Blasting Beyond Blast-off: The Use of Explosives for Blasting Applications in Lunar, Martian, and Other Space Environments

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ABSTRACT

As we approach the turning of another decade a new space race is well underway. Humankind's renewed push into space is driven by the allure of scientific discovery, the human tendency toward exploration and adventure, the fear some have of Earth's future livability, and in many cases the dream of accessing and commercializing vast deposits of natural resources. We also venture back into space knowing that our first tentative steps to return to the moon are only the beginning, setting the stage for future voyages to Mars and possibly other moons, planets and planetoids. But establishing a prolonged and sustained human presence on these bodies will require more than big dreams and even bigger funding. We must be able to access and utilize the local resources for building and producing the materials necessary for sustaining life. Doing so will require the development of techniques and materials suitable for use in these hostile environments. Blasting with explosives is one activity that will eventually become a necessity in the lunar and Martian environments if we are too build and mine those bodies. The techniques and methods that will be necessary must be researched now. This paper explores the lunar and Martian environments, the resources believed to be found there, and sets forth thoughts on the methods and technology that exists and that will have to be developed in order to use explosives for blasting on the moon, Mars, and beyond.

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I. INTRODUCTION

Background information and introduction of subject

As we approach the turning of another decade, we are drawing ever nearer to humankind's return to the moon. Fifty years ago, just getting to the moon was a feat in and of itself, and landing on it was a challenge to be conquered. Today, as we prepare to return to the moon we do so not just to prove it can be done, but to stay and establish a permanent, or at least a sustained, human presence on our nearest neighbor. Beyond simply surviving, thriving, and exploring, private enterprises and governments are actively planning the extraction of natural resources to obtain everything from rocket fuel to rare and precious metals.

As humans venture back into space beyond low earth orbit, we do so knowing that our return to the moon is only the beginning. Early lunar missions will set the stage for future voyages to Mars, and possibly even to other moons, planets, and planetoids. But establishing a prolonged and sustained human presence on these bodies will require more than big dreams and even bigger funding. We must be able to access and utilize the local resources for building and producing the materials necessary for sustaining life.

Establishing a sustained human presence on the moon or Mars will require effective gathering, processing, and use of local resources to produce fuels, electricity, water, heat, growing mediums, building materials, and more. Most current plans for the harvesting of local natural resources appear to focus on sifting regolith (the layer of loose material covering the surface of the ground), and using abrasive mining techniques on lunar and Martian rock formations to gather the raw materials for processing. In fact, one rather comprehensive article from the University of Washington's Department of Aeronautics and Astronautics outlines only two main sources of raw materials on the lunar surface which can both be mined with a single vehicle, those being lunar regolith as one source, and large nickel-iron fragments from past meteor impacts on the surface of the moon as the second source. (Amah, et al.)

But simply sifting regolith, gathering chunks of meteorites from past impacts, and grinding surface rocks will not be enough. Whether for protection from cosmic radiation and meteorite impacts, or for access to mineral resources, humans will eventually have to mine into subsurface rock on the moon and Mars. On the moon, people and structures on the surface will be especially subject to micrometeorite impacts, and high doses of cosmic radiation. Lunar surface cratering indicates the violence of meteorite impacts as shown in Figure 1. Even if humans never have to build underground structures on the moon or Mars, if Earth is any indicator of what to expect, it is still reasonable to assert that many of the richest mineral deposits likely exist deep within the lunar and Martian geology.

Figure 1 - Lunar surface showing impact craters in regolith. Image taken by the author.

Purpose of this paper

The intent of this paper is to examine the eventual necessity of blasting with explosives in the lunar and Martian environments if humans are to conduct construction and mining operations to any extent beyond sifting surface materials and grinding near surface rock. In speaking of mining on the moon and asteroids, an article in *Mining Engineering* notes multiple technologies will need to be developed to provide for planetary surface and orbital bases, special mining and metallurgical methods for extraction and processing, planetary materials characterization, materials handling and transportation, drilling, blasting, construction, power and life and safety systems. (Peacock, 2017)

The materials, methods, and science of blasting with explosives on the moon and Mars must be developed and researched now in order to keep pace with humankind's progression toward space outposts and commercial operations. This paper offers some basic ideas regarding the use of explosives for mining and construction purposes on the moon and Mars.

Scope of this paper

In some respects, the process of mining will be similar to that of terrestrial operations. Much like leveraging resources on Earth, there are four basic steps to exploiting asteroid resources: (1) prospect, (2) extract or harvest, (3) process and (4) utilise [sic]. (Anderson, Christensen, & LaManna, 2019) Returning finished products economically to Earth falls under the fourth category, utilize. This statement is equally true for bodies other than asteroids; the same four steps would apply to mining operations based on the moon, Mars, or any other celestial body. The focus of this paper has to do primarily with step 2, the extraction of natural resources, and, while some organizations are preparing missions to asteroids, this paper will focus primarily on the lunar and Martian environments, the resources believed to exist there, and the considerations necessary for operations in those environments.

Organization of information

The treatment of the subject will begin with further background and introductory information in the following two subsections. The second section of this report will examine the challenges of mining in nonterrestrial environments along with consideration of new methods, materials, equipment, and technologies that will be necessary for the development of blasting in space environments. The second section also contains information about autonomous drilling systems taken from a personal interview conducted at the *19th Pennsylvania Drilling and Blasting Conference* in State College, Pennsylvania. The third section will examine the development of blasting standards and regulations related to blasting and explosives use in space-based operations. The fourth section will briefly comment on next steps industry researchers and developers should take as humanity edges ever closer to the reality of nonterrestrial mining operations. The conclusion summarizes the material discussed throughout the paper.

Why mine the moon and mars?

The question of why we might want to mine the moon, Mars, or any other body in the solar system really begins with the question, why go to space at all? The reasons are as varied as people themselves are, but there are a few key reasons, one being the fact that human beings have a drive for adventure and an insatiable curiosity about the unknown, desiring to know what is knowable and to understand the place each of us has in the unfolding story of all that exists. Exploring space is simply a logical step in the progression of humankind.

But scientific exploration only begins with the first tentative steps onto the surface of another world. Real knowledge and in depth exploration require long stays and dedicated study, and that means colonization, or at least the establishment of permanent facilities to which people can come and go, just as easily as they do the International Space Station. This is another reason many desire to go to the moon and beyond.

Whether human beings colonize the moon, Mars, or any other planetary body, staying for long periods will require the utilization of local resources to provide everything from drinking water, to rocket fuel, to breathable air, to useful materials for farming and building. An article in *Space Policy* points out that, the value of locally processed rocket fuel alone cannot be understated. Our ability to use lunar sourced propellants has the potential to dramatically lower the cost of transportation within cislunar environs.

Lowering costs means reducing the challenge of overcoming at least one of the barriers to entry of an array of space-based opportunities. (Sowers, 2016) So, using the moon as a stepping stone is another key reason some give for why we should go there and learn to use its resources.

Apart from exploration for scientific knowledge stands commercial interests in the moon, Mars, and even asteroids and comets. There are enterprises who are positioning themselves to establish commercial mining operations to recover, process, and profit from the valuable natural resources available in these environments. In the commercial models, private companies would mine and process the excavated materials to recover water, metals, and potential fuel sources, and then either transport those products back to Earth or establish resupply outposts in space where they would sell their products to space faring nations and organizations.

Investment versus return potential is believed by these commercial enterprises to be worth the effort and upfront capital. The moon alone is believed to contain resources that are rare on Earth, and being our nearest neighbor, is the most accessible body for such an operation. Peacock notes, the moon regolith contains valuable rare-earth metals, platinum-group minerals (particularly where the Moon has been impacted by asteroids), volatiles (useful for processing and habitation), Helium-3, and titanium. (Peacock, 2017)

Other potential bodies that could be mined are likewise believed to be brimming with valuable materials. Near-earth asteroids, or NEAs, are one such possibility that has gained the keen interest of potential space mining entrepreneurs. Kargel, of the United States Geological Survey in Flagstaff, Arizona, emphasizes that the large majority of all asteroids, especially those that contain abundant metals, are veritable treasure troves of platinum-group and precious metals. His analysis shows that kilometer-sized metal bearing NEAs contain up to 400,000 tonnes of these metals, worth about \$5 trillion ($5x10^{12}$ US dollars) at present market prices. (Lewis, 1994) Demand is outpacing supply of certain materials on Earth. Computer chips and flat screens need trace amounts of various scarce elements and reserves of these elements are in such short supply that costs have been doubling every year. (Amah & al, Defining a successful commercial asteroid mining program, 2014)

One natural resource that has governments and commercial enterprises equally interested in recovery is the possibility of recovering large quantities of Helium-3 from the Moon. Helium-3, or He-3, has had scientists excited since its discovery in 1939. Peacock explains that while Helium-3 is almost nonexistent on earth, it is abundant and accessible on the Moon and can be used in nuclear fusion power plants, producing much more energy than fission reactions and with much less radioactive waste. (Peacock, 2017)

A final reason worth mentioning is the concern some people, companies, and governments have about the future condition of Earth. Some believe the Earth will be so environmentally unfit for life in the future, that it is important to begin developing off-planet alternatives on which to settle now, for the sake of future generations. This is a controversial topic on several fronts and will not be further addressed in this paper. Yet it is a topic that, if pursued to the point of construction on the moon or Mars, would be another reason certain organization might need to utilize blasting and explosives technology in space.

The future need for blasting technology on the moon and mars

As previously noted, sifting regolith, gathering chunks of meteorites from past impacts, and processing surface rocks will eventually not be enough to support human settlement or the significant fuel requirements needed for deep space exploration. Regolith may provide the immediate source of raw materials, but at some point, if Earth is any indicator of what to expect in other environments, mining deeper into the constituent rock of the moon or Mars will become necessary. On Earth, the kinds of mineral deposits thought to also exist on the moon and Mars were formed in subsurface magmatic intrusions and in tectonic subduction zones. (Copper, for example, as shown in figure 2 is an element that may exist on the moon. It is a mineral formed in and mined from deep beneath the surface of the earth.) These minerals are currently bound in rock, which we access by mineral mining techniques that involve blasting, digging, hauling, and processing huge masses of that rock.

Figure 2 - Copper embedded in basalt. Sample collected by the author in Blue Ridge Summit, Pennsylvania from a mine cut approximately 300 feet deep.

An article in *Scientific Reports* points out that valuable platinum group metals are also formed within magmatic chambers, either by settling of crystals on the magmatic chamber floor by the force of gravity, or in situ. (Chistakova, Latypov, Hunt, & Barnes, 2019) It stands to reason, then that the best and most useful mineral deposits on the moon and Mars will also be found deep within the lunar and planetary bodies, respectively.

Apart from actually extracting the natural resources available on the moon and Mars, blasting could play a valuable role in site development where mining and the construction of habitats and research stations will take place. A typical construction site on Earth, as shown in figure 3 below, requires the excavation and leveling of the site to remove boulders and provide a suitable construction surface. A typical surface mining site, as shown in figure 4 below, requires the excavation and removal of massive amounts of overburden. Overburden is defined here as the soil, boulders, and waste materials that cover the rock formations the mining operation is targeting. Both operations regularly require the removal of rock formations too large to excavate with machinery alone.

Figure 3 - A typical construction site. Note the level surface. Soil has been compacted to specification suitable for construction. Image provided by the author.

Figure 4 - A typical basalt surface mine with drills and a bulk explosives truck on the bench. Note the level benches and straight highwalls. These features enhance safety and accessibility. Image provided by the author.

Blasting may play an important role in the in establishing subsurface living environments on the moon for the sake of protection from cosmic radiation and physical impacts. The lunar environment is especially susceptible to micrometeorite impacts, which could be hazardous to both people and infrastructure. One study simulated the effects, indicating "Hypervelocity impacts result in a variety of impact shock phenomena, depending on the mass and velocity of an impactor. Dents, implanted particles, craters, cracks, and ejected surface material can be observed. Impact shock effects are also observed to spread over a wide area surrounding the impact site, indicating structural and chemical changes in the material, for example, the formation of glasses." (Fiege, et al., 2019) Larger impacts present an even greater danger, the evidence of which is clearly indicated by the formation of impact craters visible on the moon's surface (see figure 1). Even an impact that does not hit a habitat directly may still cast ejecta a long distance, which could kill people or damage structures.

One proposal set forth by researchers at the Department of Aeronautics and Astronautics at the University of Washington, Seattle suggests habitats would be constructed and then covered with lunar regolith to protect from radiation. (Amah & al, Defining a successful commercial asteroid mining program, 2014) However, this may not be substantial enough protection from the physical impacts of large pieces of meteorite or ejecta. Subsurface construction should be considered as a potential necessity of living and working in the hostile lunar environment. If subsurface spaces are constructed, deep mining techniques that involve blasting may well be required, presenting the potential need for establishing explosives and blasting techniques suitable for the environment.

Finally, research and development operations using explosives may one day become a reality on the moon. Currently, metallurgists on Earth are fusing metals at the molecular level with explosives. The moon may offer a unique and specialized environment to conduct research and processing of materials that could not be as easily achieved on Earth. As Anderson, Christensen, and LaManna point out, despite the difficulties, manufacturing in space has several benefits. Those benefits include taking advantage of the vacuum of space to aid in creating very pure materials, and taking advantage of the temperature extremes in space, which are often difficult to create on Earth. (Anderson, Christensen, & LaManna, 2019)

II. Development of Blasting Materials, Equipment, Methods, & Science

Mining will be necessarily different in nonterrestrial environments, even if there are apparent similarities to conventional terrestrial mining operations. And, blasting, like all other aspects of nonterrestrial mining, will require the development of new technology, methods, mathematics, and materials suitable for operations in those environments. As one article points out, the technology used will need to be able to operate in deep space, which means low gravity, high vacuum, substantial harmful radiation, and varying available sunlight. (Anderson, Christensen, & LaManna, 2019) More than that, the location, purpose, and targeted resources will dictate how mining will best be accomplished. Mining surface materials will require different technology than that for mining subsurface materials, and mining water will be distinct from mining metals. (Anderson, Christensen, & LaManna, 2019)

Explosives

The first question that should be addressed is very simply, would explosives even work in space? Most commercial explosives used in blasting operations are stoichiometrically balanced combinations of fuels and oxidizers, meaning they carry within themselves both the fuel and oxygen required for the propagation of the detonation. So, most commercial explosives materials, from the standpoint of the general chemistry of explosives, should be able to operate in space.

However, space environments are places of wide temperature extremes, so understanding the effect of extreme cold and extreme temperature swings is imperative to understanding the viability of using explosives in space. In 2004, John Kells and Norman Paley published a report detailing testing of ammonium nitrate prill type and emulsified bulk explosives in frigid climates. They pointed out that temperatures in their test location ranged from -40°F to 70°F, and yet the choice of explosives was ultimately determined by handling characteristics. (Kells & Paley, 2004) While on Earth explosives are successfully being used in such extreme hostile environments as within the Arctic Circle, space environs are far more extreme than any offered terrestrially. The temperatures on the moon range from -387°F to +253°F and it is a vacuum. (National Aeronautics and Space Administration, 2019) Such extremes could potentially affect the detonation characteristics of explosives and the ability for those materials to be detonated at all. Research into using explosives under these kinds of conditions must be carried out in order to understand the full effects of such extremes on explosives. It is very likely that explosives used in space applications will require specialized packaging and initiation systems at the least, and perhaps will require methods designed to continually warm the explosives once loaded, as loading a blast often takes hours of work. If free flowing explosives are possible on the moon or any other celestial body, there is also the question of how and when the individual explosives components should be mixed and sensitized.

Interestingly, in 2013 it was reported that a patent had been awarded in China for liquid oxygen explosive composite and liquid oxygen explosives. (Global IP News. Defense Patent News., 2013) Since oxygen is one of the materials companies are most interested in harvesting from the moon, this also may provide an avenue of research for use as an explosive suitable for mining in space.

Detonators and initiation systems (and perhaps the explosives themselves) will also have to be studied to understand any potential negative effects cosmic radiation may have on the materials over time, including potential for unintended detonations and overall degradation of sensitive explosive compositions.

Blast Loading Equipment and Methods

Terrestrial blasting has been well refined over the years. It has become very safe and is standardized enough that even different product lines often have similar methods for transporting and loading explosives. A bulk truck for hauling, mixing, and loading an ammonium nitrate prill type explosive or a pumped emulsion type explosive is easily recognizable as such across the industry. We take for granted the ease with which we can load a truck, drive to a jobsite, and offload a product, often mixing the ingredients at the point of use.

But for lunar and Martian applications, loading, testing, measuring, transporting, manufacturing, and storing explosives will likely be very different. Mixing explosives at the point of use and the practice of bulk loading may be impossible or impractical in the lunar and Martian environments. Even if some of the equipment looks familiar to the terrestrial blaster, the equipment for space-based applications will nonetheless be specialized.

Whether or not lunar and Martian based blast loading equipment would be remote controlled remains to be seen. The safety benefits of being able to operate loading equipment remotely may be the greatest determining factor. The technology exists for autonomous loading apparatus, but blasting is a very hands-on skill that requires a blaster to continuously identify geologic features, anomalous measurements, and to adjust accordingly. Even before a blast is drilled, and then again after drilling, dozens of measurements of a rock formation's profile are required to determine the proper blast design and the amount of explosives to use. Sometimes human experience alone dictates the best way to load a blast. There are few hard and fast rules that apply to blasting with explosives.

Drilling Equipment

Blast hole drilling is likewise an operation unto itself. Drilling rigs are huge pieces of equipment that run at full speed for entire shifts. They consist of powerful diesel engines that drive hydraulic motors and operate an air compressor that pumps massive volumes of air through the drilling rods and into the hole to flush it of rock cuttings. While some environments outside of Earth may offer an atmosphere to work with, such as on Mars or even Saturn's moon Titan, Earth's moon has no atmosphere. Specialized drilling equipment will have to be developed to allow drilling of boreholes with relative efficiency in space-based applications, and yet take into account the local atmosphere or lack thereof.

Historically, most drilling through hard rock has had to be done as described above, with the rock hammer being pneumatically driven either in the hole at the cutting head or at the top end of the string of drilling rods. Auger type drills are rarely found on blasting sites, as auger type drilling is best suited for boring holes in loose soil or soft rock. But basalt is a hard and abrasive rock, and that is what the moon and Mars are primarily made up of. A US based company in Kentucky has developed and demonstrated a type of flightless rock auger (US Federal News Service, 2006) that could serve as a model for lunar drilling apparatus. While a drilling system for use on the moon or Mars may not be based on this particular design, it does demonstrate that drilling deep holes through hard rock is possible without using conventional terrestrial techniques.

The moon and Mars have a lower acceleration due to gravity than Earth, which poses additional challenges. The lower gravity will likely affect the amount of down pressure the drill can apply to the cutting head, as it will take less application of downward force to cause the drill to lift off its outriggers or mode of traction. Less gravity means less force can be applied to the cutting head as it penetrates the rock, which means less efficient drilling.

Drills on Earth are rugged machines that take significant wear and tear. The drill hammer alone is constantly hammering on the string of drill rods and the drill head, causing direct strain on them. Specialized drill rods may be required to take that kind of strain in the temperature extremes of space environments. The constant hammering also causes the whole drill to experience some amount of vibration which can also lead to a certain amount of wear and tear in an environment where there will be little margin for things to break and go wrong.

Perhaps the most exciting drilling technologies currently coming into use are (1) intelligent drill data logging systems, which sense and record rock hardness and anomalies, and (2) drills that can be remotely operated or made fully autonomous. Joey Accardo, Technical Manager, Surface Drilling Equipment, for a company called Epiroc explained the extent of modern capabilities in an impromptu interview conducted at the *19th Pennsylvania Drilling and Blasting Conference* in State College, Pennsylvania. He explained that rock drills are already being outfitted to run completely autonomously, with the ability to recognize and record rock data for the blaster, which is then sent to the blaster by email. The only human intervention required for these drills is routine maintenance and refueling. The technology utilizes obstacle detection and even has the ability to distinguish humanoid forms so that it will stop if a person approaches the machine while it is running. When asked about hostile environments, he stated that drills with autonomous capability are already operating within the Arctic Circle in far northern Canada. With regard to the adaptability of this technology to space-based operations, specifically lunar and Martian applications, Mr. Accardo confirmed that it should in fact be possible. (Accardo, 2019)

The Challenge of Field Repairs

Any blaster or driller who has been on the job for more than a few weeks will attest to the harsh conditions to which terrestrial drilling and blasting equipment are routinely subjected. Bulk explosives are made of powerful oxidizers that corrode metals, including the delicate electrical connections associated with loading and mixing controls. Drills run at full speed for hours on end hammering rock nonstop. Hydraulic hoses wear through and leak in the most unexpected of places and usually at the worst possible time. The need for field repairs on equipment, whether terrestrial or space-based, is inevitable, and it will present a unique challenge in the lunar and Martian environments, especially given the cumbersome nature of spacesuits built for the harshest of environments.

New Blasting Science

Rock blasting is very much a scientific discipline of its own. Dozens of mathematical relationships explain how rock moves, how energy waves pass through the ground, and predict the effects of blast induced vibrations on structures, just to name a few. The mathematics and mechanics of blasting will have to be assessed and perhaps entirely reworked in some cases for applications in environments where things are very different than on Earth.

Some things that will have to be considered are: (1) understanding how air pressure waves may move differently through atmospheres that are different than Earth's, (2) understanding if and how the lower gravity may affect the transmission of ground vibrations, (3) determining how the different acceleration due to the force of gravity will affect everything from how far blasted rock will cast uncontrollably to how manmade structures may be affected by vibration, (4) making mathematical predictions related to the effects of blasting on structures, and (5) understanding the intricacies of the local geology.

III. Development of Blasting Regulations for Space-Based Operations

To protect people, infrastructure and the new local environments, it is imperative that we develop standards to safely and effectively achieve humanity's goal of settlement beyond Earth, which means new regulations. Utilization of explosives in space introduces a whole new brand of blasting and explosives regulatory considerations. Any regulations that take shape must adequately account for the realities of the new environments in which explosives will be used. Since there are so many unknowns, the best approach may be to begin with a series of basic regulations that can evolve with the new industry as it matures and as new standards and best practices are discovered, tested, and applied. Ultimately, regulations are intended to address mainly security and safety. The two subheadings below cover some basic regulatory considerations that may provide a good basis upon which to build.

Explosives Security Considerations

Security considerations will probably not be an immediate concern as the first people to use explosives in space-based applications will probably consist of a select few who have been exhaustively vetted prior to even being admitted into a space program, whether private or government. Nonetheless, basic regulations pertaining to explosives security should be developed early on. Issues surrounding explosives security must address how explosive materials are stored and inventoried, how storage areas will be protected from unauthorized access, who will be permitted to handle explosives, and how explosive materials will be transported, both to space and in space. As the numbers of people involved in lunar and Martian mining operations and settlements increases, security regulations will have to be continuously reviewed and adjusted accordingly.

Explosives Safety Considerations

Blasting with explosives, whether on Earth or anywhere else, is an extremely hazardous activity with little margin for error. When things go wrong using explosives, the results tend to be catastrophic. So any explosives use authorized for mining, construction, research, or for any other purpose in space must come with a reasonable expectation that something untoward is not going to happen when the blast is initiated. On Earth, regulatory agencies usually require a permit prior to blasting. While some blasters and blasting contractors think of permits and regulations as an annoyance that has to be dealt with, one main reason the agencies and permits exist is to have a system whereby plans for explosives use may be laid out to ensure that all reasonable safety concerns have been considered.

Space-based operations should also require a system whereby plans for explosives use are clearly laid out and subsequently authorized based upon whether or not standards are being followed and safety concerns are being reasonably addressed. The regulations will require thinking in nonterrestrial terms, applying the science and mathematics of blasting in nonterrestrial environments. The regulations will also be different based upon where the blasting will be conducted. Just as on Earth we have separate standards for blasting in coal strips versus quarries, separate standards will have to be developed for blasting in environments with differing atmospheric compositions, surface conditions, and geologic features.

Airblast regulations, for example, probably would not even be needed on the moon, as there is no atmosphere to carry an air pressure wave. However, on Mars, the carbon dioxide atmosphere may carry airblast much differently than we are used to on Earth. The same kind of considerations will have to be applied to flyrock rules and standard powder factors (the ratio between the quantity of explosives used and the mass of the section of rock), understanding that in a lower gravity environment than we are used to on Earth, blasted rock (known in the industry as muck) will likely travel further before coming to a rest, posing a serious safety concern if not taken into account.

Storage, packaging, and transportation regulations on Earth likewise exist to provide a reasonable expectation that the public will be protected when in proximity to explosives storage and use areas or when traveling near vehicles transporting explosives. Space environments are likely to introduce new challenges that will require standards to address how explosives are stored, packaged, transported, and used, given the conditions to which they will be subject. Some of these new standards may only be developed after some research has been conducted to determine potential safety concerns unique to the space environment. For example, in terrestrial blasting operations, the wires connecting detonators must be shunted to prohibit extraneous electricity from static or a nearby lightning strike from detonating the charges. Lightning will not be a concern on the moon. However, on the moon there is less protection from the effects of solar coronal mass ejections (CMEs) and the accompanying energetic particles that travel through space. While CMEs may not typically affect detonators connected to a blast on Earth, the possible affect they could have in space will need to be investigated and accounted for, thus establishing a unique standard for operating in that environment.

The wide temperature fluctuations at the surface of the moon and on Mars may be such that packaging alone cannot provide adequate protection from the degradation or possible detonation of explosives laying on the surface. Even once loaded, packaging alone may not be enough to protect explosives from the cold inside a drilled borehole. The extreme cold over a certain duration may affect the length of time explosives can be allowed to sit undetonated (known in the industry as sleep time) before becoming ineffective due to subfreezing temperatures. Regulations, standards, and best practices will need to be developed to address these kinds of environmental concerns.

Additional safety and security concerns will likely present themselves over time as human space operations mature. But these are a few of the most basic considerations offered as examples of the depth of thinking necessary to establish a working basis from which to monitor explosives use in space and ensure the safety of everyone who could possibly be affected by such blasting operations.

Space-based mining health regulations

Mining health regulations for space-based mining operations are beyond the scope of this paper, but should be researched and developed as part of the safety considerations taken into account for any human mining and construction efforts that take place on the moon, Mars, and beyond. Respirable rock dust is a major safety concern in terrestrial mining operations and should be a matter of elevated concern as human space mining operations progress. A report from the Los Alamos National Laboratory stated that, during the Apollo missions, it was impossible for the astronauts to avoid bringing at least some dust into the landing module at the end of each period of surface activity. (Heiken, Vaniman, & Lehnert, 1991)

IV. Next Steps for Industry, Governments, and Developers

Public and private organizations working toward establishing a sustained and sustainable human presence on the moon, Mars, and beyond must adopt a forward thinking approach in assessing the extent of mineral extraction that will be necessary to meet their needs. In light of their forward thinking projections and the kinds of considerations presented in this paper, they must realistically assess their possible future need for blasting technology as specifically as possible. Finally, public and private sector organizations engaged in the business of going to the moon and beyond must begin working with industry and technology partners and other specialists to develop blasting programs for lunar, Martian, and other space-based applications.

In terms of cooperation between government and private entities, the hurdle of getting government and private sector companies to work together has largely been crossed. This cooperative environment has allowed opportunities to abound for private entities to work in various areas of expertise, even on behalf of organizations like NASA and ESA. Government organized space agencies of today recognize the value of allowing the commercial space industry to blossom, as evidenced in November 2019 when NASA again increased their pool of commercial vendors for their current lunar program to fourteen, with the addition of five more U.S. based companies: Blue Origin, Ceres Robotics, Sierra Nevada Corporation, SpaceX, and Tyvak Nano-Satellite Systems, Inc. (NASA, 2019) and NASA has also partnered with private companies and awarded millions to develop technology and space systems. (NASA, July)

V. Summary & Conclusions

As we approach the turning of another decade, we are drawing ever nearer to humankind's return to the moon. Fifty years ago, just getting to the moon was a feat in and of itself, and landing on it was a challenge to be conquered. Today, as we prepare to return to the moon we do so not just to prove we can do it, but to stay and establish a permanent, or at least a sustained, human presence on our nearest neighbor. We go realizing that the moon is a testing ground and a stepping-stone as we venture even further out into our solar system to Mars and perhaps beyond.

Establishing a human presence on the moon or Mars will require far more than just the resources we can transport there. Humans will have to harness and utilize every available resource for food, fuel, water, building materials, and tools. Knowing this, public and private sector organizations are leading the charge back into cislunar and on into deep space by developing systems and methods that can process and utilize the natural resources found in these foreign environments.

For as advanced as these systems are, they have been primarily focused on obtaining natural resources by sifting the loose materials lying on the surface, or by abrasive techniques. However, if Earth is any indicator of what we can expect, the most useful and valuable mineral resources are likely to be found deep inside the constituent rocks that make up the moon or planet. This paper has attempted to demonstrate that blasting with explosives on the moon, Mars, and other space environments is possible and will eventually become a necessity. This paper has further attempted to bring forward some foundational considerations upon which space-based explosives use standards, technologies, and regulations could be built to bring the use of explosives in space for peaceful commercial purposes to fruition. The time for research and development in this area is now so that the new methods, technology, and materials will be ready for application when the time comes.

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