	5.00	10.00
Carriage Mass (tons)	.36	.26	.52	1.31	2.63
Barrel Mass (tons)	290	212	423	1058	2120
Barrel Length (m)	172	147	207	329	1.31
Barrel Bore (m)	1.00	.92	1.10	1.38	1.64
Stored Energy (GJ)	2.50	1.82	3.64	9.12	18.20
Barrel Current Density (kA/ cm2)	14.0	15.2	12.7	10.1	8.5
Axial Force (MN)	16.5	14.2	20.2	26.7	44.9
Acceleration of (gees) Projectile	973	1150	819	514	362

Mass of support system components

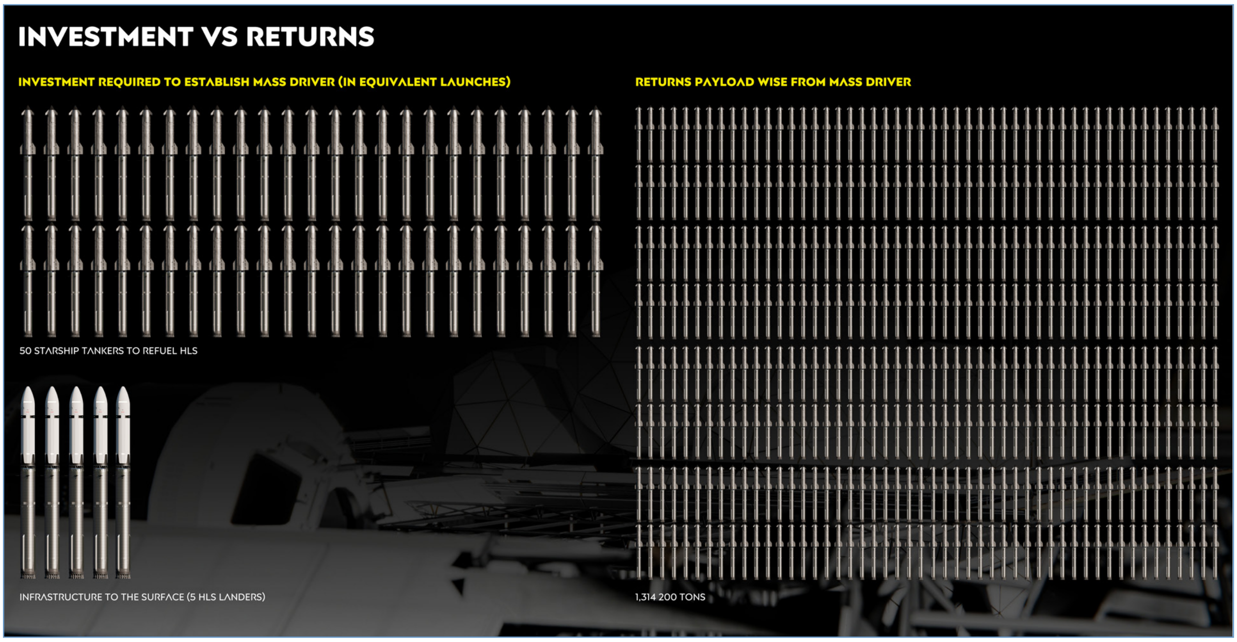
For 2 Hour Launch Rate

Power Supply	62	45	90	225	449
Refrigerator	87	65	128	319	638
Radiator	70	51	102	255	511

only a tenth of spin launcher systems. The supporting systems, about 45 tons for the power supply, 64 tons for the cryogenic refrigerator, and 51 tons for radiators, add a comparatively modest ~160 tons.[23]

A mass driver with this architecture would mass in at about 372 tons and could be deployed to the Lunar surface in four HLS. An additional 10 tanker Starships each would be required to fuel them for their Lunar rendezvous for a total of 44 Starship launches.

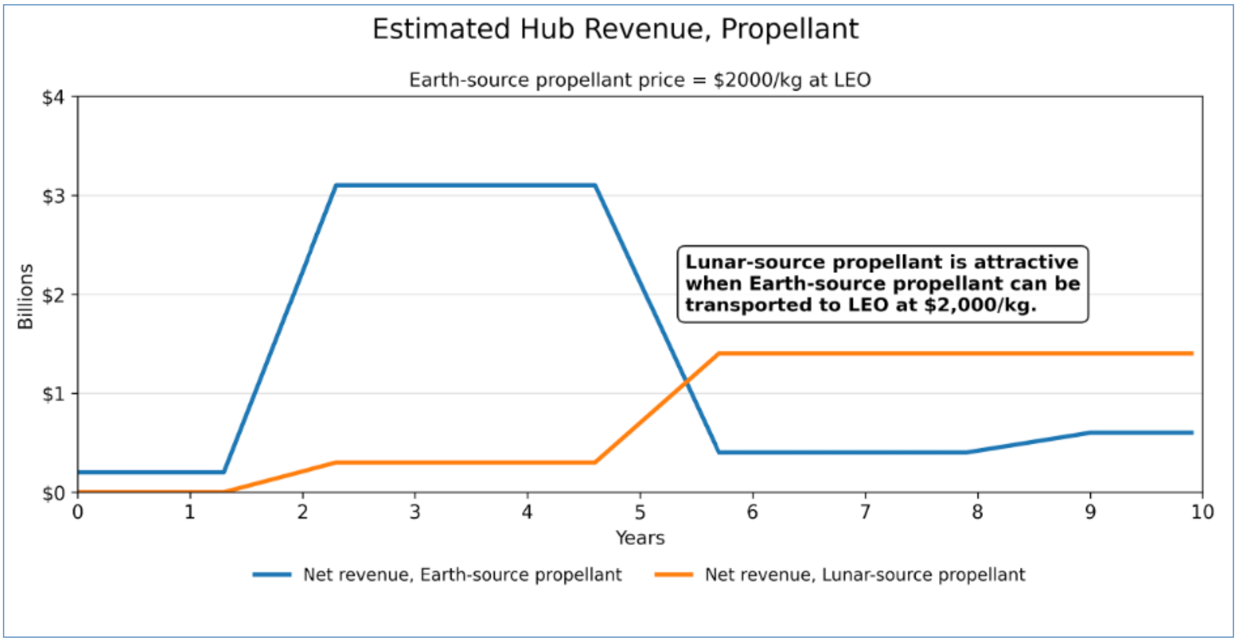
FIGURE 8. MASS DRIVER RETURN ON INVESTMENT[27]



The rate of fire of quenchguns is limited by power supply, they can scale up their rate of fire only by adding more power. With a supplied power of only 350kw, a quenchgun would be able to send 1 tonne (t) of payload to LEO at least once every 2 hours.[25] At this baseline rate of 1 ton every 2 hours, approximately 4,380 tons of payload could be delivered to LEO per year. **With 20MW of power, a quenchgun can send a 1t payload on its way to LEO once every 2 minutes**. About 262,800 tons of payload could be sent to LEO per year with that rate of fire. A single 100t HLS could deliver enough solar arrays to provide this 20MW of power.[26] 262,800 tons of payload could be delivered to LEO from Luna per year for a minor initial investment of 5 HLS and their 55 Starship launches. In terms of return on investment, a mass driver of this architecture would be able to deliver the equivalent of more than 1,314 200-ton starship launches per year. That would be a 2300% return on investment. Achieving the same throughput as a single quenchgun over a year would require about 4 launches of Starship every single day and would cost upwards of 134 billion dollars.

A mass driver would be able to move itself and rapidly pay for itself many times over. The most profitable business for a mass driver would be that of returning ISRU liquid oxygen to LEO. Operators could charge as little as $50 per Kg (*$50k per ton)* and still be more profitable than propellant sourced from Earth.[28] The absolute lowest Starship can likely achieve is $200 per Kg (*$200k per ton*). Even at a market rate of only $50 per Kg, a quenchgun mass driver would be able to generate $13.4 billion per year.

FIGURE 9. REFUELING MARKET BEHAVIORS[29]



USA Strategic Goals

American space strategy is built around maintaining freedom of action, deterring aggression, and leveraging space for national advantage. *The National Space Policy of the United States of America* (2020) recognizes that space is paramount to national security and economic growth. The policy commits to leading in the responsible and constructive use of space. Space policy outlines six over-arching principles (space security and stability, commercial growth, international cooperation, scientific advancement, human exploration, and long-term sustainability) which together guide civil, commercial, and defense space efforts. Civilly, it directs NASA to establish a sustainable human presence on the Moon as a stepping stone to Mars and to expand research that enhances understanding of Earth and the Solar System.[30]

As the United States seeks to expand its commercial presence beyond Earth orbit, American industry leaders are increasingly emphasizing the need for high-throughput, reusable transport systems capable of returning resources from the Lunar surface to usable orbits. While originally only really advocated for by the National Space Society, major corporations and emerging space startups alike no recognize that mass drivers and other forms of electromagnetics launch systems are not just paradigm shifting technology, but a bonafide requirement. They are necessary to support long-term, scalable logistics such as the Artemis program and future Cislunar operations.

Lockheed Martin considers mass drivers a cornerstone of future Lunar operations. In their Water-Based Lunar Architecture vision, they note that “once it becomes operational, the EM launcher changes the paradigm, allowing resources to be sent to orbit using electricity rather than expending more propellant than the payload itself delivers."[31] It is clear they do not view mass drivers as simply advantageous, but essential for scalable, long-term Cislunar logistics.

Beyond traditional aerospace contractors, prominent private space entrepreneurs also recognize the strategic importance of mass drivers. Visionaries like Elon Musk and Jeff Bezos, both committed to large-scale space colonization, understand that moving the massive quantities of material required for off-world settlements will demand new transport paradigms. As Musk recently highlighted on Twitter, "Starship could deliver 100 GW/year to high Earth orbit within 4 to 5 years if we can solve the other parts of the equation. 100 TW/year is possible from a Lunar base producing solar-powered AI satellites locally and accelerating them to escape velocity with a mass driver."[32] It's not just that mass drivers are recognized as strategically important, investors are putting real capital behind the technology, funding startups that are actively developing operational systems.

For example, Auriga Space secured $5 million in funding in 2023 to build a ground-based electromagnetic launch track (mass driver). Their facility in Los Angeles is focused on demonstrating how a kinetic accelerator can replace the first stage of a rocket, reducing launch costs and environmental impact by substituting a reusable track and electric power.[33] In addition to Auriga, other private companies are actively developing mass driver or launch-assist technologies.

The company Electromagnetic Launch Inc. (EML) recently patented a design for a superconducting quench launcher. Quench launchers are widely regarded as the most feasible mass driver architecture, as they require less power and infrastructure compared to other designs. EML developed the concept in collaboration with the Robinson Research Institute at Victoria University of Wellington in New Zealand, further validating the engineering behind the system and its potential for scalable, reusable transport.[34] Of the public mass driver companies, EML Inc seems to have the most scalable design.

Compared to the two previously mentioned companies, SpinLaunch imparts velocity through centrifugal acceleration rather than linear acceleration. The company successfully conducted a series of subscale flight tests at Spaceport America, culminating with Flight Test 10 in September 2022, demonstrating that payloads could be accelerated to high speeds and recovered intact.[35] Since then, no additional public flight tests have been reported, and the company has recently shifted focus toward developing its Meridian Space satellite constellation, at least initially using conventional rockets.[36] While the strategic value of mass drivers is clear, current investment remains cautious.

The majority of funding focuses on Earth side space launch, competing with traditional rockets, rather than focusing on its greater potential as Lunar infrastructure. As the Artemis program establishes a permanent presence on the Lunar surface, a race to develop and field mass drivers will follow.

PRC Strategic Goals

China's space strategy is built around self-reliance, technological leadership, and the pursuit of long-term national strength through the peaceful development of outer space. The State Council Information Office of the People's Republic of China published the 2021 White Paper *China's Space Program: A 2021 Perspective*, which outlines the nation's official policy for space activities. The document emphasizes that space development is a core component of China's national modernization strategy and a reflection of its growing comprehensive power. President Xi Jinping summarized this ambition clearly, stating, "To explore the vast cosmos, develop the space industry, and build China into a space power is our eternal dream." The space industry is presented as a critical element of the national strategy, with China upholding the principle of exploration and utilization of outer space for peaceful purposes.[37] The PRC recognizes that Lunar ISRU is a key cornerstone for supporting their long-term space ambitions.

China has been investing heavily in mapping and sampling the Lunar surface in preparation for future, long term efforts. The Chang'e 5 mission returned roughly 1.7 kg of Lunar material in late 2020, making China the third nation to return Lunar samples successfully.[38] Building on that success, Chang'e 6 landed on the far side of the Moon and successfully returned 1.9 kg of material to Earth in June of 2024. Chang'e 6 is currently the only successful mission to return samples from the far side of the Moon.[39] Chang'e 7 is planned for the second half of 2026. In effect, it is a Lunar Prospector, with its primary mission to explore the resources of the South Pole, especially for evidence of water. Chang'e 7 is set to consist of an orbiter, a lander, a rover, and a mobile hopper, capable of exploring deep in the unlit regions of Lunar craters where ice and water are likely abundant.[40] Compared to previous Lunar efforts by the PRC, Chang'e 7 will additionally be a joint venture with ROSCOSMOS, the Russian space agency. ROSCOSMOS will provide equipment to study the dust components and dynamics of the Moon's near-surface exosphere.[41] Chinese and Russian collaboration extends beyond robotic Lunar missions, encompassing long-term initiatives such as the International Lunar Research Station (ILRS), a multinational effort to establish a semi-permanent research and operational outpost on the Moon.

The ILRS represents the centerpiece of China's long-term Lunar ambitions. Initiated by China, it currently involves 17 countries and international organizations, as well as more than 50 research institutions worldwide.[42] The first mission set for ILRS will enable research and human occupation. Immediately following habitation and the identification of material, the PRC and ILRS signatories intend to begin ISRU validation and the exploitation of Lunar resources.[43] Like with Western and American efforts towards Cislunar industrialization, the value of mass drivers is not lost on the Chinese. Researchers from the Shanghai Institute of Satellite Engineering and the China Academy of Aerospace Science and Industry have proposed several architectures that combine magnetic levitation and rotational acceleration technologies to return Lunar resources to Earth efficiently and repeatedly. Their 2024 study, *New Technology of Lunar-Based Magnetic Levitation Rotational Ejection Return System* published in Shanghai Aerospace, describes a hybrid mass-driver concept designed specifically for the Moon's low gravity, vacuum, and cryogenic environment.

Their system, referred to as a "magnetic levitation rotary ejection return device" uses superconducting motors and a rotating arm suspended on magnetic bearings to accelerate payloads to beyond Lunar escape velocity, releasing them precisely into return trajectories. According to the study, the device would require only electrical power, leveraging the Moon's cold, vacuum environment to minimize cooling and mechanical wear, and could operate multiple times per day with minimal maintenance. The proposed prototype features a suspended track less than 100 meters in diameter and would consume roughly 1.3 MWh per launch, while recovering up to 70% of that energy through regenerative braking. The authors estimate that such a system could reduce the cost of transporting Lunar material to Earth by an order of magnitude compared to traditional rocket ascent methods.[44]

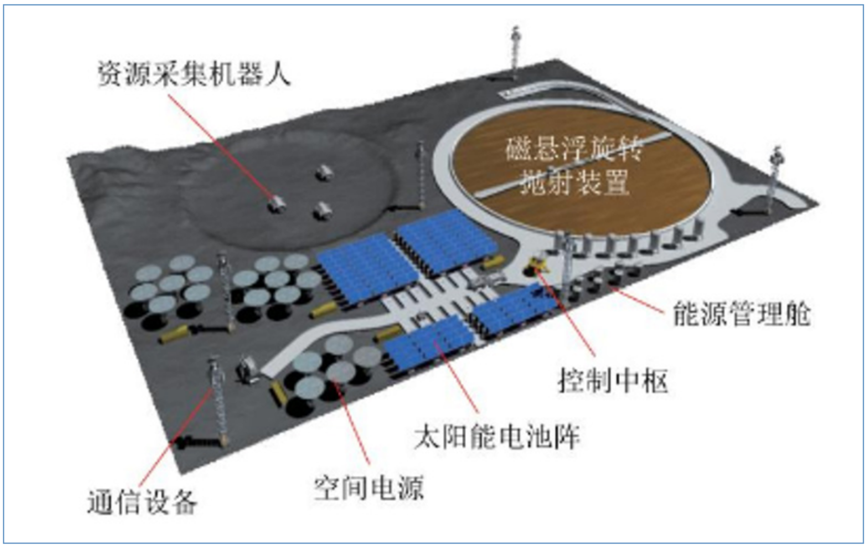
In parallel, Chinese scientists at the Shanghai Institute of Satellite Engineering have also developed plans for a rotating Lunar launcher, a centrifugal acceleration system analogous to the American SpinLaunch concept. This rotating launcher would use mechanical rather than linear acceleration to impart orbital velocity to payloads, offering a high-throughput, fully electric means of launching cargo from the Lunar surface. Researchers have claimed that the system could operate at roughly 10% of the cost of conventional rockets while supporting frequent, automated launches to Lunar orbit or Earth return trajectories.[45]

Both initiatives reflect a clear recognition by the PRC that mass drivers and related launch-assist technologies are critical to achieving large-scale Lunar resource utilization. By linking these developments with its ILRS program and long-term Lunar industrialization goals, China positions itself to gain a first-mover advantage in establishing a repeatable, low-cost logistics chain between the Moon and Earth, a foundation for the broader "Earth-Moon economic circle" envisioned in Chinese space policy.

MASS DRIVERS AS A MILITARY WEAPON

First-strike weapons are systems engineered to disarm an adversary before it can mount an effective counter-value or counter-force response. Historically, systems like the Pershing II Medium Range Ballistic Missile (MRBM) and SS-18 Satan were considered first strike weapons as, due to their short response time, accuracy, and payload, they could strike an adversary's strategic nuclear forces or command infrastructure before launch orders could be issued or executed.

FIGURE 10. CONCEPT OF LUNAR RESOURCE DEVELOPMENT SYSTEM[46]



Any complete disarming first strike would have to, at minimum, target missile fields, strategic bomber bases, and Nuclear Command, Control, Communications infrastructure (NC3). Doing so with “traditional” means would require hundreds of nuclear warheads, likely committing the majority of a state’s strategic inventory in a single “strategic launch.” Since the 1960s, early warning and tracking systems have been, and are still being optimized to watch for the unique signatures of SLBMs and ICBMs that would be used in such a strike. While launch sites can be disguised and Fractional Orbital Bombardment systems (FOBs) can evade known radar sites, any ballistic missile launch would still alert systems like Space Based Infrared System (SBIRS). Any ICBM or SLBM launch against the United States would provide enough warning and attribution sufficient to enable counter force, or counter value retaliation. As such, any enemy is greatly deterred from engaging in a strategic launch against the United States from the threat of Mutually Assured Destruction.

While mass drivers can bootstrap an off-world economy, they carry an equally potent and unsettling military capability: the ability to operate as an **unassailable, undetectable first-strike platform**. A mass driver that can send a 1 ton payload of propellant from the Lunar surface on its way to LEO can likewise fire a 1 ton warhead at anything in orbit or on the surface of the Earth. Survivability being a primary consideration in any strategic weapon system, the Moon offers mass drivers an inherent advantage in this regard.

During the 1960s Cold War, planners studied the military potential of Project LUNEX, which examined basing nuclear missiles on the Lunar surface where Earth-based strike systems would have virtually no ability against them. Similarly, Lunar mass drivers would inherently be invulnerable to all existing strike systems and plans. Any counterforce action from Earth would require a dedicated launch vehicle and multiple days in transit. During said transit, a weaponized mass driver could unleash its entire magazine with impunity. Because of that temporal gap, effective counterforce would necessitate pre-positioned strike assets in Cislunar space.

Pre-deployment carries its own technical, political, and fiscal costs. It requires a sustained logistics tail, robust space-domain awareness, and credible strike capability in Cislunar orbit. Stationing kinetic assets in Cislunar space, due to a potential, unrealized threat would raise serious escalation and arms-control questions. Since it would be based on a celestial body, a Lunar mass driver would not be constrained by the same mass requirements spacecraft are. As such, they could readily be reinforced with regolith and armor plates to survive most kinetic attacks.

Reinforced mass drivers would likely be significantly more resistant to nuclear strikes than Earth side missile silos. Nuclear weapons derive most of their destructive power from their blast pressure wave. As the Moon lacks an atmosphere to conduct said pressure wave, a nuclear detonation force would be reduced to thermal and other forms of radiation. Without needing to account for the shockwave, strategic assets would not require the same degree of hardening as Earth side assets.

Apart from hardening, a Lunar mass driver site would likely have the power supply and support infrastructure to support high power systems such as radars and lasers capable of providing a defensive screen against most incoming fires.

Lunar mass drivers are most vulnerable while still under construction. Acts short of war, such as physically disrupting construction through rover interference or on-site sabotage, could halt or delay their completion. Political and economic pressure could also be applied on the Earth side to restrict the launch of critical hardware or components needed to complete the system.

Earth-based segments of the supply chain present additional points of vulnerability. Launch vehicles, integration facilities, and transport infrastructure are all potential targets for disruption. Interference at launch sites, delays in vehicle readiness, or damage to ground support equipment could significantly slow deployment timelines. Similarly, components could be compromised prior to integration through tampering, or supply chain interference.

Cyber operations present an additional and potentially covert attack vector. Regardless of design, all mass drivers will require precise timing, power management, and thermal control systems to operate. Manipulating firing sequences, power delivery, or guidance inputs could result in catastrophic or total loss of a system.

In a more escalatory scenario, direct military action could be taken to prevent or delay the completion of a mass driver. This could include the interdiction of launch vehicles prior to or during ascent, denying the delivery of critical components to the Lunar surface. Integration facilities and launch pads represent concentrated, high-value targets which, if damaged or destroyed, would bring mass driver and space operations to a halt.

Launch vehicles and payloads may also be vulnerable during transit, particularly in predictable transfer or staging orbits, where they could be tracked and targeted before reaching their destination. The reliance on a limited number of launch windows and trajectories further compounds this vulnerability.

On the Lunar surface itself, construction sites could be directly targeted with kinetic fires to damage or destroy partially completed infrastructure. Even absent kinetic fires, low and close overflight could disrupt operations by kicking up regolith via its engine plume. Given the fragility of early-stage infrastructure and the difficulty of repair in the Lunar environment, even limited disruption could have outsized effects on timelines and overall viability.

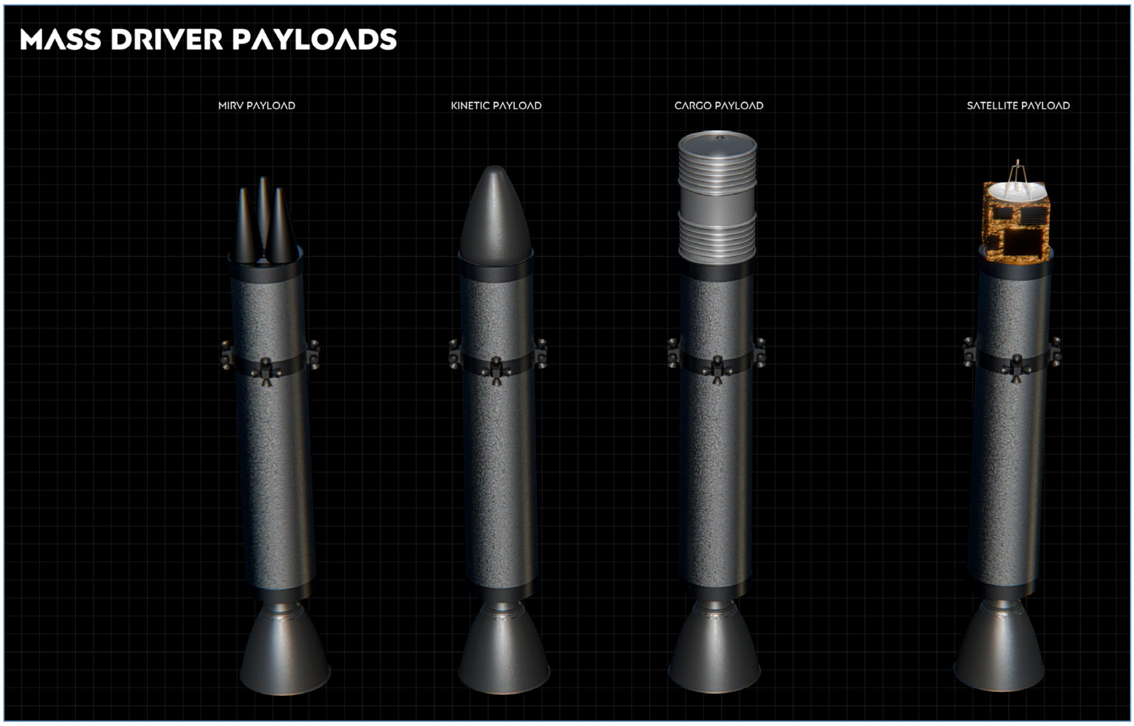
Apart from being highly survivable assets, Lunar mass drivers are uniquely positioned to provide nearly undetectable strike capability. They sit entirely outside the view of current early warning systems. Compared to missile systems, they do not have an easily detectable infrared signature.

Since the 1960s, the United States has invested heavily in successive generations of ground-based radars and satellite systems to provide early warning of a strategic attack. Space based early warning-based systems like SBIRS look down towards Earth to detect and track missile launches from their large infrared (IR) signature. Ground based radar systems like Upgraded Early Warning Radar (UEWR) provide early missile warning, tracking, and classification. These systems are excellent at what they were built for: detecting high-energy rocket plumes, boost-phase signatures, and objects in reentry on steep ballistic arcs. They are optimized to watch for ballistic missile attacks from elsewhere on Earth. Even dedicated space-based tracking systems like the AN/FPS-85, part of the Space Force Space Surveillance Network (SSN) and the most powerful radar on Earth, are only optimized to track targets out to GEO.

Lunar mass drivers located on the moon sit entirely outside of existing early warning and attribution architectures. Additionally, without propellant, mass drivers do not give off a major IR signature like a missile or spacecraft launch would. As such, any early warning and tracking system tasked with watching for hostile use of a mass driver would necessitate a space-based, high power radar system. Such a system would likely require many space-based high power radar stations in order to cover all potential orbits a strike may pass through.

In addition to their survivability and a complete lack of assets to provide early warning, a mass driver could deliver massive, precisely timed strike packages capable of penetrating defenses. As mentioned previously, a mass driver could fire a 1 ton, 1m payload at a rate between once per minute to once per hour. With this rate of fire, a mass driver could deliver between 24-1,440

FIGURE 11. REPRESENTATIVE MASS DRIVER PAYLOADS[47]



tons of payload per day. By comparison, all 76 remaining B-52s combined have a total max strike capacity of 2,660 tons. In a single day, one mass driver can deliver the same tonnage as 50% of the B-52s currently in service. Compared to strategic bombers, which are limited by their sortie rates, a Lunar mass driver could continue to deliver tons on target until it runs out of munitions.

As a weapon, payloads would likely fall into one of three categories:

1. Kinetic Energy Impactor (KEI)

2. Satellite & Anti-Satellite (SAT/ASAT)

3. Nuclear Reentry Vehicle (RV)

Kinetic Energy Impactor (KEI)

KEIs need little in the way of introduction. Think of a rock smashing into something fast. A Lunar mass driver could be used exactly as depicted in Heinlein's 1966 classic *The Moon is a Harsh Mistress*—to strike targets with dense, non-explosive slugs made from ISRU material at high velocity. Coming in from a Lunar trajectory, the terminal velocity of KEIs would be at minimum

3.7 Km/s. Even assuming in the worst case that half of a 1000kg slug was used for course correction and minor maneuvering, it would still result in 3400 MJ of energy on target. A conventional BGM-109 Tomahawk Land Attack Missile (TLAM) has roughly 2000MJ of energy on target. A single KEI from a Lunar mass driver has almost double the energy on target than a TLAM. Consider it comparable to a TLAM striking U.S. forces and allies anywhere on Earth at least once an hour with absolute impunity.

Satellite & Anti-Satellite (ASAT)

While modern ASAT systems offer little in terms of warning, the launches can still be tracked and categorized by systems like SBIRS. ASATs deployed from a Lunar mass driver could strike with no warning. As ASATs are highly complex and sensitive systems, in order to survive being launched from a mass driver, they would need to be majorly hardened. Assuming the worst case, a mass driver could deploy two 500kg ASATs in a single launch. This is akin to the U.S. or its allies losing at least two satellites every hour. Thankfully, compared to KEIs, which would be primarily manufactured on site using ISRU material, ASATs are highly complex and would more than likely have to be manufactured on Earth and then shipped up. This supply chain would provide more vectors for gathering intelligence of a potential attack. As off-world industry develops, the supply chain would evolve, resulting in the capability of shipping up ASAT systems whole. Instead, components like the seeker, or even subcomponents, could be freighted up from Earth. However, until off-world industry matches that on Earth, it is very unlikely that ASATs would be manufactured wholesale on the Lunar surface.

Beyond ASAT applications, a Lunar mass driver could also be used to rapidly emplace space-based missile defense systems such as those envisioned under the Strategic Defense Initiative, as well as more recent concepts like Golden Dome. While little public detail is available regarding Golden Dome, it is likely to draw heavily on the same foundational research conducted under SDI, particularly in the area of space-based interceptors and layered missile defense architectures. Large space-based laser or particle beam platforms would not be viable for emplacement via a mass driver due to their high mass, volume, and structural sensitivity requirements. In contrast, hit to kill interceptors such as Brilliant Pebbles (BP) are well matched for mass driver emplacement.

Hit-to-kill kinetic interceptors are well suited to mass driver launch primarily due to their relatively compact form factor and simplicity when compared to beam systems. Historical SDI designs indicate that a complete interceptor, including its Kinetic Kill Vehicle (KKV) and its support systems "Lifejacket," would have a combined mass around 800 kilograms.[48] Depending on the amount of post-launch Delta-V required for maneuvers, a mass driver launch could set in motion at least one BP unit to LEO per shot. To provide effective coverage, hit to kill systems like BP require hundreds to hundreds of thousands of units to be fielded. As such, the practicality of mass driver deployment comes down to its rate of fire.

A system like Global Protection Against Limited Strikes (GPALS) required 4067 BP interceptors to provide protection from limited ballistic missile attacks.[49] At a low rate of fire of once every two hours, it would take around 11 months to field a complete network. At a high rate of fire, once every two minutes for example, it would take only six days to field the full network. A “small” system like GPALS would provide very limited protection against ballistic missile attack, but still take at best weeks to field. Like with ASATs, Hit-to-Kill vehicles like BPs are highly complex and would require a massive Cislunar industry to support their local fabrication. As such, for the foreseeable future, they would have to be manufactured on Earth and delivered to the Moon prior to deployment. This long logistical chain and long deployment time makes the use of mass drivers for fielding space-based missile defenses somewhat impractical.

Nuclear Reentry Vehicle (RV)

Apart from enabling conventional strikes, Lunar mass drivers are uniquely suited to deploy nuclear warheads, acting in a manner analogous to ICBMs or SLBMs. The American W87 Mod 0 nuclear warhead and RV, currently fielded on the Minuteman III and planned for the LGM-35 Sentinel, is estimated at under 300kg while yielding roughly 300kt. Even with additional hardening and a maneuvering bus, two to three W87-sized RVs could be launched on a single 1,000kg mass-driver payload.

While warhead flight time from the Moon would take days compared to hours with traditional launch vehicles, more time in flight does not equate to more warning of a strike. This is especially the case if non-hostile, civilian industrial payloads follow a similar trajectory. As a result, attribution and timely targeting decisions would be severely degraded. Even space-based interceptor concepts (i.e. Golden Dome) would likely be ill-suited to engage such threats because they will be optimized for targeting high-energy, short-arc boost signatures. Terminal ballistic-missile defenses would likely be the only useful defense against such a strike. That said, there are a number of hurdles inhibiting use of Lunar mass drivers as a vector for strategic nuclear strikes.

The Outer Space Treaty prohibits military installations on celestial bodies as well as the deployment of nuclear weapons in space. As mass drivers are mixed use and would be primarily for civilian applications, this would heavily obfuscate the exact purpose of any system as to whether it is a military installation. Staging nuclear weapons on the Moon would be an unequivocal violation of the Outer Space Treaty and unmistakably a hostile act. Any attempt or serious consideration to staging warheads on the Moon would be treated as an existential threat, and most states would interpret it as an imminent warning of a first strike. Observers would be forced to assume the worst and act accordingly.

Like with ASATs, nuclear warheads are incredibly complex systems and, without serious Lunar industrial capability, they would have to be secretly transported up from Earth. In a modern intelligence environment, such movements would leave many observable seams: tightened security and unusual manifesting at launch sites; masked or obfuscated payloads; deliberate attempts to blind or confuse GEOINT assets; discrepancies in declared inventories or "missing" warhead components; and anomalous, sustained industrial signatures on the Lunar surface. Any one of these signals would be cause for concern. Taken together they would strongly indicate an adversary attempting to arm a mass driver with special weapons. It is not inconceivable, however, that a hostile power could covertly transport a number of warheads without detection by Western intelligence agencies.

As with ASATs, it is possible to manufacture nuclear warheads from ISRU material. There is a small but non-zero amount of fissiles (such as uranium and plutonium) in the Lunar regolith. These fissiles are significantly more common than Helium-3 and would likely be captured and kept as part of any ISRU harvesting process. Enriching these fissiles would require very specialized equipment. As such, it is likely that any attempt to make nuclear weapons using Lunar ISRU material could be detected. Nevertheless, as industry grows in Cislunar space, fissile material must be closely tracked.

ENSURING PEACEFUL USE

With the unique potential to completely upend logistics and security in space, it is very likely that nations not included in the development of mass drivers will view them as hostile systems, even if built with innocent intent. States that are left out of the construction process will have strong incentives to portray mass drivers as dangerous and in bad faith in an effort to delay or prevent their deployment and preserve the status quo. Ensuring peaceful development and use will require international cooperation and political treatment similar to other strategic technologies. Just as the INF Treaty, SALT I and II, and the NPT relied on limits, transparency, and verification to manage destabilizing capabilities, any future governance regime for mass drivers will require similar mechanisms.

Oversight should begin at the political level and agreements should restrict the development of architectures that are easily weaponized and establish limits on acceptable payload flight paths. Smaller and lighter individual payloads reduce the risk of use as a weapon, while trajectories that avoid aerobraking maneuvers are less threatening to Earth. Although such design and trajectory limitations can mitigate weaponization risks, they also reduce the overall logistical effectiveness of mass drivers. As such, a careful balance needs to be struck. Should a political solution be viable, verification becomes possible.

Verification would occur primarily in space or on the Lunar surface. Although mass driver components and payloads intended for Luna could in theory be inspected before launch, there are far too many ways to evade this process. Any prohibited hardware could be launched on a conventional rocket with minimal notice, and no nation would even contemplate allowing foreign inspectors to examine its space payloads. Any physical inspections for verification would likely occur at the mass driver site on the Lunar surface. Inspections there would verify compliance with design and configuration. Physical inspections of the site could also verify that weaponized payloads are not present. Physical inspections by international personnel would require a great amount of international good will and cooperation, but would provide the highest level of confidence in ensuring peaceful use.

Regardless of cooperation, the first and last leg of ensuring peaceful use of mass drivers would stem from Cislunar intelligence, surveillance, and reconnaissance (ISR) assets. Imaging and remote sensing platforms in Lunar orbit would provide vital intelligence on facilities and infrastructure. Both surface and subsurface activities could be monitored via existing sensors such as EO/IR as well as LIDAR. While much could be obfuscated from imaging and sensing, attempts to deliberately blind imaging platforms designed to keep tabs on mass drivers could only be interpreted as an immediate prelude to hostile use.

Apart from keeping track of mass driver development, a robust Lunar imaging network could provide benefits for landing telemetry, prospecting, science, industrial development, disputing incidents as well as aiding in any potential search and rescue efforts. While a robust Lunar imaging network could provide early indications of hostile development, a robust space-based radar and tracking network would provide early warning of hostile use. Radar platforms based throughout Cislunar space, akin to "Space Fence," would provide tracking information on mass driver payloads and would give ample warning time should payloads deviate from their declared trajectory. Regardless of mass driver development, in theater space domain awareness (SDA) assets will be of utmost importance for orbital deconfliction, space traffic control, planetary defense, search and rescue operations, as well as potential security operations. Should "arms control" efforts and diplomatic means of preventing hostile use fail, the United States must have the means, in theater, to detect hostile action and promptly and kinetically respond.

A WORST-CASE SCENARIO:

Should the United States fail to invest in a robust Cislunar tracking and strike capability, the following scenario will be more than entirely possible.

We only got a chance to figure out what had happened after the surrender. The PRC's brand-new Lunar mass driver had been operating for nine months at the time it all happened. We had been watching the payload slugs arrive in Low Earth Orbit at the Chinese propellent depot. With their cheap stockpiled ISRU propellant, they had been able to capture the market for off world logistics. With their glut of reaction mass and Lunar steel, they were clearly going to beat us to the red planet. For every Starship we put into LEO, it would take us another 10 launches before we could send it anywhere. With a hydrolox transport system, they only had to launch what they needed—why ship up the gas as well? While the Chinese clearly had us beat economically and industrially, we still had military parity, as well as nuclear superiority. We even had a Golden Dome protecting us from any counter value strikes they may try if it came to that.

While they may be able to keep us from protecting Taiwan, at least we were protected at home—or so we thought. Every wargame, posture review, and briefing to Congress said the same thing: any attempted strike against the homeland would light up our warning grid like a Christmas tree.

There was nothing our satellites could have seen. The first indicators weren't alarms, they were absences. Data feeds died, relays cut out, and for a few confusing minutes we assumed it was just interference. Then we realized it wasn't just a single satellite that was down, it was almost the entire C4ISR network constellation. It didn't matter where or what it was. Our birds in LEO, GEO, MEO, and even some of our distributed Starshield and Starlink networks were just gone. There were no launches detected, no IR signatures, nothing for SBIRS to flag or the Golden Dome to engage during its boost phase.

By the time anyone realized an attack was underway, the sky was already falling. It all happened so fast it might as well have all happened at once. Kinetic Energy Impactors rained down on the missile fields. While not as survivable a deterrent as boomers, one of the primary benefits of our silos was that an attacker would have to waste limited warheads to destroy them, warheads that would otherwise be bound for cities. While our silos were hardened to survive near misses from nuclear weapons, there isn't much that can shrug off an encounter with half a ton of Lunar steel traveling at 3km/s. They didn't even bother using nukes for that part of their plan.

The Chinese probably could have pulled off the whole strike without even bothering to use any nukes. They could have just kept firing KEIs—and probably would have if not for the fact that they could fire at least two warheads in the time it took to fire one KEI. All said and done, it was considered a "very limited nuclear strike." Our bomber bases at least got the dignity of needing a nuclear warhead to put them fully out of commission. Whiteman, Barksdale, and Minot all found themselves on the receiving end of a strike that they had been poised to deliver for nearly a century. With no warning, no alert, and no scramble order, almost the entire air fleet was lost on the ground. Our triad was down to its last leg.

While our submarine-based deterrent was safe from strike, being mobile and nearly undetectable, our methods of ordering them to strike were not nearly so safe. To talk to boomers on patrol you need special equipment: ELF/VLF transmitter farms at Cutler, Jim Creek, and Lualualei would all experience a multi kiloton sunrise to keep them from talking. Tinker, Travis, and Offutt would share a similar fate. While they were not bomber bases, they hosted aircraft such as the E-6B TACAMO and E-4B NAOC, airborne backups for ensuring that nuclear launch orders could be sent. While our boomers remained afloat, they and their crews had no idea that anything was happening. As we tried to establish the deep-reach link, and strike in kind, it was all called off. National command authority had been given an ultimatum with only one real option—accept the strike and attempt no launch of our own or our cities would be next.

There was nothing we could do…after all, they had the ultimate strategic high ground.

RECOMMENDATIONS

The United States faces a narrowing window to shape the strategic environment of the Lunar frontier. Mass driver infrastructure will be an unparalleled source of space power due to its ability to move strategic mass at a rate traditional systems cannot hope to compete against. For these reasons, the United States must take measurable steps towards practical development of Lunar mass drivers as soon as possible. If the United States fails to invest in the practical development and ample fielding of Lunar mass drivers, competitors will be granted the ability to dictate their use and control space power. To secure the economic benefits and negate strategic risk, the United States should undertake the following actions:

1. The United States, via the Artemis Program, should pursue an aggressive campaign to establish a distributed permanent presence at certain locations of the Lunar south pole and equatorial regions.

Regardless of design and economics, perhaps the most limiting factor when it comes to mass driver development is that of location. The location of a mass driver on the Lunar surface dictates the trajectories it can support and the destinations its payloads can reach. Only certain regions on the Moon can launch payloads onto efficient Earth-intercept orbits and there are only a few viable polar sites capable of sending material directly to low Earth orbit.

These limited polar locations are arguably the most valuable real estate on the Moon. The adjacent permanently shadowed craters are expected to hold high concentrations of volatiles such as carbon, ammonia, and water. Outside the shadowed areas, the terrain receives near-continuous sunlight rather than the long, cold Lunar night that dominates equatorial regions. This makes solar power consistently available, which is ideal for supporting consistent mass driver operations. Mass drivers operating via solar power outside of the poles would need large amounts of power storage or they would be reduced to 50% availability during the long Lunar nights.

Due to the abundant continuous power, increased presence of volatiles and very limited sites for mass driver development, the United States should pursue an aggressive campaign to establish presence at polar sites ideal for future mass driver development. Having an established presence at these locations would give the United States de facto control of these strategic locations. With supporting ISRU infrastructure in place, the United States could develop its own drivers at these locations, work cooperatively with friendly nations, and prevent the use of these sites by hostile powers.

Apart from impacting mass driver development, establishing a distributed presence at the Lunar south pole has the secondary advantage of establishing de facto control of areas with high-value resources. Even if the United States fails to invest or develop mass drivers, having access to the largest reserve of volatiles in Cislunar space will give the United States significant leverage.

2. The United States should collaborate with allied nations and commercial entities in investing in Lunar Mining Operations and ISRU efforts to maximize the capabilities of a Lunar mass driver.

Mass drivers are only as effective as the industrial ecosystem that feeds them. Even a modest driver operating at low cadence will require a steady supply of processed regolith, water ice, refined volatiles, and construction materials. Without robust Lunar mining and ISRU infrastructure, a mass driver becomes an underutilized asset rather than a transformative logistics system.

To enable long-term, high-throughput operations, the United States should pursue joint mining and ISRU efforts at the same strategically valuable sites identified for permanent presence. Commercial operators within the Artemis coalition should be supported in fielding excavation systems, regolith handling equipment, volatile extraction plants, and refining units capable of producing both propellant and bulk materials. These activities will create the material flow needed to justify mass driver construction and ensure that the system is not limited by supply constraints.

Cooperation with allied nations provides two primary advantages. First, it distributes the financial and technical burden of establishing mining and processing hardware. Second, it creates shared equity and transparency in the early stages of mass driver development. As actors process ISRU material on hand, they will become invested in developing and maintaining systems like mass drivers, allowing them to get their greatest return on investment.

Through combined investment, joint operational sites, and clear interoperability standards, the United States can ensure that the industrial foundation for mass driver operations is in friendly hands. This creates long-term stability, lowers costs, and strengthens the position of the United States and its partners as leaders in the Lunar economy.

3. The United States Space Force must develop a robust Cislunar sensor network in order to maintain Space Domain Awareness.

The need for robust Cislunar Space Domain Awareness does not depend on whether the United States chooses to build a mass driver. At present, the Earth Moon system remains largely unmonitored, with only limited and intermittent visibility beyond geostationary orbit. As activity expands outward from Earth, this region will transition from a benign frontier into a contested environment. While not inherently hostile, Cislunar space will host competing national, commercial, and scientific interests whose actions must be observed and understood in real time. Without a substantial expansion of awareness, the United States risks operating in a domain where meaningful activity can occur without detection.

Robust Cislunar awareness is essential for planetary defense. Many potentially hazardous natural objects already transit the Earth Moon system, and future resource extraction or redirection missions by other spacefaring nations could alter their trajectories. Without the ability to continuously observe and characterize small bodies across the entire region, the United States could miss early signs of a developing hazard or fail to detect activities that unintentionally increase risk to Earth.

It is equally important for space traffic management. As more spacecraft, tugs, depots, and uncrewed platforms begin operating near and around the Moon, the probability of collision or interference will rise. Cislunar operations will require new routing standards, deconfliction procedures, and shared situational awareness. A lack of tracking capacity would turn the region into an opaque and hazardous environment, where even routine maneuvers create uncertainty and operational friction.

Most critically, inadequate Cislunar SDA creates opportunities for adversaries to operate below the threshold of open conflict. With today's sparse monitoring, a foreign actor could assemble infrastructure, shift assets, or launch small payloads without timely detection. Incremental moves that alter the strategic balance could occur without triggering immediate political response simply because they were not observed. This visibility gap invites gray zone behavior that undermines stability.

To close this gap, the United States Space Force should pursue high capability in space and on orbit systems. In space, high power radar platforms will be vital to providing broad SDA capabilities. To augment this capability, the Space Force should increase investment in on-orbit imaging as well as EO/IR systems akin to SBIRs, but optimized for tracking signatures in Cislunar space. Together, these systems would allow continuous monitoring of natural objects, commercial traffic, and foreign operations, ensuring that no actor can conduct significant activity in Cislunar space without being observed. Without a comprehensive and resilient SDA capability, the United States risks being strategically blind in a region that will rapidly become central to security, commerce, and long-term space governance.

4. The United States should establish a strategic Lunar ISRU propellant reserve through long-term bulk procurement agreements.

The primary obstacle to mass driver development is not technical feasibility, but the absence of guaranteed demand. No private firm can justify the capital investment required to build high throughput Lunar transport infrastructure without confidence that a sustained market will exist. Rather than attempting to prescribe specific architectures or development pathways, the United

States should create demand conditions that allow industry to determine the most efficient means of delivery.

The United States government should establish a strategic reserve of Lunar derived propellant and bulk materials, analogous to terrestrial strategic reserves, sourced through long-term procurement contracts. Under this model, the government would commit to purchasing large quantities of oxygen, water, or other ISRU products delivered to specified orbits. To further reinforce these incentives, procurement contracts for the strategic ISRU propellant reserve should be structured around throughput rather than transport method. Baseline pricing would apply to initial delivery quantities, with higher unit prices or milestone-based cash awards triggered as delivery volumes increase. This structure rewards systems capable of sustained, high-cadence operations, while avoiding prescriptive requirements on how that throughput is achieved.

Under such a framework, mass drivers gain a natural advantage. Their ability to move large quantities of material with low marginal energy cost makes them well suited to meeting escalating volume thresholds. At the same time, contractors would retain the freedom to pursue alternative high efficiency transport concepts during early phases or in parallel, provided they can meet the same delivery benchmarks. Innovation would be driven by economics rather than compliance.

Throughput based incentives also reduce risk for the government. Payments are tied directly to delivered material rather than promised capability, ensuring that federal spending produces tangible logistics capacity. As delivery rates rise, the industrial base is forced to scale power generation, ISRU processing, and transport infrastructure in a coordinated manner, accelerating the transition from experimental systems to reliable, industrial operations.

By rewarding volume, reliability, and sustained performance, the United States can shape the Lunar logistics market toward solutions that enable true industrial scale activity. Mass drivers are likely to emerge as the dominant approach under these conditions, but the policy remains flexible enough to accommodate unforeseen breakthroughs. This balance between strategic direction and technological freedom is essential to ensuring that high throughput Lunar logistics develop under United States leadership rather than through externally imposed realities.

5. The United States should advocate for a new Outer Space Treaty with guidelines for Lunar Resource Exploitation and Transport.

The United States should lead the creation of a new international framework governing Lunar resource exploitation and transport that establishes hard, agreed upon standards for behavior. As industrialization and permanent presence on the Moon develop, territorial claims will occur in every practical sense except in name. Without clearly defined rules, overlapping “safety zones” and “operational zones” will lead to de facto claims and territorial disputes.

For nearly a century, the Outer Space Treaty has preserved stability in space by prohibiting explicit territorial claims and promoting peaceful use. In practice, this prohibition has largely held as no state has possessed the incentive and capability to establish control over Lunar territory. That condition is now changing as sustained presence and industrial scale activity become feasible.

The Artemis Accords, while lacking, represent an attempt to address the realities of sustained Lunar activity. They encourage transparency, interoperability, the sharing of scientific data, and the establishment of safety zones to prevent harmful interference. These principles are valuable, but they are deliberately framed as voluntary norms rather than binding rules. The Accords do not specify objective criteria for the size, duration, or geographic scope of safety zones, nor do they define how overlapping zones should be adjudicated when multiple actors seek access to the same location.

Participation in the Artemis Accords is also limited to a subset of spacefaring nations and is entirely voluntary. There are no procedures for dispute resolution, no mechanisms to challenge excessive or exclusionary safety zones, and no enforcement tools to address noncooperative behavior. As Lunar activity scales from exploration to industrial competition, these gaps will become increasingly consequential. While the Artemis Accords establish important principles, they are not sufficient to manage the operational and strategic realities of large-scale resource exploitation and high throughput transport.

A new treaty should build on the principles of the OST and the Artemis Accords while addressing their limitations. It should define acceptable uses and defined areas for safety zones, establish rules for coordination in high value regions, and set clear expectations for mass drivers and other high energy transport systems. These standards must be specific enough to prevent abuse while preserving freedom of access and peaceful use.

Transparency and verification should be core elements of this framework. Advance notification of major operations, shared awareness of operational zones, and cooperative monitoring of trajectories would reduce ambiguity and prevent misinterpretation of industrial activity as hostile. These measures do not eliminate competition, but they reduce the likelihood that competition escalates into conflict.

By leading the creation of this framework, the United States can shape the rules of the Cislunar frontier before precedent is set by unilateral action. Establishing hard standards now will protect freedom of operation, reinforce peaceful use, and ensure that Lunar development proceeds under norms that reflect strategic reality rather than legal fiction.

ACRONYM KEY:

ASAT: Satellite & Anti-Satellite
BP: Brilliant Pebbles
DRDO: Defence Research Development Organization (Indian DARPA)
EMALS: Electromagnetic Aircraft Launch System
EMRG: Electro Magnetic Railgun
EO/IR: Electro-Optical Infrared
FOBs: Fractional Orbital Bombardment System
GEO: Geostationary Earth Orbit
GEOINT: Geospatial Intelligence
GPALS: Global Protection Against Limited Strikes
HLS: Human Landing System (SpaceX's Lunar Lander)
ICBM: Intercontinental Ballistic Missile
ILRS: International Lunar Research Station
INF: Intermediate-range Nuclear Forces (treaty)
IR: Infrared
ISR: Intelligence Surveillance Reconnaissance
ISRU: In Situ Resource Utilization
KEI: Kinetic Energy Impactor
KKV: Kinetic Kill Vehicle
LEO: Low Earth Orbit
MRBM: Medium Range Ballistic Missile
NASA: National Air & Space Administration
NC3: Nuclear Command, Control, Communication
NPT: Non-Proliferation Treaty (treaty)
OST: Outer Space Treaty
PLAN: People's Liberation Army Navy (China's Navy)
PRC: People's Republic of China
RV: Nuclear Reentry Vehicle
SALT I & II: Strategic Arms Limitation Talks (treaty)
SBIRS: Space Based Infrared System
SDI: Strategic Defense Initiative
SLBM: Submarine Launched Ballistic Missile
SDA: Space Domain Awareness
SSN: Space Surveillance Network
TLAM: Tomahawk Land Attack Missile
UEWR: Upgraded Early Warning Radar

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