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ENERGY STORAGE AND PULSED POWER WITH A LUNAR SUPERCONDUCTING MAGNETIC ENERGY STORAGE (SMES) SYSTEM

by

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June 2023

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13. ABSTRACT (maximum 200 words)

This thesis investigated utilizing a superconducting magnetic energy storage (SMES) system to support power generation, sustainment, and utilization on the Moon, primarily to support NASA’s Artemis Program and development of the Artemis Base Camp, and for other lunar pulsed-power requirements such as directed energy, radar, and lunar manufacturing applications. Power is the most vital resource to maintain a sustainable lunar base, and NASA’s projected plan for power generation uses a fission power plant and multiple vertical photovoltaic arrays, with batteries and regenerative fuels for energy storage. However, there is a significant gap in technological readiness with a long-life grid-scale secondary energy storage on the MW scale to support industrial scale in-situ resource utilization (ISRU) production facilities. An in-depth system study was conducted on alternate energy storage systems to include batteries, fuel cells, supercapacitors, and flywheels and compared to the SMES system to assess their feasibility for addressing the technological shortfalls in terms of lunar power requirements. When compared to the other energy storage systems, the SMES system was found to be the most beneficial for lunar power because of its high-power density, fast discharge time, high efficiency, and low capital cost per unit power.

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ABSTRACT

This thesis investigated utilizing a superconducting magnetic energy storage (SMES) system to support power generation, sustainment, and utilization on the Moon, primarily to support NASA's Artemis Program and development of the Artemis Base Camp, and for other lunar pulsed-power requirements such as directed energy, radar, and lunar manufacturing applications. Power is the most vital resource to maintain a sustainable lunar base, and NASA's projected plan for power generation uses a fission power plant and multiple vertical photovoltaic arrays, with batteries and regenerative fuels for energy storage. However, there is a significant gap in technological readiness with a long-life grid-scale secondary energy storage on the MW scale to support industrial scale in-situ resource utilization (ISRU) production facilities. An in-depth system study was conducted on alternate energy storage systems to include batteries, fuel cells, supercapacitors, and flywheels and compared to the SMES system to assess their feasibility for addressing the technological shortfalls in terms of lunar power requirements. When compared to the other energy storage systems, the SMES system was found to be the most beneficial for lunar power because of its high-power density, fast discharge time, high efficiency, and low capital cost per unit power.

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TABLE OF CONTENTS

I. INTRODUCTION 1
A. STATEMENT OF PROJECT 1
1. Background 1
2. Objective 3
3. Methodology 3
4. Research Questions 3

II. REVIEW OF RELEVANT LITERATURE 5
A. UNITED STATES INTENT TO RETURN TO THE MOON 5
1. The Artemis Program 5
2. Importance of a Lunar Base such as Artemis Base Camp 10
3. Orbiting Outpost: The Gateway 11
4. Lunar ElectroMagnetic Mass Accelerator (LEMMA) 12
5. Artemis Base Camp Technological Shortfalls for Power 13
B. ENERGY STORAGE AND PULSED POWER OPTIONS 14
1. Batteries 15
2. Fuel Cells 17
3. Capacitors 17
4. Flywheels 18
C. SUPERCONDUCTING MAGNETIC ENERGY STORAGE 20
1. SMES Construction and Operation 20
2. Historical Uses of SMES 25
3. Lunar SMES (LSMES) System 28
D. COMPARISON OF ENERGY STORAGE SYSTEMS 30

III. SMES LOCATION, SIZING, AND THERMAL REQUIREMENTS 33
A. SMES LOCATION AND LUNAR CRATER GEOMETRY 33
B. SMES SYSTEM HEAT TRANSFER 34
1. Thermophysical Properties of Lunar Regolith 34
2. Conduction 37
3. Quantity of Heat 38

IV. ADDITIONAL LUNAR POWER APPLICATIONS 41
A. LUNAR MANUFACTURING 41
B. LUNAR RADAR 42
C. DIRECTED ENERGY SYSTEMS 43

V. CONCLUSION AND RECOMMENDATIONS 47
A. CONCLUSIONS 47
B. RECOMMENDATIONS 48
C. FUTURE RESEARCH 48

LIST OF REFERENCES 51

INITIAL DISTRIBUTION LIST 57

LIST OF FIGURES

Figure 1. Artemis Firsts and Key Milestones. Source: [1]. 7

Figure 2. Artemis Path to Mars. Source: [1]. 8

Figure 3. Potential landing sites for Artemis Base Camp near PSRs. Source: [1]. 9

Figure 4. a) 3D representation of Shackleton Crater and b) Shackleton Crater elevation profile. Source: [15]. 10

Figure 5. Artist Illustration of The Gateway with Orion Approaching. Source: [1]. 12

Figure 6. NASA Power Generation/Distribution on the Moon. Source: [21]. 14

Figure 7. Schematic of Battery. Source: [23]. 15

Figure 8. Supercapacitor Design. Source: [26]. 18

Figure 9. Flywheel System. Source: [31]. 19

Figure 10. SMES System Breakdown. Source: [5]. 20

Figure 11. Hexagonal Solenoid Arrangement. Source: [34]. 22

Figure 12. Ideal MgB_2 SMES Magnet Design. Source: [35]. 22

Figure 13. MgB_2 SMES Magnet Design Measurements and Specifications. Source: [35]. 23

Figure 14. Comparison of the operating ranges for HTS YBCO compared with LTS NbTi and Nb_3Sn. Source: [37]. 24

Figure 15. Temperatures on the Moon's South Pole. Source: [39]. 25

Figure 16. Japanese 10 MVA/ 1 sec system. Source: [41]. 27

Figure 17. SMES System Connected to Power Grid. Source: [41]. 27

Figure 18. Conceptual Location of LSMES within a PSR. Source: [22]. 28

Figure 19. Prototype of LSMES. Source: [22]. 29

Figure 20. Results of Magnetic Field Strength over Time for LSMES Prototype in Liquid Nitrogen. Source: [22]. 29

Figure 21. Ragone Plot Assessing Differing Energy Storage Systems. Source: [9]. 31

Figure 22. Lunar Regolith Bulk Density and Thermal Conductivity Profiles from the Moon's Surface to a Depth of 1 meter. Source: [51]. 36

Figure 23. Overview of DC/DC Converter and Superconducting Magnet within a Cooled Chamber. Source: [62]...50

LIST OF TABLES

Table 1. Lunar Regolith Specific Heat Values from Various Resources................35

Table 2. Lunar Regolith Thermal Conductivity from Various Resources..............35

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LIST OF ACRONYMS AND ABBREVIATIONS

AC	alternating current
CC	cryocooler
CE-4	Chang'E-4
DC	direct current
DE	directed-energy
DOD	Department of Defense
DSN	Deep Space Network
EGS	Exploration Ground Systems
FACTS	Flexible AC Transmission System
GPS	Global Positioning System
GSSR	Goldstone Solar System Radar
HEL	high-energy lasers
HTS	high temperature superconductor
IAPG	Interagency Advanced Power Working Group
ISRU	in-situ resource utilization
ISS	International Space Station
LEMMA	Lunar ElectroMagnetic Mass Accelerator
LI	Lunar Infrastructure
LOLA	Lunar Orbiter Laser Altimeter
LPS	lunar power station
LRO	Lunar Reconnaissance Orbiter
LSII	Lunar Surface Innovation Initiative
LSMES	Lunar Superconducting Magnetic Energy Storage
LTS	low temperature superconductor
LTV	lunar terrain vehicle
NEO	Near-Earth Object
NMO	Near-Moon Object
NRHO	Near-Rectilinear Halo Orbit
O2O	Orion Artemis II Optical Communications System
PDCO	Planetary Defense Coordination Office

PEM	polymer electrolyte membrane
PSR	permanently shadowed region
RFC	regenerative fuel cell
SA	simulated annealing
SLS	Space Launch System
SMES	superconducting magnetic energy storage
SPS	solar power satellite
TDRS	Tracking Data Relay Satellite System
TRL	technology readiness level
UPS	uninterruptable power supplies

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I. INTRODUCTION

A. STATEMENT OF PROJECT

1. Background

This year marks 51 years since astronauts last set foot on the Moon with the Apollo program. NASA intends to reset this timeline by landing astronauts on the lunar surface in 2025 under the Artemis program [1]. The goals of the Artemis program are to land the first woman and first person of color on the Moon, to demonstrate the technological capability required for future space exploration including a Mars landing, and lastly to establish a lunar base known as the Artemis Base Camp [2]. The four astronauts selected for the first lunar orbital flight have recently been announced. To help meet these objectives, NASA will establish a permanently orbiting space station known as the Gateway in a Near-Rectilinear Halo Orbit (NRHO) that will serve as a staging point for human and robotic lunar missions [3]. Lunar resources and supplies will be transported to and from the Gateway to the Artemis Base Camp to maintain the lunar base, facilitate research, and eventually assist with a mission to Mars. Previous research has been conducted on utilizing a Lunar ElectroMagnetic Mass Accelerator (LEMMA) as an alternative to chemical rockets to enable the transportation of materials to and from the Artemis Base Camp to the Gateway [3]. Both the Artemis Base Camp and LEMMA will require significant electrical power, and this thesis will provide a thorough system study of a superconducting magnetic energy storage (SMES) system to supplement the power requirements.

Currently, NASA's goal is to generate "base load" electrical power for the Artemis Base Camp with an advanced solar collection and a small, lightweight fission power system [1]. In addition to the need for lunar base load power for the Artemis Base Camp, there is also a potential need for short-term, pulsed power for various applications such as pulsed radars, directed energy systems, LEMMA, and lunar manufacturing. As a short-term energy storage technology, SMES can be leveraged to meet these short-term power requirements. In addition, it can supplement and stabilize the base load power grid against load fluctuations and provide improved power quality [4]. Essentially, SMES efficiently provides a quick response to a high energy demand with an energy transfer rate that can be greater than 95 percent of the maximum possible demand [5]. SMES can achieve such a high energy transfer rate because it does not require energy conversion from electrical to mechanical or chemical energy. It stores energy in a magnetic field created by the current flowing through superconducting wires that are formed into a large solenoidal or toroidal magnet [6]. Typically, a SMES system consists of four main components: the superconducting magnet, a cryogenic refrigeration system, a power conditioning system, and a control system [5]. After a superconducting coil has been energized from a direct current source, it will store the energy permanently without losses until the coil is commanded to discharge into a load. Depending on the load requirements, the power conditioning system either converts the direct current (DC) of the coil to alternating current (AC) of the required frequency or transforms it into a higher voltage or current (DC) [5]. The power output of a SMES system can range from 100 kW to 10 MW with an extremely fast response time of around 5 ms, making it beneficial for rapid, pulsed power required by LEMMA [7]. A SMES system can also help to stabilize the power grid on the Artemis Base Camp by operating as a Flexible AC Transmission System (FACTS) to enhance the operation of the electric grid in terms of controllability and power transfer capability [5].

Another research area that will be discussed in this thesis is the advantages of placing a SMES system within a lunar crater. For a SMES system to operate properly, the magnetic coils must be kept at very low temperatures to stay in a superconducting state [6]. To maintain the required low temperatures, a refrigerator must be within the cryogenic system. New high-temperature superconductors (HTS) are now able to operate at up to liquid nitrogen temperatures (77K), much higher than the prior low-temperature superconductors (LTS) that required 4K or lower. It is possible that this cooling requirement for an HTS SMES system can be achieved without a refrigeration system if it is placed within a lunar crater because NASA's Lunar Reconnaissance Orbiter (LRO) has measured the coldest temperatures in the solar system inside these craters, with temperatures that drop as low as 40K (-388 F) [8].

2. Objective

Both NASA and the United States Department of Defense (DOD) will benefit from this study as it will provide a viable option for power distribution and short-term pulsed power for lunar utilization. NASA's Artemis program currently lacks a solidified solution for generating "base-load" electrical power to support the Artemis Base Camp, and this study will illustrate that a superconducting magnetic energy storage (SMES) system can potentially supplement the base-load power grid requirements. In addition to utilizing SMES for lunar purposes, the DOD can leverage SMES for systems such as railguns, high-energy lasers (HEL), and directed-energy (DE) radar that require short-pulsed energy ranging from 5 to 100 MJ [9].

3. Methodology

This thesis will conduct an in-depth system study of the SMES system and assess the pros and cons of utilizing this system to address lunar power requirements. Additionally, the SMES system will be thoroughly compared with other energy storage systems. Other potential energy storage and pulsed power options include batteries, capacitors, flywheels, and gravity energy storage. The two most vital aspects of an energy storage system to assess are energy and power and these will be evaluated for each varying system. Additionally, each system will exhibit advantages and disadvantages in terms of initial costs, operating costs, maintenance, and operational lifetime.

4. Research Questions

This thesis seeks to address the question: What are the advantages and disadvantages of utilizing a SMES system for power distribution on the Moon? Subsidiary questions guiding this research are as follows:

- How can SMES be leveraged for specific lunar missions such as NASA's Artemis program?
- How does SMES compare to other energy storage and pulsed (electrical) power options such as batteries, capacitors, and flywheels in terms of power, energy, maintenance requirements, and cost for use on the Moon?

- How can lunar craters be utilized to reduce the cooling requirements for high-temperature semiconductors (HTS) within SMES?
- How can SMES be optimized in terms of power, cost, and size?

II. REVIEW OF RELEVANT LITERATURE

This literature review provides an overview of the Artemis Program, a NASA-led initiative to explore the Moon and eventually Mars. The review focuses on the technological systems that NASA is employing to achieve the objectives of the Artemis Program, the timeline and milestones of the program, and the potential location of the Artemis Base Camp on the lunar South Pole. The review also highlights the advantages and disadvantages of the proposed location of the base camp and the challenges that may arise from the rugged terrain of the Shackleton Crater, highlighting power as the key required resource to ensure successful operation and sustainment of the base. Additionally, the review briefly discusses some of the research that has been conducted on the lunar surface and terrain parameters around the Moon's North and South Poles. Lastly, this literature review discusses various options for energy storage and pulsed power that can assist with potential energy requirements on the Moon, including lithium-ion batteries, fuel cells, capacitors, flywheels, and the SMES system. Each option demonstrates pros and cons, especially when applied in the unique lunar environment.

A. UNITED STATES INTENT TO RETURN TO THE MOON

1. The Artemis Program

Half a century has passed since mankind last explored the surface of the Moon with the Apollo program in 1972. NASA, by direction of the White House, intends to reset this timeline and conduct further exploration of the Moon, and eventually Mars, under the Artemis program. The initial plans for the Artemis program began following the release of Space Policy Directive-1 in December of 2017, in which President Trump stated the United States will:

> lead an innovative and sustainable program of exploration with commercial and international partners to enable human expansion across the solar system and to bring back to Earth new knowledge and opportunities. Beginning with missions beyond low-Earth orbit, the United States will lead the return of humans to the Moon for long-term exploration and utilization, followed by human missions to Mars and other destinations. [10]

Technologically, NASA was prepared to meet the president's directive with transportation systems such as the Space Launch System (SLS) rocket, the Orion spacecraft, and the supporting Exploration Ground Systems (EGS) [1]. These technological systems set the initial foundation for the Artemis program, which was divided into three major phases, Artemis I, Artemis II, and Artemis III.

On November 16, 2022, the Artemis I mission began with the SLS rocket launching the Orion spacecraft unmanned into a lunar distant retrograde orbit. [11]. The mission lasted 25 days in which the Orion spacecraft traveled 1.4 million miles, and then safely returned to Earth on December 11, 2022 [11]. Overall, Artemis I successfully demonstrated the capability of the SLS rocket and Orion spacecraft. Over 161 test objectives were accomplished on Orion, demonstrating every aspect of the spacecraft is functional [12]. The Artemis II mission will build on Artemis I by transitioning from an unmanned flight to a crewed flight of four astronauts; Reid Wiseman, Victor Glover, Christina Koch, and Jeremy Hansen, utilizing the SLS rocket and Orion spacecraft in a hybrid free return trajectory to the Moon [13]. Artemis II is an extremely involved mission as it will provide a "proof of concept" for a multitude of operations and equipment [1]. The crew will conduct a proximity operations demonstration, assess the performance of the life support systems on Orion, and determine the communication and navigation capability of NASA's Deep Space Network (DSN) by flying beyond line-of-sight of the Global Positioning System (GPS) and Tracking Data Relay Satellite System (TDRS) communication satellite networks [1]. Finally, the Artemis program will culminate with Artemis III in which the crew of four will return to the Moon but this time land on its surface [1]. This mission will make history with the first woman and first person of color to walk on the lunar surface [1]. Figure 1 provides an overview of the "firsts" that will be achieved via the Artemis program, as well as a summary of the program's major milestones [1].

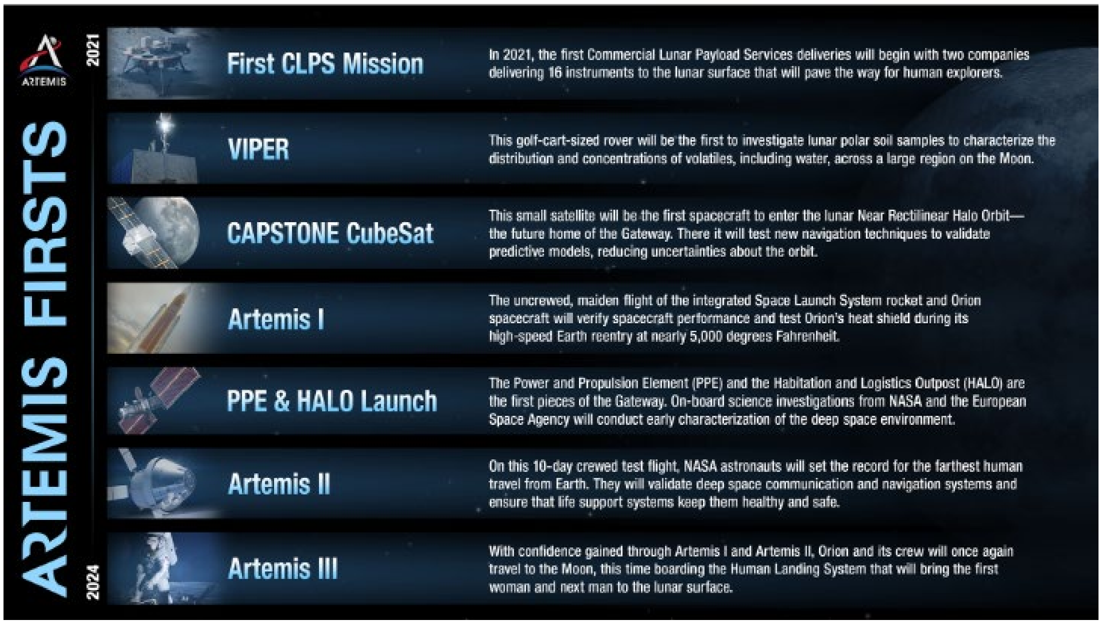

Figure 1. Artemis Firsts and Key Milestones. Source: [1].

Following Artemis III, NASA intends to enable a sustained presence on the Moon by creating the Artemis Base Camp on the lunar South Pole. The Artemis Base Camp will serve as the “first sustainable foothold on the lunar frontier” and will increase knowledge about the Moon and the universe, thus allowing the development of new technologies potentially required for missions to Mars [1]. Figure 2 illustrates how NASA intends to leverage the Artemis program and the Artemis Base Camp to achieve Mars missions.

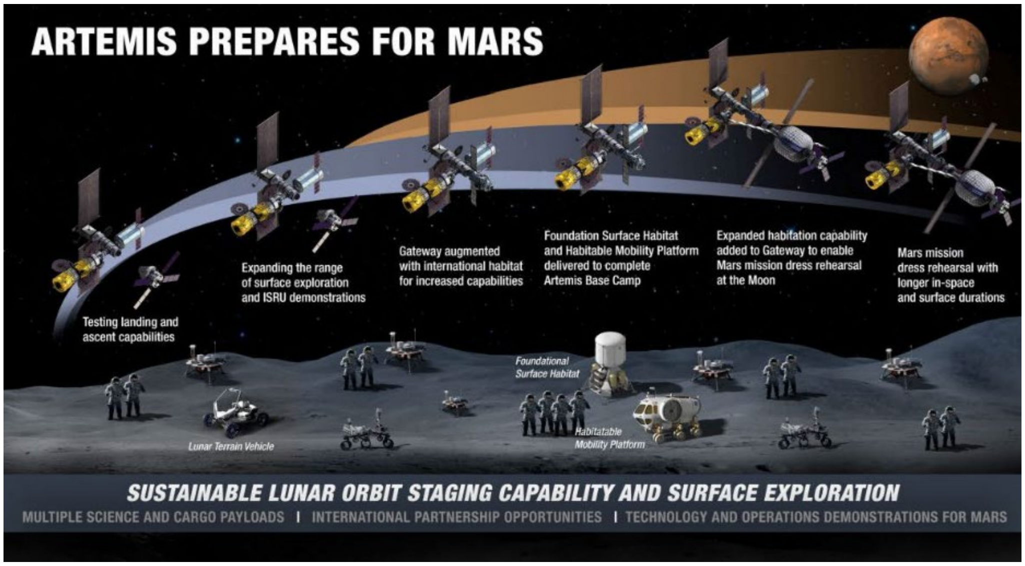

Figure 2. Artemis Path to Mars. Source: [1].

NASA is presently considering potential sites for the Artemis Base Camp. When determining the location of a lunar base, a few factors that should be considered: access to sunlight for solar power, vicinity to shadowed regions that contain lunar ice and other volatiles, and finally line-of-sight to Earth for communication. Because the Moon's tilt is only 1.5 degrees on its axis (compared with 23.5 degrees for the Earth), neither of the Moon's poles point toward or away from the Sun throughout the year, unlike Earth, making the poles ideal for access to sunlight [14]. With these factors in mind, NASA is contemplating the area near the Shackleton Crater on the Moon's South Pole for the location of the Artemis Base Camp. If the base camp is placed on the ridge of the crater, the base will remain highly illuminated and have line-of-sight communication access to Earth. The Shackleton Crater, as well as other craters in proximity, also have permanently shadowed regions (PSRs) that contain mission enhancing lunar resources, such as lunar ice. Figure 3 showcases the potential base sites and PSRs. Of note, Site 001 and Site 004 are near the Shackleton crater, representing the current proposed location for the Artemis Base Camp [1].

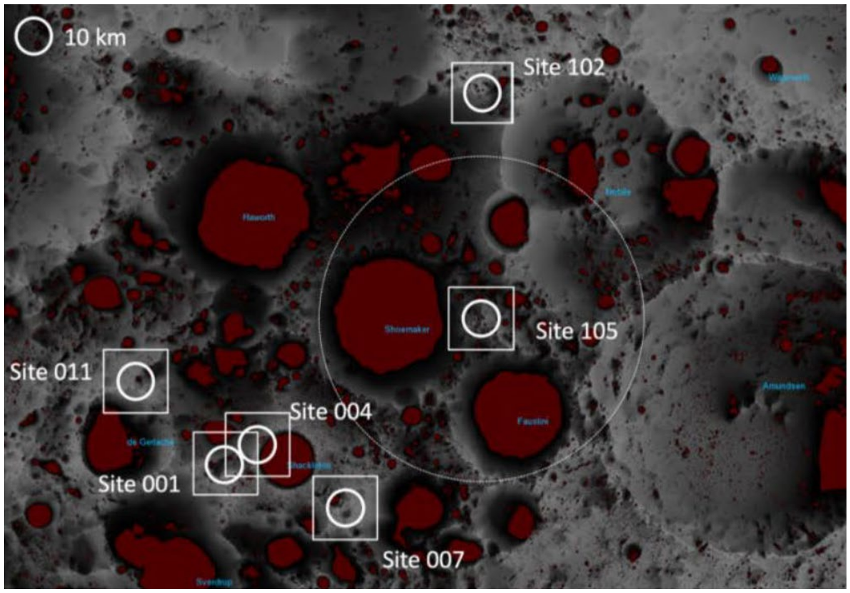

Figure 3. Potential landing sites for Artemis Base Camp near PSRs. Source: [1].

Additional research on the construct and location of a lunar base was conducted in [15], where a detailed analysis of the surface conditions and terrain parameters around the Moon's North and South Poles was conducted. This study found that a significant disadvantage of placing the lunar base near the South Pole and Shackleton Crater was the depth and slope of the Shackleton Crater. The depth of the crater is approximately 4 kilometers, with a slope of around 30 to 45 degrees, as displayed in the 3D representation shown in Figure 4 (a) with the crater's elevation profile in Figure 4 (b) [15]. The 3D image and elevation profile were created using data from NASA's Lunar Orbiter Laser Altimeter (LOLA), an instrument aboard the Lunar Reconnaissance Orbiter (LRO). Such a steep slope in the crater could make possible operations within the crater, such as mining for ice, very difficult. Part of NASA's objectives with the Artemis program are to field and implement a lunar terrain vehicle (LTV) [1]; however, further research will be required to determine if the LTV can handle transportation of astronauts and resources on the steep slope of the Shackleton Crater.

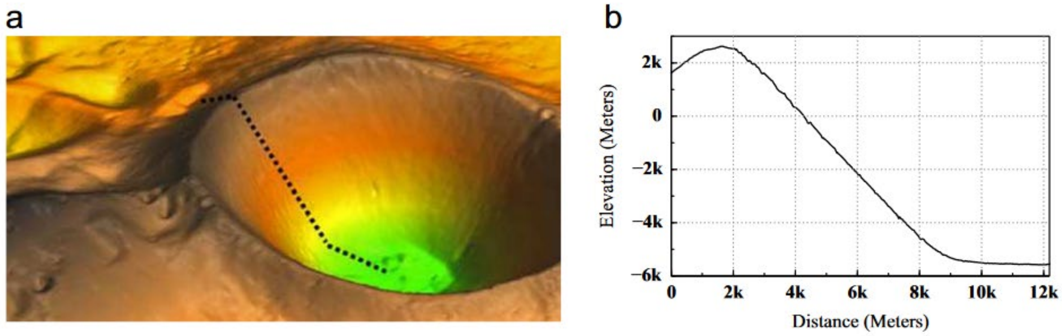

Figure 4. a) 3D representation of Shackleton Crater and b) Shackleton Crater elevation profile. Source: [15].

2. Importance of a Lunar Base such as Artemis Base Camp

As part of the Artemis program, NASA created the Lunar Surface Innovation Initiative (LSII) to "develop and test new approaches, technologies, and systems that will enable us to function in other, more challenging environments" [1]. One of the major priorities of LSII is to implement in-situ resource utilization (ISRU) technologies for obtaining and processing resources found on the Moon. The lunar resources of interest include ice from the polar regolith, minerals in the lunar regolith (ilmenite, pyroxene, olivine, anorthite), and gases such as carbon monoxide, carbon dioxide, and hydrocarbons [16]. Potential uses of these resources are the production of drinking water, fuel, hydrogen, and oxygen with longer-term applications of extraterrestrial metal processing and construction of habitats [16]. Because of the plethora of benefits that come from obtaining and using the lunar resources, it is evident that ISRU significantly assists with space exploration as it increases sustainability with potential reuse of lunar landers with in-situ propellants, reduces mission risk with decreased logistics required from Earth, and increases scientific knowledge with greater access to subsurface lunar samples through ISRU excavation [17]. Having a sustained presence on the Moon with a lunar base such as the Artemis Base Camp allows for the advancement of ISRU technologies, which will lead to more efficient lunar operations with less dependence on logistical support from Earth.

In addition to permitting mining of the Moon and advancing ISRU technologies, a lunar base would allow access to other parts of space, including Mars. Launching from the lunar surface is significantly more efficient than launching from Earth because the lunar escape velocity is 2380 m/s, substantially smaller than Earth's escape velocity of 7910 m/s [18]. Furthermore, achieving a lunar orbit requires at least 1.4 MJ/kg of specific energy whereas achieving an orbit from Earth requires at least 31.3 MJ/kg [18]. Lastly, there is no aerothermal loss associated with transit through the Moon's atmosphere as there is on Earth. This increased efficiency from launching from the Moon simplifies space exploration due to decreased technological constraints imposed by acquiring a high escape velocity and specific energy required to launch and reach orbit. The Moon can serve as a steppingstone to support Mars missions by launching resources and supplies to and from the Moon and Mars, thus again stressing the importance of a sustained lunar presence with a lunar base camp.

3. Orbiting Outpost: The Gateway

As well as establishing a lunar base, NASA intends to utilize the lessons learned from the International Space Station (ISS) and create a smaller, more specialized orbiting outpost known as "The Gateway" [1]. The Gateway will be placed in a near-rectilinear halo orbit (NHRO) in which it orbits between the lunar south pole and the L2 Lagrange point [3]. This orbiting outpost will permit a continued presence between the Moon and Earth and serve as an intermediate supply station for longer missions, such as Mars missions. Resources obtained on the Moon can be delivered to the Gateway and then back to Earth, or to support other deep space missions. Figure 5 shows an artist's rendition of what the Gateway will look like [1].

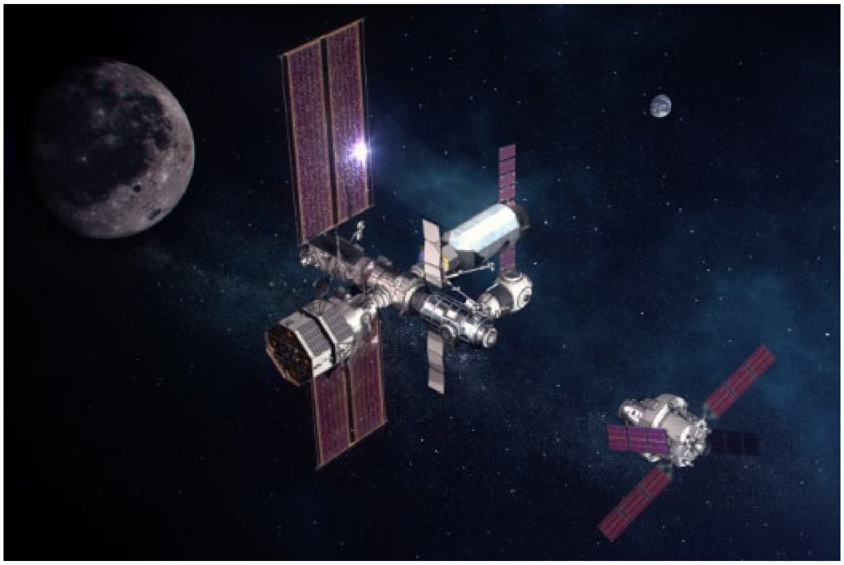

Figure 5. Artist Illustration of The Gateway with Orion Approaching.
Source: [1].

4. Lunar ElectroMagnetic Mass Accelerator (LEMMA)

Previous research was conducted on utilizing an electromagnetic launcher known as LEMMA, which is similar to the technology developed by the U.S. Navy for tactical railguns, to facilitate the transfer of lunar resources from the Moon to the Gateway [3]. Specifically, this research considered manned missions to Mars that would utilize a nuclear-thermal rocket engine due to its high specific impulse, which would substantially reduce the overall required transit time to Mars [3], [19]. To facilitate the trip to Mars with a nuclear rocket engine, it is estimated that approximately 90 MT of lunar hydrogen (LH_2) would need to be readily accessible at the Gateway transfer point [3]. For purposes of this study, manufacturing LH_2 on the Moon and launching it to the Gateway was considered. Current estimates approximate a delta-V of 2.3 to 2.5 km/s would be required for a launch from the planned location of the Artemis Base Camp (lunar South Pole) to the Gateway (L2 Lagrange point) [20]. This study also assumed delivery of LH_2 from the Moon to the Gateway would follow a "production line" model with a launch occurring every hour for two years, making the LH_2 payload mass per launch 5.1 kg. The overall mass to be launched was approximated as 7.65 kg and included the LH_2 in a containment flask, armature, guidance controls, terminal guidance thrusters, and other ancillaries required for the railgun launch. With a required launch mass of 7.65 kg and a delta-V of 2.8 km/s, the muzzle energy needed is 30 MJ, which is comparable to the values achieved by the U.S. Navy railguns [3].

Given the launch mass and muzzle energy requirements with an assumed railgun efficiency of 80%, the energy input needed per launch is 37.5 MJ, which equates to 10.4 kW of power required from an energy storage system with a recharge period of an hour [3]. The type of energy storage system that could satisfy these requirements is not mentioned in this research and states that a “more detailed evaluation is required to choose the best type of pulsed power and also resolve this issue” [3]. This thesis poses using SMES to satisfy the energy storage necessary for LEMMA.

5. Artemis Base Camp Technological Shortfalls for Power

Power is the most vital resource to accomplish building a sustainable lunar infrastructure. John H. Scott, Principal Technologist for Power and Energy Storage at NASA, participated in an Interagency Advanced Power Working Group (IAPG) on 24 August 2022 in which he gave a presentation on NASA’s Technology Priorities for Lunar Surface Power. Within this presentation, Scott stated that the Lunar Infrastructure (LI) goal is to “create Global Lunar Utilization infrastructure where U.S. industry and international partners can maintain continuous robotic and human presence on the lunar surface for a robust lunar economy without NASA as the sole user, while accomplishing Mars testing and science objectives” [21]. Currently, NASA plans to generate power with a fission power plant and vertical photovoltaic arrays, store it with low temperature battery modules and regenerative fuel cells, and distribute it with power beaming and cables. A depiction of the potential layout of the lunar power scheme is shown in Figure 6 [21].

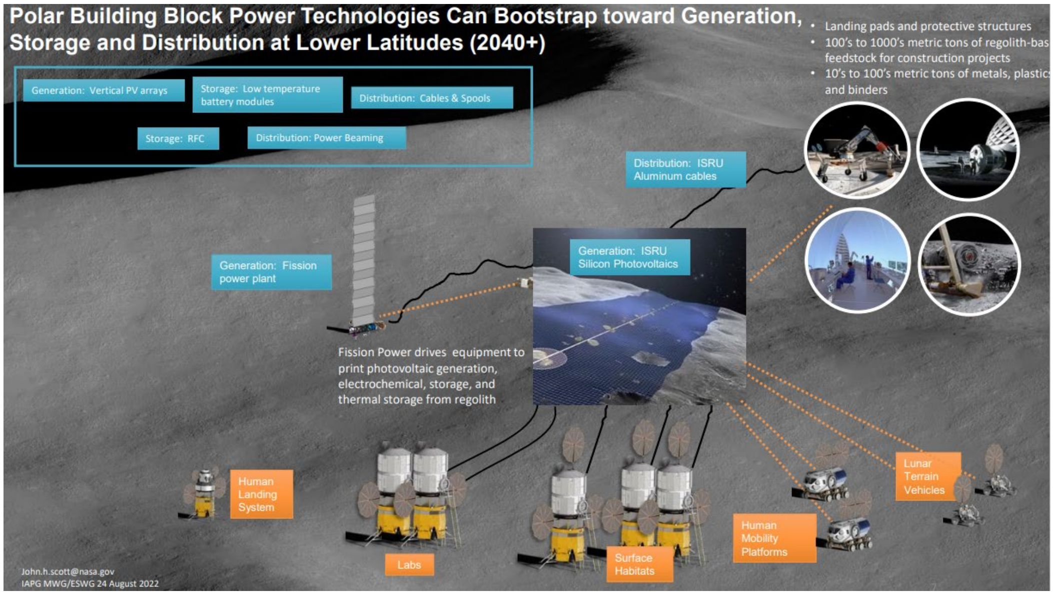

Figure 6. NASA Power Generation/Distribution on the Moon. Source: [21].

There are a multitude of gaps in technological readiness to achieve the power requirements to support the Artemis Base Camp. Scott delineated each of these gaps and outlined what would be required to overcome them, although generally the technology required does not presently exist or is still in the research and development phase [21]. This thesis seeks to focus on what Scott labeled as "Gap D2: Long Life Grid-Scale Secondary Energy Storage" which explains that "an eclipse-period support of industrial scale ISRU production facilities and a crewed outpost at the Lunar pole will require Earth-sourced, large-scale, long life, maintenance-free electrical energy storage at a MW scale" [21]. Scott then described a potential solution to the gap in energy storage to be a regenerative fuel cell energy storage system. This study has considered HTS SMES as an alternative. Only towards the end of this study (April 2023) did we find that a separate NASA group has also suggested a very similar concept to ours, coined LSMES for "Lunar SMES" and an overview of their research is provided in [22].

B. ENERGY STORAGE AND PULSED POWER OPTIONS

Energy storage systems capture, and store produced energy for an extended period for eventual utilization. These systems can be leveraged to improve the efficiency and quality of energy generation systems, stabilize power grids when they reach their capacity, and reduce the imbalance between energy demand and energy production. Energy storage is especially critical for renewable energy sources, such as solar panels and wind turbines, because of the temporal nature of when energy is produced versus when it is required. For example, wind turbines produce more energy at night when there is a minimum demand for power, thus the energy can be stored and released when the demand is higher [23]. Energy storage is vital to support power distribution on the Moon due to the gaps identified previously by the IAPG. Presently, there are a myriad of options for energy storage such as batteries, regenerative fuel cells, supercapacitors, flywheels, and SMES. This chapter of the thesis will provide a brief description of how these systems function, example applications, and lastly their advantages as well as disadvantages.

1. Batteries

Batteries store chemical energy and convert it into electrical energy. The three main components of a battery are an anode, a cathode, and an electrolyte. Electrons flow from the positively charged anode through the electrolyte to the negatively charged cathode. The electrolyte is typically an aqueous solution that restricts the flow of electrons while permitting the flow of ions [23]. A picture depicting the typical composition of a battery is shown below in Figure 7 [23].

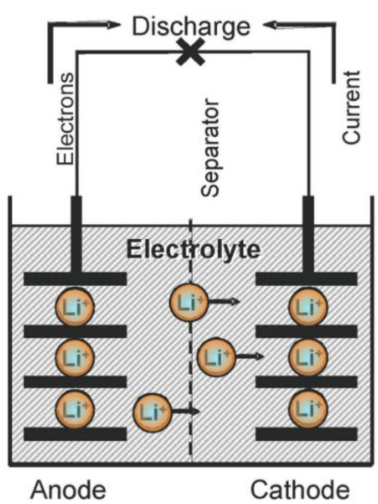

Figure 7. Schematic of Battery. Source: [23].

A chemical reaction at the anode releases electrons while a simultaneous reaction occurs at the cathode in which the electrons are absorbed. The freed electrons from the anode travel through an external electrical circuit, like the one seen in Figure 7, to the cathode converting the chemical reaction to electricity [24]. For a primary cell, this discharge process continues until the electrodes are depleted of electrons, thus ending the useful life of the cell. A secondary cell, however, can be recharged by adding an external source of direct electrical current to supply electrons to the anode and remove electrons from the cathode until the cell is recharged [24].

a. Lithium-Ion Batteries

Presently, lithium-ion batteries are the most common rechargeable batteries used for portable consumer electronics and electric vehicles, with growing utilization in grid-scale energy storage as well as military and aerospace applications [25]. Lithium-ion batteries use a reaction known as intercalation to store energy. Intercalation is the reversible insertion of an ion or molecule into a crystalline lattice without causing significant changes to the lattice [23]. During the charging process, the cathode is turned into lithium ions that move through the lithium salts electrolyte where they combine with external electrons at the anode [26]. These types of batteries are ideal because they are efficient, have a high energy density, rapid response time, and long life cycle [26]. Additionally, their energy storage capability ranges from kilowatt-hours (kW/h) for residential applications to multimegawatts for power grid services such as frequency regulation [26]. However, in terms of large-scale utilization, there are shortfalls in terms of the cost required to protect the internal circuits. For space-based utilization on the Artemis Base Camp, Scott stated in the IAPG that "the principal challenge from Artemis for battery technology is mobility energy storage for ISRU operations. Lithium-ion batteries lose 75% of their room temperature (295 K) capacity when operating at 235 K" [21]. He then explained that to close this gap "a 50 kilowatt-hour class battery module with capability to provide greater than net 150 Wh/kg specific energy at 1 kW discharge for 500 cycles in a 70 K environment and to survive with full operational capability after long-duration cold soak at 70 K" is required [21]. Currently, a battery module with this capability does not exist.

2. Fuel Cells

Fuel cells have a similar construct to batteries in that they consist of an anode and a cathode with an electrolyte between them. Unlike batteries, fuel, such as hydrogen, is fed to the anode and air is fed to the cathode [27]. The hydrogen from the anode is then broken into protons and electrons by a catalyst within the electrolyte. The electrons then travel to the cathode via an external circuit, thus creating electricity. The protons travel through the electrolyte to the cathode, in which they combine with oxygen and electrons to produce water and heat [27]. Fuel cells themselves do not store energy – the energy is stored in the fuel that is supplied to the cell, which is an energy converter.

a. Polymer Electrolyte Membrane (PEM) Regenerative Fuel Cell (RFC)

PEM fuel cells utilize a solid polymer as an electrolyte and carbon electrodes containing a platinum alloy, and they only require hydrogen, oxygen, and water for operation [28]. According to David Bents and Vincent Scullin from NASA's Glenn Research Center, this type of fuel cell system is potentially "the highest storage capacity and lowest weight non-nuclear energy storage system for extra-terrestrial applications" [29].

PEM RFCs are NASA's current plan for grid-scale secondary energy storage to support the Artemis Base Camp. From the IAPG, it was revealed that by 2030 a "technology readiness level (TRL) 6 H_2/O_2 regenerative fuel cell energy storage system in up to MW/h and 10 kW increments with maximum specific energy and maintenance-free in the Lunar polar environment of 50,000 hours and 500 charge/discharge cycles" is required to meet the energy storage requirements of the Artemis Base Camp [21]. Presently, a PEM RFC of that capability does not exist but is under development.

3. Capacitors

There are several types of capacitors. Electrostatic capacitors use a dielectric film, such as polypropylene, sandwiched between two electrodes, to store energy at a high voltage and deliver it to a load when a switch is closed to connect the capacitor to the load. Modern capacitors of this type use essentially mono-atomic layers of aluminum pre-applied to the dielectric film as electrodes. Manufactured rolls of this material are connected in series and parallel before installation in a container to provide the appropriate voltage and current ratings. Based on the dielectric constant and thickness of the plastic film used (generally a few microns) such capacitors typically have voltage ratings of a few kV. They are used where the load requires such a high voltage and can discharge high currents very quickly – microseconds to milliseconds. A different type of capacitor is known as the ultracapacitor, which are also known as supercapacitors or double layer capacitors. In these, energy is stored across the double layer formed at the interface between an electrically conductive carbon and an electrolyte, as shown in Figure 8 [26]. They differ from electrostatic capacitors by utilizing the double-layer electrostatic rather than a solid dielectric [30].

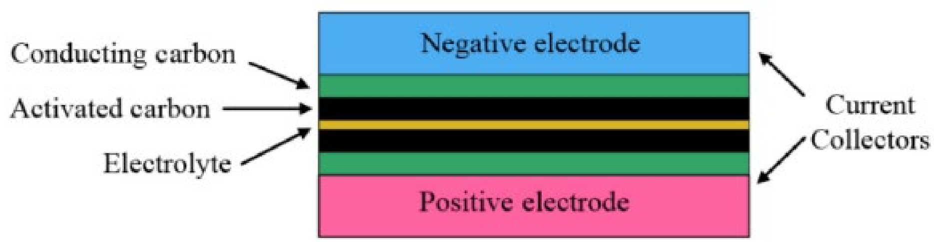

Figure 8. Supercapacitor Design. Source: [26].

Supercapacitors can store 10 to 100 times more energy per unit volume than electrolytic capacitors and because only electrons move and not ions in the material lattice, they can withstand many more charge and discharge cycles than rechargeable batteries before reaching end of life [30]. Because of this they are typically used for short-term energy storage applications such as in automobiles for regenerative braking.

4. Flywheels

Flywheels store energy by accelerating a rotor to a high speed and maintaining the energy in the system as rotational energy [31]. A typical flywheel system includes a flywheel supported by a bearing connected to a motor/generator, as shown in Figure 9 [31].

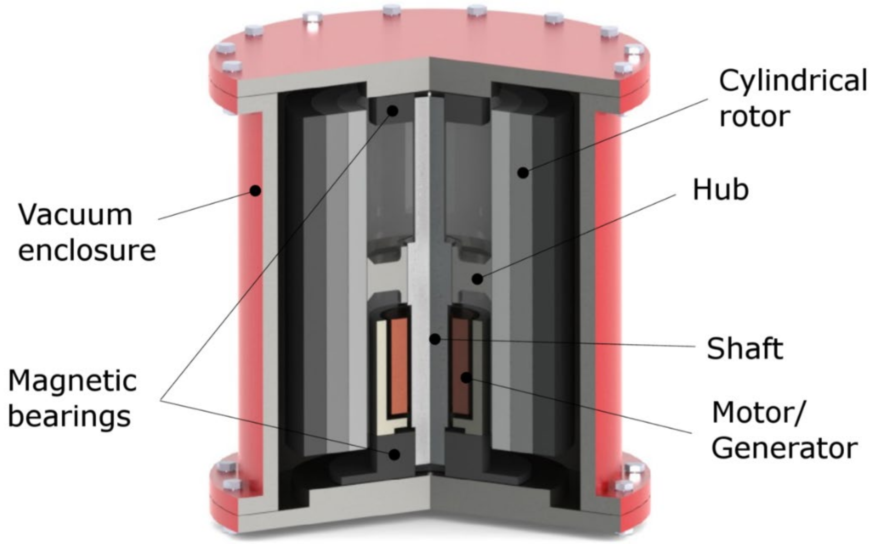

Figure 9. Flywheel System. Source: [31].

More energy is stored as the flywheel's rotational speed is increased, as energy varies with the quantity of rotational speed squared. They have a high power density but low energy density, making this system suitable for frequency regulation and short-time power quality services for power grid applications [26]. Additionally, flywheel energy storage systems require little maintenance (depending on the bearings used), have long lifetimes, specific energy values ranging from 100–130 W*h/kg, and an achievable round-trip efficiency of 90% [31].

In addition to energy storage, flywheels have been utilized in spacecraft for attitude control. An attitude control system orients the spacecraft while simultaneously detecting and correcting errors in attitude, and a flywheel can achieve this because of its ability to exert torque on the spacecraft [32]. By utilizing flywheels for both energy storage and attitude control, the overall mass of the spacecraft is reduced because what typically requires two systems is combined into one. Reducing the mass of the spacecraft has a multitude of benefits that include greater system efficiency, less propellant required, and smaller solar arrays due to smaller power requirements.

C. SUPERCONDUCTING MAGNETIC ENERGY STORAGE

The primary objective of this thesis is evaluating the possibility of using a SMES system for lunar power applications; therefore, most of the literature reviewed was relevant to this system: how it is constructed, how it operates, its historical uses, and its advantages and disadvantages. The main disadvantage of the SMES system is that it requires a significant cryogenic cooling system to maintain the superconductive state of the magnetic coils. However, this is alleviated with the new "high temperature" superconductors (HTS) based on doped copper oxide perovskite crystals that remain superconducting up to at least 50K, in contrast with the "traditional" "low temperature" superconductors (LTS) made from niobium alloys, which need to be cooled with liquid helium at 4K or lower. This study evaluated the concept of taking advantage of the very low temperatures (<40K) that occur in permanently shadowed regions (PSRs) of lunar craters by burying an HTS SMES system under the lunar regolith and relying on conduction cooling to maintain the low temperature and minimize active cooling loads.

1. SMES Construction and Operation

A SMES system consists of four primary components: a superconducting magnetic coil, cryogenic system, power conditioning system, and a control system [5]. An illustration of the SMES construct connected to an electric grid is shown in Figure 10 [5].

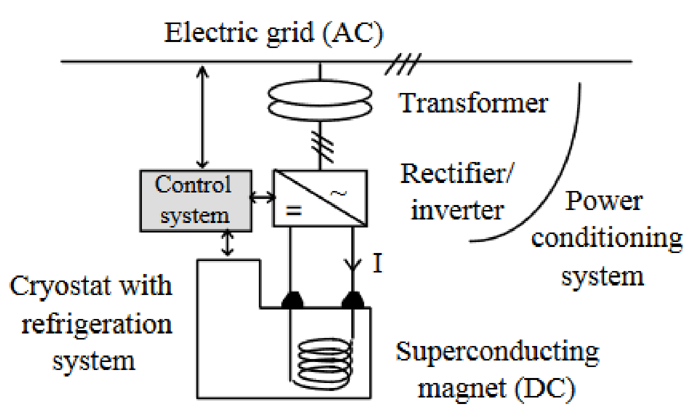

Figure 10. SMES System Breakdown. Source: [5].

Energy is stored in the magnetic field created by the flow of direct current in the superconducting coil, which is cooled by the cryogenic system to maintain a superconductive state. When the coil is charged, the current remains constant due to the absence of resistance in the superconductor [5]. Discharging the coil transfers the stored energy to be used as required.

a. Magnet Configuration and Conductor

The design of the superconducting magnet within the SMES system is vital because it is key to storing and transferring energy. The magnet must be constructed to meet the electromagnetic signature while simultaneously reducing quench [5]. Quench in a superconductor is defined as a "a sudden, unexpected and unrecoverable transition to the normal state of the superconductor in the device which enforces the conversion of the stored energy into mostly heat, which can lead to destruction of the device when not properly controlled" [33]. Although quenches are always to be avoided if possible, the consequences of one occurring are so severe that they should be anticipated in the overall design and operation, and allowances made to ensure safe shutdown and restart. For a SMES system, two magnet topologies are considered: solenoid and toroid [5]. The solenoid has a simpler structure when compared to a toroid, thus the electromagnetic forces are more manageable, but it creates external magnetic fields that can interfere with nearby electrical and mechanical equipment. Toroids experience a large radial force towards the central axis, and may be susceptible to experiencing quenching due to the imbalanced distribution of electromagnetic forces [5]. However, because the magnetic field is largely contained within a toroid, it creates fewer stray fields when compared to the solenoid. Solenoids can be designed with active shielding around the main magnet or placed in arrangements to minimize stray magnetic fields, as the hexagonal example shown in Figure 11 [34]. Solenoids typically require less of the expensive HTS than toroids and are therefore often preferred for the SMES system design.

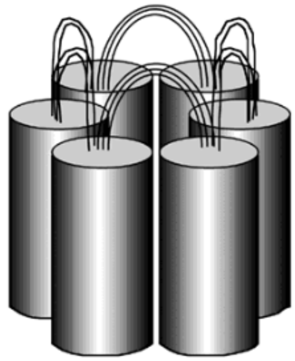

Figure 11. Hexagonal Solenoid Arrangement. Source: [34].

One study explored SMES magnet design by comparing optimal magnet configurations of a single solenoid magnet, a 4-pole magnet, and toroidal magnets with varying number of coils at different thicknesses, lengths, radiuses, and operating currents wound with MgB_2 and YBCO conductors [35]. The remaining configuration parameters were determined by using an optimization method known as simulated annealing (SA), which is a direct search method that can manage discrete variables [36]. The results of this study concluded that an ideal design for SMES magnets should utilize helical coils made with MgB_2 as the conductor. A depiction of this magnetic configuration is shown in Figure 12, with design measurements and specifications displayed in Figure 13 [35].

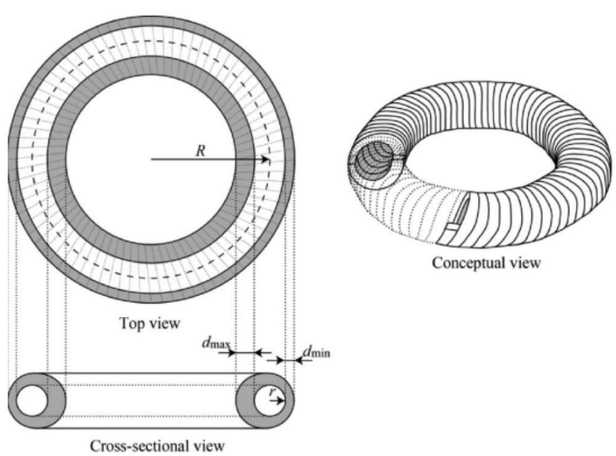

Figure 12. Ideal MgB_2 SMES Magnet Design. Source: [35].

Specifications of Ideal MgB_2 SMES Magnet	
Storage energy E (MJ)	558.9
Winding Volume V (m^3)	1.127
Radius R (m)	3.43
Helical radius r (mm)	597.9
Minimum thickness of coil d_{min} (mm)	11.70
Maximum thickness of coil d_{max} (mm)	16.71
Number of turns	2166
Cross-sectional area of MgB_2 conductor A_m (mm^2)	136.9
Operating current I_{op} (kA)	21.97
Inductance L (mH)	2315

Figure 13. MgB_2 SMES Magnet Design Measurements and Specifications. Source: [35].

The helical design was considered preferable to the toroidal structure because it minimized magnetic flux leaks between the coils, and had the potential to store 5.6 times more energy than the single solenoid magnet [35]. Further research in magnetic configurations for energy storage optimization within a SMES system should be considered.

The conductor within the magnet winding in early SMES systems was typically NbTi because it is inexpensive; however, its operating temperature is exceedingly low as it is only superconducting at very low temperatures (LTS). LTS materials are required to be cooled to 4K or even lower, whereas newer high-temperature superconductors (HTS) can operate at up to 77K or above, the same temperature as liquid nitrogen. Not only can the HTS materials operate at higher temperatures, thereby reducing the cost of the cryogenic system, they have much higher magnetic field and current density capability, so they are very attractive for SMES applications. Figure 14 [37] provides an example of the advantages of HTS YBCO compared with LTS NbTi and Nb_3Sn. However the cost of HTS materials is approximately two orders of magnitude higher than LTS materials, although reducing as manufacturers learn how to better produce the material [5].

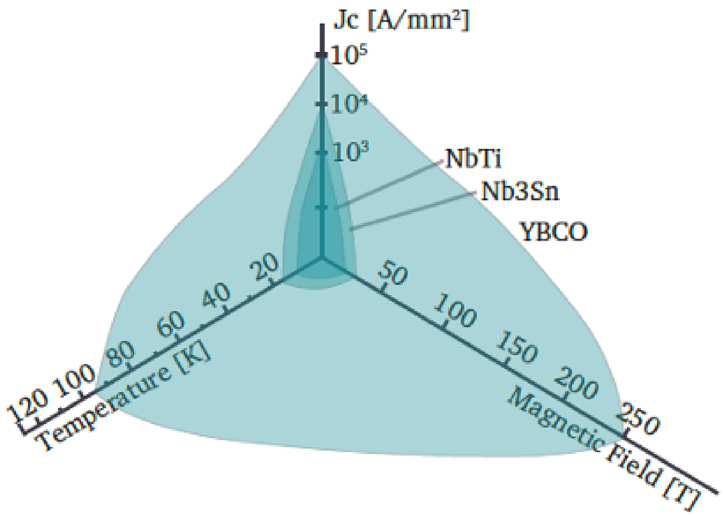

Figure 14. Comparison of the operating ranges for HTS YBCO compared with LTS NbTi and Nb_3Sn. Source: [37].

b. Cryogenic Cooling System

An essential component of a SMES system is the cooling system because keeping the SMES system from overheating ensures that the magnetic coils maintain a superconductive state, allows the use of higher critical currents, and results in less AC losses. Cooling of the magnetic coils is typically achieved by immersing the coil into a cryogenic liquid (LN_2, LHe, LNe, LH_2), or by using a refrigerator known as a cryocooler (CC) to circulate cryocoolant in the form of a liquid or a gas [38]. The cooled magnetic coil is housed in a cryostat to protect it from ambient temperature. Like the differing magnetic topologies offering varying advantages and disadvantages, the two cooling methods also present contrasting advantages and disadvantages for a SMES system. Immersing the coil in cryogenic liquid is more thermally stable, however this method experiences heat loss from the cryogenic liquid to the cryostat. As illustrated in Figure 15 [39], lunar craters experience temperatures that drop as low as 40K (-388 F), therefore this thesis recommends placing the cryostat of the SMES system within a lunar crater to minimize the overall cooling requirement of the system.

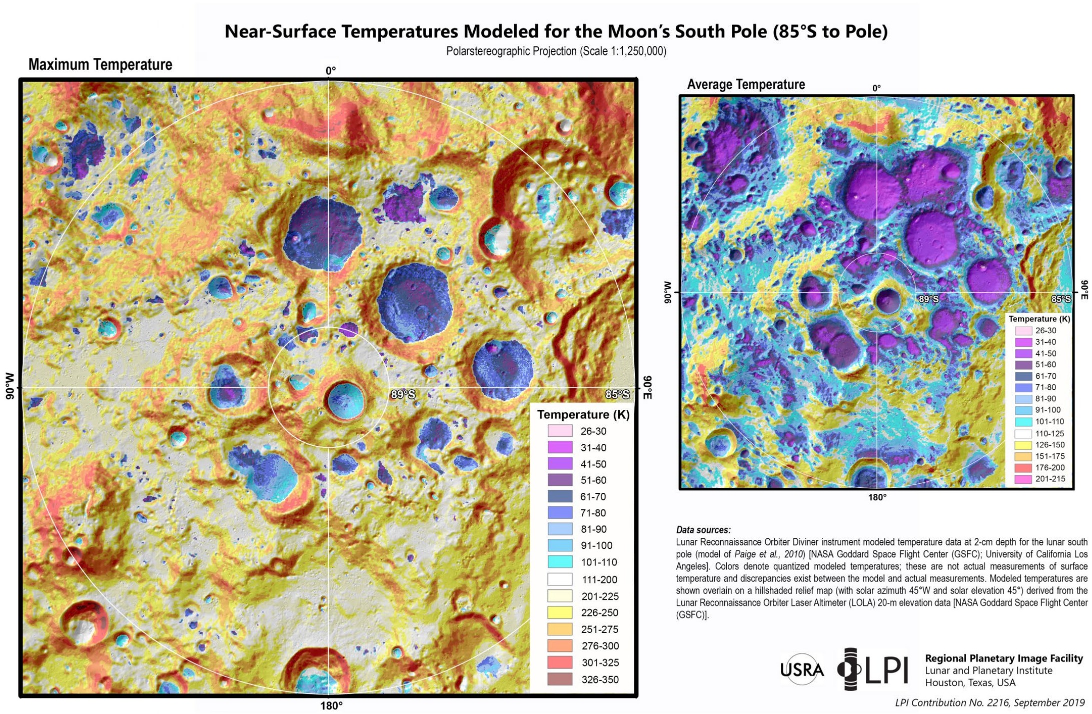

Figure 15. Temperatures on the Moon's South Pole. Source: [39].

Further research should be conducted as to what type of cooling system is more advantageous and how placing the SMES system within a lunar crater at a lower ambient temperature will affect the overall design of this cooling system.

2. Historical Uses of SMES

a. SMES to Support a Power Grid

The first proposed use of a SMES system was in 1970, when it was envisioned to be used to level the load in the French electricity network, however this idea was discarded due to the overwhelmingly large magnets required and low energy density generation provided by SMES systems [5]. The next experiment with a SMES system was conducted by the Bonneville Power Authority in the 1980s when they used a 30 MJ SMES system as a Flexible AC Transmission System (FACTS) to damp low-frequency power oscillations [5]. This SMES system was able to support the power grid for approximately one year, with over 1200 hours of energy transfers [5]. While Bonneville Power Authority's SMES system experienced no problems with the magnetic coil, it had issues with the refrigerator and as a result they turned to alternative solutions to damp oscillations within the grid [5]. In 2000, the American Superconductor company also utilized a SMES system for a power grid in Wisconsin that was experiencing consistent voltage instability problems that had the potential to lead to a complete grid collapse [5]. To resolve the voltage instability issues, the American Superconductor company placed six SMES units at key locations in the grid to boost the voltage, which resulted in a 15 percent increase in power transmission capability [5]. The SMES systems were discontinued when a newly installed power line was able to solve the voltage instability issues of the grid.

b. SMES for Voltage Depressions

In addition to leveraging a SMES system to support a power grid, these systems have also been operated in uninterruptable power supplies (UPS) for critical loads requiring significant power for sensitive processing. This was demonstrated in 1997 when a SMES system developed by the American Superconductor company was installed in South Africa at a paper mill for use as a "dip protector" by boosting voltage during voltage depressions while not completely separating the load, thus maximizing power during the dip [40]. The paper mill consistently suffered from voltage dips which affected its sensitive machinery due to its geographical location that is prone to lightning strikes, pollution from fires in fields, and consistent mist from the sea. Since install of the SMES system, the machinery within the mill has not experienced a single shutdown caused by voltage dips from the grid [40].

Japan used SMES systems in a similar fashion to protect sensitive loads from voltage dips when one was installed in 2003 to support a liquid crystal manufacturing company. Additionally, Japan has invested in a national program that developed a SMES system using Bi-2212 HTS wire in the magnetic coil to bridge voltage dips in a commercial power grid, shown in Figure 16 [41]. A schematic of how the SMES system was connected to the power grid is also shown in Figure 17 [41] where the arrows leading to grid current, load current, and coil current illustrate the system's measuring points when voltage dips occurred.

Figure 16. Japanese 10 MVA/ 1 sec system. Source: [41].

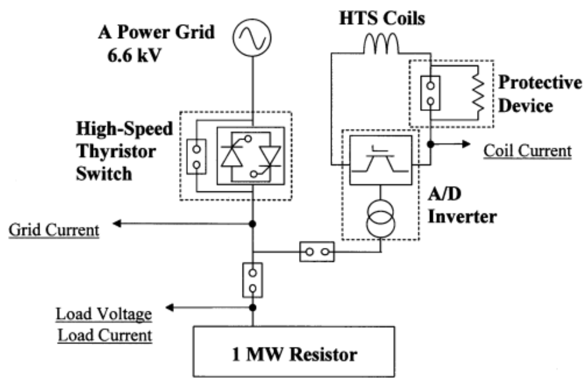

Figure 17. SMES System Connected to Power Grid. Source: [41].

c. SMES for Pulsed Power

Pulsed power sources, such as electromagnetic launchers, require high values of power density in short periods of time. Because a SMES system power output can range from 100 kW to 10 MW with an extremely fast response time of around 5 ms, it is highly suitable for electromagnetic launchers [7]. The operation of SMES for an electromagnetic launcher is described in [5]. The idea of using a SMES system for pulsed power was also studied in Russia, in which an experiment was conducted using a 5 MJ toroidal SMES system was able to produce a peak current of 600 KA [42]. This thesis seeks to utilize a SMES system in support of LEMMA, but other lunar pulsed power applications will be explored in Chapter III.

3. Lunar SMES (LSMES) System

Towards the end of this research, we discovered a group at NASA working on a similar project known as LSMES. Within their study [22], they propose utilizing Yttrium Barium Copper Oxide ($YBa_2Cu_3O_7$) as the HTS wire for a LSMES coil because it has a critical temperature of 91K. Additionally, they also suggested placing the coil within a PSR lunar crater to eliminate the need for cryogenic cooling, as depicted in Figure 18 [22]. A LSMES test coil was designed and tested at the University of Houston Physics Department in which they used 350m of $YBa_2Cu_3O_7$ HTS wire in a double pancake coil magnetic configuration, as illustrated in Figure 19 [22].

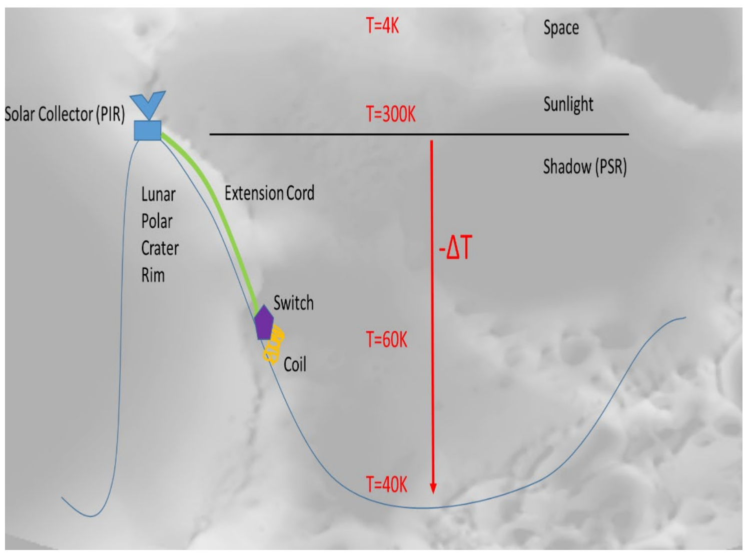

Figure 18. Conceptual Location of LSMES within a PSR. Source: [22].

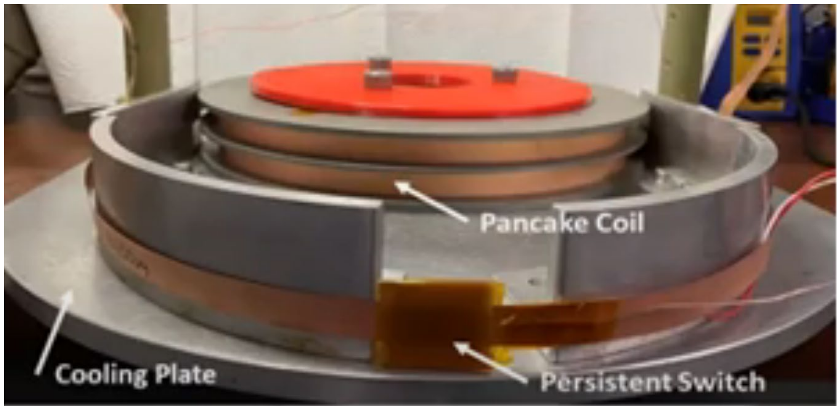

Figure 19. Prototype of LSMES. Source: [22].

During testing of the prototype coil, the cryocooler and vacuum chamber were unavailable so the test could not be conducted at 40K to simulate the PSR of the lunar crater and was instead tested in liquid nitrogen at a temperature of 77K [22]. At 40K, the test was expected to generate a max power output of 11 W, but instead at 77K the test yielded a maximum power output of only 0.1 W [22]. This test was conducted at varying current inputs assessing the strength of the magnetic field over time, shown in Figure 20 [22].

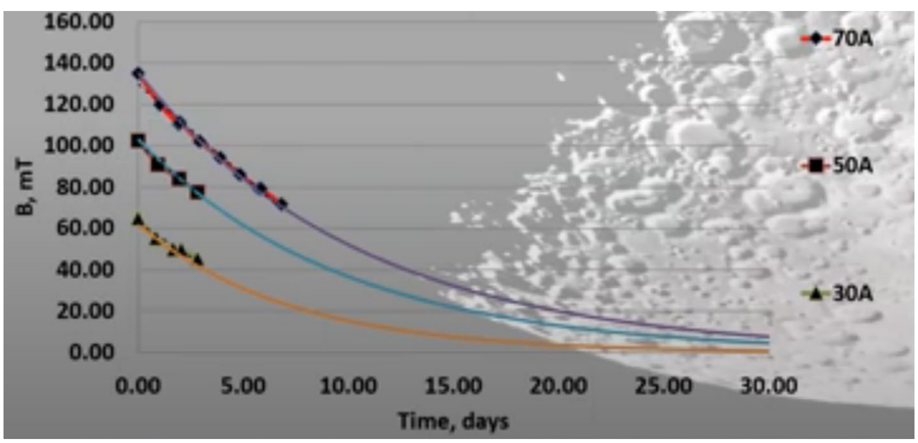

Figure 20. Results of Magnetic Field Strength over Time for LSMES Prototype in Liquid Nitrogen. Source: [22].

While conducting the test at 77K instead of 40K degraded the expected results, the LSMES system still demonstrated 30% energy retention over 14 days [22]. While retaining energy for 14 days is significant, the current within the system is expected to never decay over a long period of time (years), which could potentially indicate some of the material used in this experiment requires improvement. The key takeaways and recommendations from the prototype and testing were to reduce the mass of the HTS wire by using advanced thin wire (currently designed, but not in production), and to use a toroid magnetic configuration [22].

D. COMPARISON OF ENERGY STORAGE SYSTEMS

As depicted above in the comprehensive review of the differing energy storage systems, each system demonstrates advantages and disadvantages that must be assessed based on stated requirements for application. A detailed comparison of supercapacitors, SMES systems, flywheels, and lithium-ion batteries was conducted in [26] in which the power, energy, and cost characteristics of each system were assessed.

Each energy storage system has advantages and disadvantages depending on its intended use. In terms of energy density, the lithium-ion battery trumps the other systems but the usual batteries of this type also have a low power density. However, tests have shown that certain Li-ion battery cells can produce high power when discharged into low resistive loads [43]. Electrostatic capacitors have the highest power density, and can discharge in microseconds to milliseconds, but they are expensive in capital cost per unit energy. The SMES system demonstrates high power density but is also expensive in capital cost per unit energy and has lower energy density than batteries, while the flywheel is generally average when compared against the other systems.

Another way to evaluate energy storage systems is with Ragone plots, which plot specific energy against specific power on a logarithmic scale to compare different devices on a single plot. When analyzing Ragone plots, the X-axis displays how much energy is available per unit mass, and the Y-axis demonstrates the power per unit mass (how quickly energy can be delivered) [44]. An example of a Ragone plot assessing energy storage systems is shown in Figure 21 [9].

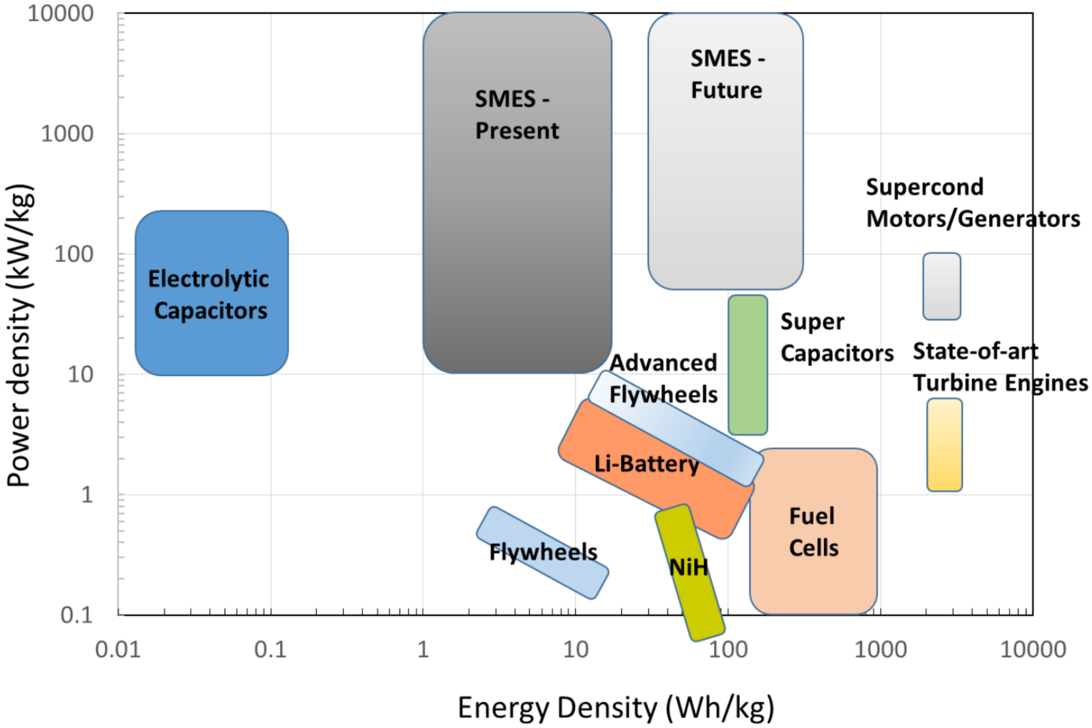

Figure 21. Ragone Plot Assessing Differing Energy Storage Systems. Source: [9].

Figure 21 comes from a study conducted by the U.S. Air Force Research Laboratory, in which they analyzed the utilization of SMES systems for aerospace applications. The goal of this study was to optimize the energy density produced by SMES systems by improving the magnetic coil solenoid design. Different solenoid geometries were modeled, and it discovered that the "pancake" configuration of the magnet produced the highest energy density [9]. In Figure 21, "SMES-Present" represents the current energy density capabilities of SMES systems and "SMES-Future" represents the possible energy density capabilities after the magnetic coil is optimized. When compared to the other energy storage systems in the Ragone plot, SMES systems offer the highest power density but are comparable to the other systems in energy density.

As illustrated above in the different plots and graphs, each energy storage system exhibits a myriad of benefits depending on their intended use. For lunar applications such the Artemis Base camp and pulsed power requirements, the SMES system appears to be the best option because of its high-power density, fast discharge time, high efficiency, low capital cost per unit power, and inherent suitability for use in very cold lunar craters. However, the current cost of launching and landing a payload onto the Moon is approximately one million dollars per kilogram, therefore the selection of a suitable energy storage system may come down to the system that has the lowest mass.

III. SMES LOCATION, SIZING, AND THERMAL REQUIREMENTS

When considering the required size of a SMES system to meet power requirements on the Moon, three primary aspects must be considered. These aspects include the location of the SMES system, the characteristics of lunar craters to potentially house the system, and finally the expected heat transfer between the lunar crater's ambient temperature and the SMES system's operating temperature. By exploring the effects of heat transfer, this chapter of the thesis will provide an understanding of how the lunar environment generates tradeoffs for how to best employ the SMES system.

A. SMES LOCATION AND LUNAR CRATER GEOMETRY

Ideally, the SMES system would be placed within a lunar crater to leverage the cooler ambient temperature of the crater. The system would also need to be relatively close to the Artemis Base Camp to minimize the amount of transmission cable systems to facilitate energy transfer from SMES to the base. Because the location of the Artemis Base Camp is currently planned for the Moon's South Pole near the Shackleton Crater, the SMES system should also be in that general area. As previously mentioned, the steep slope of the Shackleton Crater would make it difficult to house the SMES system, especially within the shadowed regions. To safely secure and establish the SMES system within the shadowed region of the crater, some regolith may have to be displaced to create a plateau in which the SMES system could be placed. Moving the regolith places additional stress on the LTVs, increasing overall operational risk. Neighboring craters to the Shackleton Crater should be explored to determine if a crater with a more optimum geometry to house the SMES system exists. Another important consideration for the location of the SMES system is where it will be safe from space environment factors, such as dust, cosmic or solar radiation, or potential asteroid/meteor strikes. Because of this, placing the SMES system outside of a crater could increase the likelihood of it being affected by the space environment and therefore may require an enclosure to be built around the system. Additional research should be conducted to identify the best location for the SMES system near the Artemis Base Camp, where it would be protected from space environmental impacts, and can utilize the shadowed region of a lunar crater for cooling.

B. SMES SYSTEM HEAT TRANSFER

As mentioned in Chapter II of this thesis, one of the limiting factors to the operation of a SMES system is its significant cooling requirement and extensive cryogenic cooling system. To mitigate this requirement, this thesis recommends burying the cryogenic system within a cylindrical container in the shadowed region of a lunar crater due to its low ambient temperature. To fully analyze and understand how the lunar crater will impact the operation of the SMES system, heat transfer between the lunar regolith and the cylindrical container encasing the cryogenic system will need to be evaluated. Ideally, heat will dissipate from the surface of the cylindrical container into the lunar regolith via conduction. We made an initial evaluation of this situation.

1. Thermophysical Properties of Lunar Regolith

To properly perform heat transfer calculations on the Moon, the thermophysical properties of the lunar regolith must be obtained. The key properties to understanding lunar thermal behavior are density, specific heat capacity, and thermal conductivity. Specific heat capacity describes the amount of heat required to raise the temperature of one unit of mass of an object or substance [45]. Thermal conductivity is the ability of an object or substance to conduct heat [46]. Knowledge of these parameters is also essential for creating technology that will interact with the regolith, like the technology required to meet the objectives of NASA’s LSII, which include mining for lunar ice/minerals and performing ISRU. Previous research was conducted on the thermophysical properties of the lunar regolith with different models used to approximate the values of specific heat capacity and thermal conductivity, as summarized in Tables 1 and 2.

Table 1. Lunar Regolith Specific Heat Values from Various Resources

Reference	Specific Heat (J/kg*K) at varying temperatures (K)
Thermophysical Property Models for Lunar Regolith [47]	228.9 J/kg*K @ 90 K
A Model for the Thermophysical Properties of Lunar Regolith at Low Temperatures [48]	86 J/kg*K @ 40 K
The Specific Heat of Astro-materials [49]	69.33 J/kg*K @ 40 K

Table 2. Lunar Regolith Thermal Conductivity from Various Resources

Reference	Thermal Conductivity (W/m*K) at 40 K
A Global Thermal Conductivity Model for Lunar Regolith at Low Temperatures [50]	0.0011 W/m*K
A Model for the Thermophysical Properties of Lunar Regolith at Low Temperatures [48]	$6.932*10^{-4}$ W/m*K
Thermophysical Properties of the Regolith on the Lunar Far Side [51]	$8.48*10^{-3}$ W/m*K

The specific heat in [47] was modeled from samples obtained from the Apollo 14, 15, and 16 missions using a fourth-order polynomial fit, however this model is only designed for temperatures 90K and greater. To accommodate for lower temperature regimes, the model in [48] used a zeroth-order approximation by assuming the structure of the lunar regolith is dominated by the amorphous component and the crystalline component is trivial. However, to verify their assumption, a sensitivity analysis was conducted to determine how much crystallinity influences specific heat and it was determined the accuracy of their zeroth-order approximation decreases with temperature [48]. Lastly, the model in [49] used "unsmoothed Apollo specific heat data, assuming a constant uncertainty of 2% and decomposed it into a best-fit composition, using a combination of minerals to represent 'astro-materials.'"

Thermal conductivity in [50] was determined by modeling data built on temperature trends on the lunar surface as observed from NASA's Diviner Lunar Radiometer Experiment (Diviner). This model primarily describes "nighttime surface temperatures, subsurface temperatures at high latitudes, and PSRs" [50]. Laboratory data of lunar simulants (particulate basalt) was used to create a formula to model thermal conductivity at varying temperatures in [48]. Finally, the thermal conductivity in [51] of the lunar regolith was calculated using a theoretical model using in situ regolith temperature measurements obtained from the Chang'E-4 (CE-4) spacecraft. The CE'4 lander landed in the Von Karman crater on 3 January 2019 and released the Yutu-2 rover that emplaced four temperature probes (T1-T4) to measure the temperature of the local regolith every 900 seconds [51]. This study calculated profiles of temperature, bulk density, and thermal conductivity from the lunar surface to a depth of 1 m. The thermal conductivity was determined to be approximately $1.53*10^{-3}$ (W/m*K) at the surface and $8.84*10^{-3}$ (W/m*K) at the 1 meter depth with a bulk density of 1500 kg/m^3 [51]. Figure 22 [51] displays the relation of bulk density and thermal conductivity of the lunar regolith at varying depths. For purposes of this thesis, the values obtained at 1 m will be utilized to simulate the cryogenic cooling system being buried beneath the regolith.

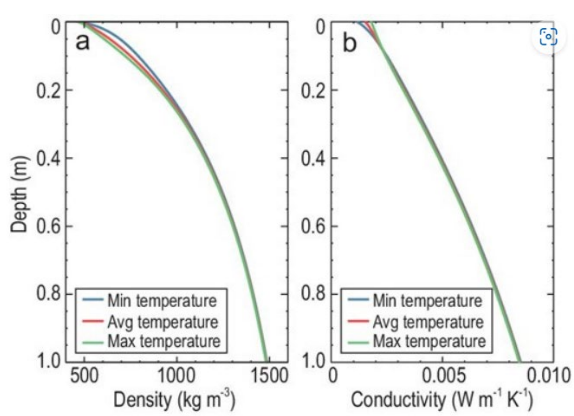

Figure 22. Lunar Regolith Bulk Density and Thermal Conductivity Profiles from the Moon's Surface to a Depth of 1 meter. Source: [51].

2. Conduction

Conduction is defined as "the flow of internal energy from a region of higher temperature to one of lower temperature by the interaction of adjacent particles in the intervening space" [52]. Conduction rate is the amount of energy transferred per unit time and is described in [53] by:

$$Q = kA\left(\frac{\Delta T}{L}\right) * t, \quad (1)$$

where:

Q= Heat Transferred (W)

k= Thermal Conductivity (W/m*K)

L= Thickness (m)

A= Area (m^2)

ΔT= Temperature Differential between Hot and Cold Reservoir (K)

t= Time to Transfer Heat (s)

Assuming (arbitrarily) that the SMES system will generate 300 W of heat while providing a single energy pulse, equation (1) can then be used to determine how much time it will take for 300 W to be dissipated into the lunar regolith. If the cylindrical container is designed to be 2 meters in diameter and 2 meters tall it will have a surface area of 18.85 m^2. The temperature gradient between the wall of the cylinder and the lunar regolith is assumed to be 37 K (77 K at cylinder wall, and 40 K in lunar regolith). Substituting these values, along with the value of thermal conductivity mentioned earlier into equation (1), and then solving for t reveals it will take approximately 48.6 seconds for 300 W of heat to be dissipated from the SMES system into a 1-meter thickness of the lunar regolith surrounding the cryostat. This means that every 48.6 seconds, 300 W of power can be removed from the system. That amount of time can be decreased by increasing the surface area of the cylinder by adding fins or using heat pipes to transfer the heat into a greater volume of the regolith. This calculation also illustrates the importance of embedding the cryogenic system within a region of lower temperature, such as the lunar regolith in a crater, because if the temperature gradient was decreased it would take more time for the generated heat to be fully dissipated. For example, if the SMES and cooling system were placed on the Moon's surface near the Shackleton crater, the average temperature is around 70 K making the temperature gradient 7 K. Performing the same calculation for time to dissipate heat and using 7 K for the temperature gradient instead of 37 K equates to a time of 257.2 seconds. These two calculations help validate the benefits of burying the cryostat within the lunar regolith of a PSR in a crater, as the SMES system can operate nearly five times as fast when compared to the situation where the cryostat is on the Moon's surface.

3. Quantity of Heat

Another way to observe the advantages of burying the cryostat within a lunar crater is to assess how the temperature of the regolith changes after the SMES system releases 300 W of heat. This can be calculated using equation (2) described in [53] as:

$$Q = mc\Delta T, \tag{2}$$

where:

Q= Heat Transferred (W)

m= Mass of Object (kg)

c= Specific Heat Capacity of Material (J/kg*K)

ΔT= Temperature Change of Object (K)

Assuming the heat generated (300W) from the SMES system is uniformly dissipated into a volume of regolith that is 1 meter larger in diameter than that of the cryostat, the total volume of regolith in which heat will be dissipated is 18.85 m^3. Multiplying the volume by the density of the regolith, 1500 kg/m^3, gives the total mass of the regolith to be approximately 28,275 kg. Lastly, the specific heat capacity of the regolith, 86 J/kg*K, calculated from [48] at 40K was used in this example. Substituting these values into equation 2, the total temperature rise of the regolith is calculated to be 0.0001K. This low temperature rise demonstrates that any heat generated during the SMES operation should be easily absorbed into the regolith, further validating the benefits of embedding the cryostat within a lunar crater. More detailed calculations using more accurate regolith data, when it becomes available, should be used to validate this result.

In summary, this chapter discusses the two critical aspects to consider when designing a SMES system for the Moon: the location of the system and its associated heat transfer characteristics. The ideal location for the SMES system is a lunar crater that is relatively close to the Artemis Base Camp and has an optimal geometry for housing the system. However, the geometry of the Shackleton Crater, NASA's presently planned location of the Artemis Base Camp, may make it challenging to house the SMES system. Therefore, other neighboring craters should be explored to assess other suitable locations. Furthermore, this chapter discusses the thermophysical properties of lunar regolith, including density, specific heat capacity, and thermal conductivity, which are crucial in determining the heat transfer between the SMES system and the lunar environment. The heat transfer calculations validate the advantages of burying the cryogenic system within a cylindrical container in the shadowed region of a lunar crater due to its low ambient temperature. Identifying an ideal location for the SMES system near the Artemis Base Camp, protected from space environmental impacts, and potentially utilizing the shadowed region of a lunar crater for cooling is of utmost importance.

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IV. ADDITIONAL LUNAR POWER APPLICATIONS

With the goal of establishing a sustained human presence on the Moon through NASA's Artemis program, leveraging innovative technologies and solutions will be essential for success. In particular, the use of in-situ resource utilization (ISRU) and self-sufficiency through lunar manufacturing, lunar radar systems, and directed energy systems could provide critical support for deep space exploration and ensure the safety of future lunar inhabitants. This chapter will explore these three technologies discussing their potential benefits and challenges, discuss their role in supporting lunar activities, and finally elaborate how the SMES system could potentially be employed for their operation.

A. LUNAR MANUFACTURING

To create a sustained presence on the Moon with a lunar station such as NASA's Artemis Base Camp, leveraging self-sufficiency and ISRU technologies to enable lunar manufacturing will be vital for success. Prof. Alex Ellery [54] addressed the requirement of using the Moon's resources. He wrote, "To maximize sustainability in our imminent ventures to the Moon, it will become essential to maximize our utilization of local resources on the Moon while minimizing the resources required to be supplied from Earth. In terms of lunar infrastructure development, it will be essential to build suitable energy generation and energy storage facilities on the Moon for the Moon from the Moon" [55]. Lunar manufacturing can be used to assist a multitude of missions and purposes that include deep space exploration, construction of lunar infrastructure, and support of terrestrial markets.

One specific use of lunar manufacturing to support space exploration while simultaneously contributing to terrestrial markets is the proliferation of solar power satellites (SPSs) [55]. This framework would include six lunar power stations (LPSs) on the Moon's surface to serve as a "mounting platform" for a solar power system that could beam power equating to 20 TW of electrical energy to Earth from the Moon [55]. LPSs could be constructed with resources solely obtained on the Moon, thus leveraging lunar manufacturing. However, a potential issue that arises with LPSs is the two-week lunar night in which solar energy is obsolete. This thesis suggests a SMES system could potentially solve this issue by supplementing energy to LPSs during the lunar night.

B. LUNAR RADAR

To ensure the protection of Earth from impact of Near-Earth Objects (NEOs) such as asteroids, meteors, and comets, the Planetary Defense Coordination Office (PDCO) was established by NASA to supervise the ongoing mission of planetary defense. To execute this mission, the PDCO detects Near Earth Objects (NEOs) that are expected to pass within 5 million miles of Earth's orbit and have the potential to cause damage to the Earth's surface due to their size [56]. A vital component of NASA's planetary defense initiative is the NEO Observations Program, which is Congressionally directed to "find, track, and characterize at least 90 percent of the predicted number of NEOs that are 140 meters and larger in size" [56]. NASA accomplishes this with a multitude of projects that leverage telescopes and radar systems. Optical or infrared telescopes are typically used to identify the NEO and then a radar system predicts its distance or speed. Presently, there is not a radar powerful enough to singlehandedly detect a NEO in space and thus they are used in conjunction with telescopes [56]. By utilizing radar systems, the uncertainty in position of an asteroid predicted by optical telescopes is reduced from several thousands of kilometers to a few meters [56].

One radar system that assists in tracking NEOs is the Goldstone Solar System Radar (GSSR), which is presently the only fully steerable, high-power ground-based radar in the world for high-resolution ranging and imaging of small-body targets [57]. The GSSR requires approximately 1 MW of input direct-current power, half of which is converted to radio frequency power and the other half is waste heat [58].

A similar radar system could be placed on the Moon to protect the astronauts, lunar base, and lunar infrastructure from asteroids, meteors, or comets that may impact the Moon. This lunar radar system would serve the same purpose as the Earth-based planetary defense radar systems but instead of predicting the distance or speed of NEOs, it would predict the distance or speed of Near-Moon Objects (NMOs). When compared to NEOs, NMOs pose a greater potential hazard because, unlike Earth, the Moon does not have an atmosphere in which objects can burn or disintegrate prior to impact. With the vast amount of time, funding, resources, and research that is involved with building a sustained presence on the Moon, it is crucial to prevent impact from NMOs. Future Mars missions will also require a similar radar system because even though Mars does have an atmosphere, it is thinner than Earth's.

Additionally, lunar-based radar systems could assist with planetary defense of Earth by identifying and tracking objects that are potentially out of view of Earth-based radars and telescopes further improving space domain awareness. It's unlikely the lunar radar would need to be as large as GSSR. If the two radars are similarly sized, the input power required for the lunar radar would assumably be 1 MW, the same as the GSSR. As mentioned previously, a SMES system can generate power in intermittent pulses that range from 100 kW to 10 MW, and a large radar such as the GSSR would not require continuous power for successful operation. Therefore, the SMES system could be suitable to provide pulsed power for the lunar radar.

C. DIRECTED ENERGY SYSTEMS

The operation of directed energy systems, like lasers, involves utilizing "stimulated emission" to create a concentrated light beam that carries electromagnetic radiation energy, which can propagate over extended distances and travel at the speed of light. Lasers are advantageous for use in space because the absence of atmosphere allows propagation at all electromagnetic frequencies with virtually no attenuation. Rogers conducted a study [59] at the Air War College in which the potential uses of lasers in space were evaluated. In this study, space-based laser concepts were grouped into four distinct classes: "enabling systems, information-gathering systems, information-relaying systems, and energy-delivery systems" [58]. In space, lasers serve as enabling systems by guiding optical signals and providing illumination for optical sensing systems [59]. For information-gathering, active illumination of the target of interest by the use of a laser source can enhance the data collected from that target [59]. Information-relaying in space primarily occurs via satellites. Most satellites utilize radio frequencies to transmit information, which are limited in bandwidth, prone to scintillation, and can be jammed. Laser communication systems offer a greater capacity for information transfer because they are not restricted by bandwidth or data rates, are able to efficiently transmit signal to the receiver due to focused signal directionality with little spreading throughout the atmosphere and are smaller than traditional radio frequency satellite systems [59]. NASA plans on leveraging laser communications as part of Artemis II with the Orion Artemis II Optical Communications System (O2O) [60]. O2O is planned to be onboard Orion, and NASA expects it to "enable live, 4K ultra-high-definition from the Moon, as well as enhanced science data transmission and more"[60]. Additionally, O2O will potentially permit transmission of valuable procedures, flight plans, and voice between Orion and Earth. O2O will contribute essential data and information that will support future Artemis missions as well as support a sustained presence on the Moon.

In addition to rapidly and efficiently relaying information, lunar lasers could also be used for space debris mitigation and protection of the Moon and lunar base from impact of asteroids and meteors, as well as other space debris. When the target of interest (asteroid, meteor, debris, etc.) is under consistent laser irradiation, part of the target is ablated while the other portion experiences an impulse that deflects the target's trajectory, preventing the target from impacting the Moon [61]. Larger objects that a laser cannot mitigate could potentially be destroyed or pushed into an alternate trajectory by launching a projectile at the object with the LEMMA system. Like LEMMA, lasers require tens of kilojoule pulse energies in short bursts of time in which a SMES system could supply with its capability to deliver power ranging from100 kW to 10 MW in a quick response time of around 5 ms [7].

In conclusion, the success of a sustained presence on the Moon, such as NASA's Artemis Base Camp, is reliant on self-sufficiency and ISRU technologies. Lunar manufacturing is an essential aspect of this approach as it enables the utilization of local resources while minimizing the resources required to be supplied from Earth. One specific use of lunar manufacturing is the proliferation of solar power satellites (SPSs), which could be constructed with resources solely obtained on the Moon. The use of a SMES system could potentially solve the issue of the two-week lunar night when solar energy is obsolete.

Additionally, a lunar radar system could be placed on the Moon as part of an early warning system for protection of the astronauts, lunar base, and lunar infrastructure from asteroids, meteors, or comets that may impact the Moon. Finally, directed energy systems, such as lasers, can be used in space for various purposes, including information gathering and energy delivery. Overall, these technologies can play a vital role in establishing a sustained and protected human presence on the Moon and improving space exploration capabilities.

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V. CONCLUSION AND RECOMMENDATIONS

The results obtained from this system study provide an in-depth analysis of multiple energy storage systems and reveal the significant benefits of utilizing a SMES system over the other energy storage systems, specifically for power requirements on the Moon. These conclusions are presented, along with recommendations for further research regarding SMES system optimization.

A. CONCLUSIONS

The Artemis Base Camp will provide revolutionary information regarding the Moon and its resources, as it will simplify research efforts by transitioning from reliance on lunar satellites and rovers to astronauts with boots on the ground. In addition to improving knowledge about the Moon, the Artemis Base Camp will also serve as a steppingstone to Mars due to increased efficiency in terms of delta V (impulse per unit mass required for spacecraft to perform a maneuver) and specific energy when launching from the lunar surface when compared to launching from Earth's surface. As previously mentioned, power is the most vital resource for building and sustaining a lunar infrastructure. NASA currently intends on generating power with a fission power plant and vertical photovoltaic arrays, storing it with low temperature battery modules and regenerative fuel cells, and distributing it with power beaming, cables, and spools. However, NASA lacks a plan for long term energy storage on the MW scale especially during periods of an eclipse, in which this research revealed that the SMES system is an optimum solution. When compared to other energy storage systems, SMES is the most favorable to maintain grid stability of the Artemis Base Camp and to support pulsed power applications such as lunar radar or directed energy systems. The attributes that make the SMES system more advantageous are its substantial power output capability that can range from 100 kW to 10 MW with an extremely fast response time of around 5 ms, notably high-power density, high efficiency, and finally low capital cost per unit power. The SMES would integrate well with a superconducting cable distribution system. The major degrader of using a SMES system for lunar power requirements is the cost to launch the system to the Moon as current launch costs are approximately one million dollars per kilogram.

B. RECOMMENDATIONS

While the Moon's environment is vastly different than Earth's environment and therefore requires detailed consideration for exploration, certain aspects of its environment can be leveraged to improve operational capabilities of the SMES system. For example. permanently shadowed regions of lunar craters have notably colder temperatures than the Moon's average surface temperatures, and thus can be used to assist the cryogenic cooling system in dissipating heat. As a result of this, this research recommends burying the SMES system within a cylindrical container at least 1 m into the lunar regolith of a crater because the time it takes to dissipate any heat generated from the SMES system can be considerably decreased. By decreasing the time to dissipate heat, the SMES system is available for use more frequently and therefore can provide power pulses for lunar operations more consistently.

C. FUTURE RESEARCH

This thesis presents the framework of how a SMES system can be beneficial to meet lunar power requirements, however the research does not cover the exact construct and design of the system. There are multiple design configurations for a SMES system that are primarily centered on the different magnet arrangements as well as the potential HTS materials available for use. The two main magnet arrangements discussed in this research were solenoid and toroid, both of which demonstrate high energy storage capability. However, solenoids generate stray magnetic fields while toroids require more expensive HTS material. One prior study [35] found that a helical design for the magnet was ideal for a SMES system, but this research used a LTS instead of a HTS and did not test the design in a simulated lunar environment. A prototype coil in a pancake configuration was built and tested by NASA [22] with recommendations from the test concluding that a toroidal magnetic arrangement is preferrable to the pancake design. Because of the varying results for different magnetic coils, further research should be conducted in a simulated lunar environment to determine which coil design generates the most optimum results in terms of energy storage capability, low mass, and compatibility with HTS. The SMES system will require assembly on Earth and then launch to the Moon, so the most ideal configuration will most likely require the lowest mass.

Additionally, this research did not cover how the SMES system will be integrated into the power grid of the Artemis Base Camp. Proposed ideas were presented of how the SMES system can support the power grid, whether it is used as a FACTS or provides power during a total lunar eclipse, but the actual configuration of the system within the grid was not discussed. Other lunar power applications in which the SMES system can be used, such as lunar radar, laser defense, and electromagnetic launchers, were also briefly discussed but not in terms of which application is best suited to utilize the SMES system. A detailed trade study of the varying applications should be conducted to determine which is best powered by a SMES system and which is most beneficial to meet the objectives of the Artemis program.

Lastly, this research briefly addressed potential locations for the SMES system on the Moon, highlighting the benefits of burying the cryostat within a PSR of a lunar crater due to the capability of the regolith to easily absorb any dissipated heat. The quick absorption time of the dissipated heat would allow the SMES system to be operated on a more rapid basis. However, the heat transfer analysis was conducted using the thermophysical properties at one temperature. To create a more accurate depiction of the heat transfer between the SMES system and the lunar regolith, a heat transfer analysis utilizing different temperature ranges with the associated thermophysical properties should be conducted. This thesis also recommended burying only the cryostat containing the magnetic coil within the lunar regolith, but additional research could be conducted to determine the benefits of burying other components of the SMES system to potentially reduce resistive losses. A study conducted in [62] explored this idea by placing a DC/DC converter with a superconducting magnet in a cooled chamber, thereby taking advantage of lower resistive properties of copper and increased semiconductor performance. An illustration of this construct is displayed in Figure 23 [62].

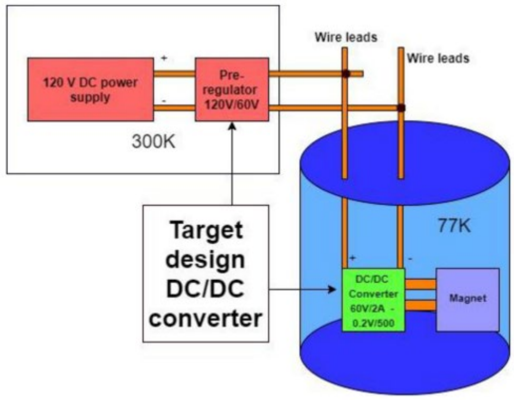

Figure 23. Overview of DC/DC Converter and Superconducting Magnet within a Cooled Chamber. Source: [62].

Furthermore, this thesis discussed the difficult geometry of the Shackleton crater with its steep slope so it may not be feasible to house the SMES system within the crater. Further research should be conducted to assess the ultimate location to ensure the protection of the SMES system while simultaneously maintaining proximity to the Artemis Base Camp to meet its power requirements.

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