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Lunar and off Earth resource drivers, estimations and the development conundrum

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Abstract

All human enterprise is based on the acquisition and use of natural resources. Space exploration highlights our greatest example of the potential utility and economic savings that would be gained in providing what is needed to spur large-scale settlement growth and operations during gravity-well hopping. As opposed to the pure economics behind resource location, extraction and production on Earth, the fruitful, successful and sustainable human expansion off Earth makes it imperative that we fully understand the distribution and abundance of extraterrestrial resources, combined with current technological capabilities and a highly defined user-base before human landing site selection can occur. A working model and methodology, entitled Planetary Resource Management System (PRMS), adapted from the terrestrial petroleum exploration model, serves as a guideline for defining extraterrestrial prospecting, which ultimately provides criteria for the selection of human landing sites. Correct selection, in fruition, will enable highly self-sustainable and growing human settlements on the lunar surface or elsewhere. Further discussions addressing the continued and potentially distracting misuse of common space-goals marketing points, used in promoting extraterrestrial mining and in situ resource utilization (ISRU), are examined in light of big picture usage, infrastructure and a priori needs. The present exemplar of extremely slow human population growth rates off Earth highlights the need for implementing the single concise goal of establishing growing and self-sustained human settlements on other worlds. Such a distinct goal will circularly drive the need for in situ resources and commercialization that the historical acquisition of basic scientific knowledge alone is incapable of rendering.

Keywords: ISRU; Moon; Prospecting; Mining; Sustainability; Habitation

1. Introduction

Plans, promises and dreams of acquiring and using space resources are older than the history of human spaceflight (Clarke, 1951; Jenks, 1956; Homes, 1962; Carr, 1963; McDougal et al., 1963). In order for humanity to sustainably expand off Earth and out of low Earth orbit (LEO) we must learn to live off the land, and in doing so, much remains to be discovered and learned about resource locations, availability and accessibility before human site selection, mining or in situ resource utilization (ISRU) can even begin to take place. Without having the most accurate prospecting information possible (the term *prospecting* is used herein because historically the word *exploration* in the spaceflight lexicon does not exclusively refer to the search for resources), selection of the first human landing site should not occur (i.e. simply placing a bull's eye on a planetary map or for scientific discovery alone) because the extensive cost of human spaceflight requires that the first site chosen should be optimized for resource acquisition. Detailed understanding of resources is especially relevant should the ultimate goal be the instillation of permanent and sustainable infrastructure (Taylor and Martel, 2003; Carpenter et al., 2016). Otherwise, sending

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multiple human surface landings to disparate and distant locations wastes resources by not reusing any in situ infrastructure and rapidly increases both the risk and danger of program cancelation and failure (e.g. between budget cycles or administrations). Potential lessons regarding misunderstanding risk, availability of resources and financial subsidizing come from the first colonial attempts in the Americas, which effectively proceeded from a single prospecting mission in 1492 (voyages of Columbus: Flint, 2019). The next year, La Navidad, a forced and rushed settlement on what is now the island of Haiti survived less than a year, and La Isabela, established a year later and itself only lasting about four years (Morison, 1940; Deagan, 1988). Though several variables are expectedly different, the analogy is insightful. The tumultuous history of further colonization of the Americas and other places shows a multitude of repeated errors and bad luck, and yet all terrestrial endeavors had the ready benefits of gravity, radiation protection, breathable atmosphere, potable water, native foods and, working and building materials. Will our transition off Earth encounter similar hurdles or can we bypass them even in the most severe environment humans will ever inhabit? Our discussion herein highlights lunar endeavors, focusing on resource identification, needs and usage as required to effectively and sustainably create a permanent human presence. Mars or small-body resource acquisition and usage have their own unique differences, yet all of the guidelines, materials and concepts herein remain directly relevant to these bodies.

Understanding the full spectrum of variables from programmatic to technical viability, distribution, access, extraction, storage and potential uses of off Earth resources is of utmost importance if headway, especially in a sustainable and long-term manner, is to be expected (Haskin, 1985; Sullivan and McKay, 1991; Seife, 2004; Anand et al., 2012; Benaroya et al., 2013; Crawford, 2015; Carpenter et al., 2016). Throughout this document, the use of all forms of the word sustainable are defined in terms of a mélange of four enabling components (see Fig. 1): Operational, Political, Engineering and Logistics. Each subset comes into play across an integrated and interdependent continuum of support and capabilities, and could range from 0 towards 99% self-sufficiency (D. Eppler, personal communications and collaboration, March 2019). The working definition of each component is as follows: Operational – the ability to continue to operate at a minimum level following planned build out; Political – the ability to continue to function through funding changes in controlling organizations (e.g. government or commercial entities); Engineering - the ability to build designs with sufficient redundancy and flexibility/adaptability such that components out last initial mission requirements; and Logistics – the ability, technology and infrastructure required to extract useful resources from the local environment thus reducing dependency on imported consumables. Each subset contributes to overall sustainability based on these pre-defined dependencies. The very center would

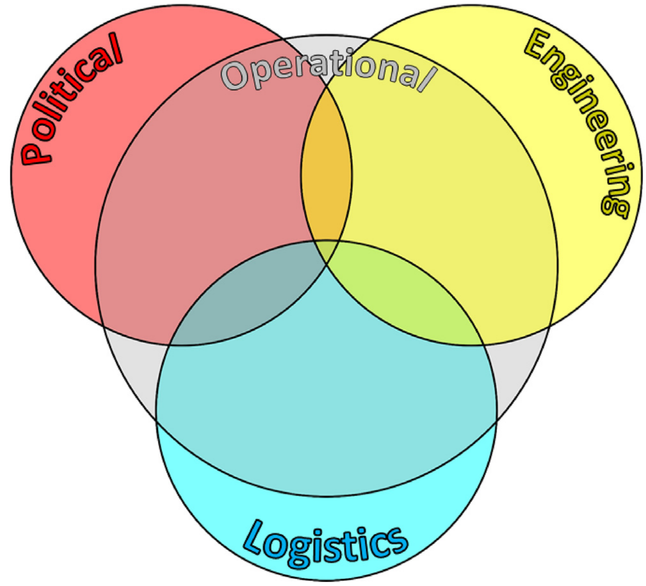

Fig. 1. Sustainability interdependency diagram.

represent the theoretical goal of 100% self-sustainable assuming all groups' contributions/resources were unlimited. Ideal self-sustainability would be to have resource independence from Earth, and be able to sell excess products back into an off Earth economy. The goal is to maximize the probability of long-term successful human space activities and settlement across all four groups.

Sustainability is alluded to throughout the body of this text, and each subset in varying amounts, contribute towards the defined relevance of this word. Yet, it is the subset of "Logistics" that is of particular interest and is further defined with the caveat that there is a relationship in the development towards independence from Earth resources regarding an initial and distinct group of space operations and settlement enabling consumables. As a bench mark, a requirement for safety margins is defined regarding the acquisition of enough in situ resources so as to not need resupply from Earth for at least one Earth year should interplanetary transportation (e.g. between the Earth and Moon) completely stop. The same term directly encompasses overall spaceflight capabilities and the potential for commercial advances as the acquisition of off Earth resources produce stockpiles and begins reducing the mass and costs to access each destination in space. Ultimately, this correlates with the knowledge components regarding exactly what resources are most needed and why, what resources are available at a given destination, how much of any given resource is available, and exactly what our current abilities are to extract said resource. This understanding is paramount for not only success but actually selecting sustainable human landing sites (James et al., 1998; Chamitoff et al., 2005; Barker et al., 2016; Barker, 2018a).

Throughout planetary space exploration history, the selection of programmatic goals, landing sites, mission platforms and instrumentation have been founded on the pursuit of basic scientific knowledge as the primary goal, as is repeatedly acknowledged in both programmatic and proposal documentation ("A Site Selection Strategy," 1990; Taylor and Taylor, 1997; "Scientific Context for the Exploration of the Moon," 2007). Dedicated lunar resource identification spacecraft, goals and arguments have historically been limited, non-descript, included as vague side notes in landing site reviews, programmatic goal statements or roadmaps (e.g. identify space resources), have proposed unrealized robotic precursors, and have included tenuous conceptualizations regarding permanent and sustainable human habitation ("The Vision for Space Exploration," 2004). An endemic rift, attributed to a few factors such as underlying group goals and financial subsidies, exists between the planetary science and the human spaceflight communities. Sending out a fleet of resource prospecting spacecraft for the sole purpose of characterizing resource types, locations and volumes for the singular purpose of preparing for human habitation, rather than doing the historical science first approach, has yet to occur. This perspective may have changed slightly over the past few years with more requirements being included regarding resource knowledge drivers, at least at the documentation level ("The Lunar Exploration Roadmap," 2016; Jawin et al., 2019). Yet the inclusion of resource verbiage and goals remains mainly in support human *exploration*, and is still far outweighed by scientific research goals (i.e. science goals remain in the forefront of human spaceflight). Instead the focus should be on a dedicated prospecting, mining and resource development paradigm in support of a permanent human habitation goal. In the US lunar program so far, only two missions have come very close being designed to focus exclusively on the quantification and location of potential resources in preparation for future human habitation; they are the Lunar Prospector (launched in 1998) and the Lunar Reconnaissance Orbiter (LRO; launched in 2009 and currently active). Today many countries are becoming increasingly interested and involved, but instrumentation choices and mission goals still remain broadly focused on addressing specific, scientifically oriented goals.

In order to achieve any sustainable human presence off Earth, we must address the ongoing questions raised about why we should send humans to space and what exactly they will be doing there (Barker, 2015). Before humans begin landing on and mining the Moon (or anywhere else off Earth), significant changes in programmatic mindsets must occur. Given the large mix of competing external and internal variables, short time scales, and high likelihoods that funding and support changes and challenges will happen, then the chance of establishing a mining base, a settlement or even a sustainable human presence on the Moon any time in the near future seems implausible. Only by changing present programmatic paradigms and designs away from the historical sequential phasing towards an integrated parallel prospecting-driven architecture will sufficient knowledge be gained rapidly enough to take the next giant leap, permanent human habitation and the potential for commercialization. Otherwise, the status quo will be maintained. Precursor missions and endeavors must be solely dedicated to identifying, assessing and defining lunar resources. This is not to say that historical science for science sake paradigms won't cross-pollinate with resource knowledge gaps, but a science-only focus itself only increases the time and therefore risk of failure in establishing any longstanding human presence or Moon mining endeavor. A growing series of resources combined with usage needs, can be expected, as in situ infrastructure and capabilities grow. Initial material usage, e.g. on the Moon, will probably include simple mechanical redistribution, sintering and thermal reduction of the loose, fine-grained regolith to construct landing pads, bolster radiation shielding and extract oxygen. Water will also be included in this inventory when and if sufficient, easily extracted abundances are identified.

This work looks at what is needed to understand and initiate human landing site selection for mining on other worlds, including how to market, persuade and guide stake holders towards a growing, sustainable and efficient program as rapidly as possible. This begins by providing a working model with a set of probabilistic requirements regarding the knowledge needed to characterize and initiate resource acquisition, as well as a proposed redirection of program goals to establish efficient and effective extraterrestrial mining operations in direct support of first human landing site selection and sustainable habitation. Criteria similar to those used to classify a resource as "Reserves" by the terrestrial petroleum exploration industry are employed to provide a preliminary set of guidelines based on concomitant risk factors and programmatic subsidies and support certainties, and resource extraction feasibilities using existing technologies. Finally, changing mindsets from a science first paradigm towards a growing, sustainable and permanent off Earth settlement perspective may be the only way that substantial headway will be made regarding human expansion into space.

2. Developing a tool for guiding resource prospecting and choosing human landing sites

The purpose of this work is to highlight and broadly introduce the Planetary Resources Management System (PRMS) (Barker et al., 2016, Barker, 2018b), which is a tool under development to support extraterrestrial resource prospecting and human landing site selection. Initially the goal is to develop objective, data driven guidelines for ensuring the efficient development of program and mission goals, architectures and hardware and spur concurrent prospecting missions that will enable resource identification and acquisition, human site selection and sustainable settlement off Earth. Therefore, the model proposed provides a framework for the classification and estimation of resource volumes by assembling all known variables and illuminating knowledge deficiencies requiring further data collection such that the probability of successful recovery of sufficient resources is maximized before humans are committed to the surface. Off Earth, ISRU is extremely important as it has the potential to reduce launch costs, enables settlement development, and reduces risk while increasing sustainability, survivability and comfort. The term *exploration* is used by the terrestrial petroleum and mining industries to reflect those activities and timeframes used to search and probe for resource accumulations. Spaceflight, on the other hand, uses the term exploration in the much broader sense of all scientific and human endeavors occurring in space and therefore, this paper uses the term *prospecting* to apply for all endeavors, procedures and process regarding the location and quantification of any given resource in space.

The model herein is directly derived from the historically pragmatic conceptualization of a Petroleum Resources Management or Classification System, which began in the 1970′s and has continued to evolve to address actual or perceived limits of accessibility and predictability for highly used terrestrial resources (McKelvey, 1972; Brobst and Pratt, 1973; McKelvey, 1972; Pratt and Brobst, 1974; Voelker et al., 1979; "Geological Survey Circular 831," 1980; Taylor and Steven, 1983; Goudarzi, 1984). International efforts that have adopted this methodology are ongoing, e.g. the United Nations Framework Classification for Resources (UNFC) in 2004 and the Committee for Mineral Reserves International Reporting Standards (CRIRSCO) in 2007. Inclusion of the Joint Ore Reserves Committee (JORC), an Australian resource reporting code, in the findings from the 19th Space Resources Roundtable (Morris et al., 2018) was derived from this author's presentation and recommendations (Barker, 2018b) regarding the need for such a framework for space resources (especially human in the loop paradigms). Ongoing evolution of such resource rating and classification schemes account for many factors including economic viability to a given entity, level of technological capability, legal disclosure obligations, benefits and potential for investment a company might get from publishing uncertainty findings, and will eventually be highly useful off Earth. The key definition in these models is that of "Reserves", which define resources by calculating the amount or volumes of a given resource estimated to exist in a given geological setting, which may be extracted in a timely and economically feasible manner given current levels of technology. The current Society of Petroleum Engineers (SPE) Petroleum Resource Management System (PRMS) was designed to provide user decision points based on commercial, business, financial, and Securities and Exchange Commission (SEC) goals (Society of Petroleum Engineers, 2018). It is a categorization process used to determine the fair market value (FMV), i.e. the price that an item would sell for on the open market, of a company's reserves. Much of the vocabulary, nomenclature and definitions from this history have been adopted and adapted from existing petroleum industry standards and their transcription herein serves as a base model for extraterrestrial resource development, and for selecting human landing sites. Development and definition, and cross-pollination with UNFC and CRIRSCO systems, remains a work in progress to provide the best fit for the unique multivariable nature of extraterrestrial resource prospecting and acquisition.

Since currently and for the foreseeable future there exists no such open market (i.e. no true or viable commercial market) for resources extracted from extraterrestrial objects a modified model, the Planetary Resources Management System (PRMS), adapting many of the petroleum side variables, is presented to align with our criteria of successfully estimating resource volumes and extraction abilities, especially the first human landing site that will serve as a growing base of operations and ISRU. Note that the terms *commercial* or *commercially viable* are carried forward from the terrestrial models but with a modified connotation of being relevant to the need to establish ISRU operations for a growing infrastructure that will drive down costs of moving large mass consumables off Earth. Not that any individual commercial entity will likely be profiting form or competing for anything at this early stage of development. Additionally, given a set of new complexities, risks and uncertainties in off-Earth resource identification and acquisition, this model attempts to establish initial levels of certainty that would be needed to begin off Earth mining operations with the goal of sustained long-term, one year or more, operations independent of Earth resupply. It also accounts for such variables as establishing user needs, infrastructure, transportation risks, storage, sustainability (per the previous definition), prospecting timeframes, and purpose of intended endeavors (i.e. long range plans), which all combined contribute to the probability of success.

Fig. 2 shows the PRMS *decision matrix* for being able to "commercially" extract a given resource; with the goal of eventual in-space acquisition, utilization and commercialization of extraterrestrial resources. It is important to remember that the adopted concept and verbiage of *commercialization* henceforth only refers to the fact that mined space resources will be only used at the location of mining or in-space and not returned to Earth. All categories are represented by a continuum of uncertainty (or a probability of success). Space resource data is expensive to acquire and limited in both quality and interpretability, giving rise to the need to know as much as possible prior to human involvement:

- Off Earth, the measure of certainty directly effects the choice of landing sites, the construction of sustainable human infrastructure, resource mining and processing, and is bound by the installation and growth of in-space users - a cart before the horse problem. This requirement drives precursor prospecting to identify said landing sites.

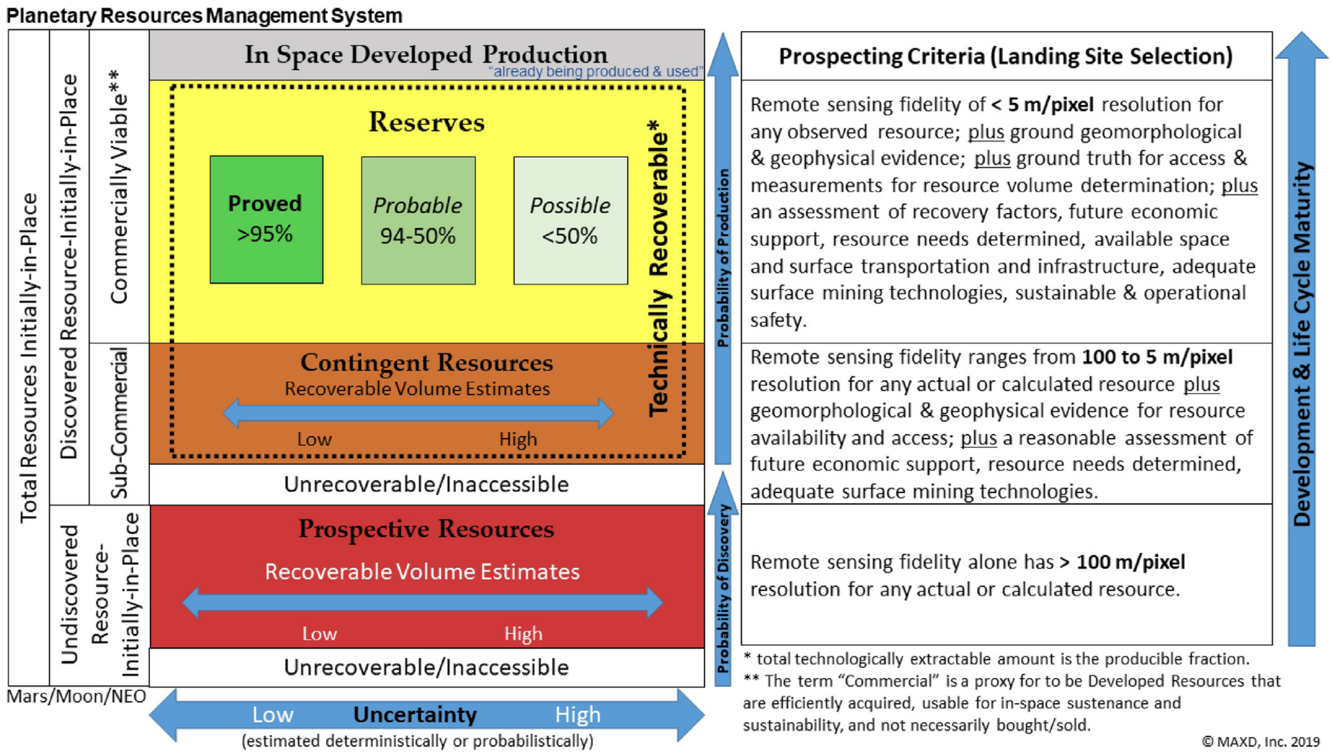

Fig. 2. The Planetary Resource Management System (PRMS) model. Adopted from historical petroleum industry practices and standards, this diagram provides knowledge requirements for resource volume or abundances combined with present technological extraction knowhow to provide a probability of successful resource extraction at any given landing location. Ascending from Prospective to Contingent (further definitions provided in later sections) and finally the Reserves levels requires ever increasing fidelity of knowledge regarding accessible resources of known abundance. The final Possible, Probable and Proved criteria give actual levels of measurement to define the highest probability of abundance and successful resource extraction at any proposed landing site. The Prospecting Criteria column represents first level expectations for knowledge fidelity and capabilities, especially regarding remote sensing instrumentation. This model remains in development. The following sections highlight the working definitions and components needed for implementing the model.

- Certainty-In-Space must be much greater than on the Earth due to many additional complexities and drivers. Prospecting in space therefore must be more rigorous and well defined from the beginning. There will not be the luxury of drilling a "dry hole" in space.
- The lack of ground-truth data has recently been exemplified in the unanticipated surface roughness observed on asteroid Bennu (by OSIRIS-REx) in light of abundant precursor Earth observations (e.g. thermal inertia and radar) and modeling, driving operational changes to planned mission designs.

2.1. Reserves: Resources ready to be extracted at a profit

Reserves, in the terrestrial definition, are the estimated volumes of resources anticipated to be commercially recovered from known resource accumulations from a given date under all defined conditions (as adapted from SPE PRMS). In other words, to be classified as "Reserves" the certainty of extraction using existing technology needs to be established. Quantities also should not be classified as reserves unless there is an expectation that the resource accumulation will be developed and placed into production within a reasonable timeframe. Three classes of Reserves, as indications of the probability of recovery, are outlined below: *Proved, Probable and Possible*.

Two traditional methods of estimation, deterministic and/or probabilistic, have been used within traditional petroleum reserves estimation ("Petroleum Resources Management System," 2018). The approach here is to calculate the chance of successfully recovering the greatest portion of the Reserves though an analysis of all relevant geological prospecting data including estimating this probability relating to current technological constraints and estimated recovery volumes measured for any given site. A test case Estimated Ultimate Recovery (EUR) analysis, provided below, is used to show probability and expected recovery for the Reserves subcategory levels for the permanently shadowed region (PSR) at the lunar south pole. Other factors must also be included to distinguish proper resource categorization (e.g. the commercial and other probability risks factors, such as sustainability of funding and having an established user base) in the final success estimation, and to give the "go-ahead" for the actual mining site selection processes to occur.

To be included in this category requires the combined, overlapping use of all data at any location of interest

(James et al., 1998; Chamitoff et al., 2005). Data must be of the most comprehensive in nature, meaning highest resolution across all metrics of instrumentation. This category will also require sufficient ground truth data from multiple locations so as to allow useful correlation to remote sensing observations, and actual quantification and discrimination between resource abundances at sites of interest. For all space resources that will support in situ human habitation and operations an extremely high level of precursor scrutiny and precision is required in understanding the quantities of extractable resources at a purported landing site. There should be a vanishingly small chance of drilling a dry-well when it comes to finding and obtaining in-space human resource needs. Current working level requirements for knowledge by category for a PRMS model are outlined in Fig. 2 and defined below.

- A Reserve is considered *Proved* when it is expected that 95% or more of the resource is recoverable under the models criteria and conditions. This category has the highest fidelity in all areas of knowledge regarding resource distribution, acquisition and program sustainability. Few extraterrestrial resources or locations are yet "Proved" with Martian water ice accumulations being one current example that can almost be classified within this category based on observational volumes (e.g. polar caps and exposed scarps of buried ice (Dundas et al., 2018)), unfettered access and extraction capabilities notwithstanding. It is this category which should drive human landing site selection criteria.
- A *Reserve* is considered *Probable* when it is expected that between 94 and 50% of the resource is recoverable under the models criteria and conditions. Potential tradeoffs may alter exact probabilities based on the current state of the art in technology (i.e. off Earth it is likely that we know the capabilities of a given technology better than the resource volumes available). Further surface exploration for larger, well characterized reservoirs would be needed prior to moving into the Proved category.
- A *Reserve* is considered *Possible* when it is expected that <50% of the resource is recoverable under the models criteria and conditions. Here again, maximizing technological knowhow could lower the volume of resource knowledge needs for a constant measure of success.
- For all extraterrestrial resources, anything below "Possible," i.e. outside a quantifiable certainty of being able to extract estimated volumes of resource under current conditions and technology falls into the lower, *Contingent-Resources* or *Prospective-Resources* categories. The utility of these lower categories comes from focused deploying of additional prospecting devices and changes in data fidelity during the interpretation and acquisition of new information as derived from either ongoing or historical scientific exploration of extraterrestrial bodies or dedicated prospecting.

2.2. Defining an estimated ultimate recovery (EUR) criteria for space resource reserves

The EUR is a full life cycle estimate of how much of a resource will ultimately be recovered from a reservoir before becoming unusable and based on present knowledge all variables. In order for a resource to be elevated to the highest category within the Reserves block, i.e. Proven, it must show an efficiency-related technological ability to extract them, a well-defined user base, secure financial fundamentals, and the most accurate understanding of physical accumulations or volumes, and so on. As this is a natural world problem of probabilities and estimations, and iterative gathering and refining of that knowledge, a Monte Carlo method was employed to assess the probabilistic variables needed for determining the distinctions between PMRS categories.

A first order resource EUR analysis is shown in Figs. 3a and b using lunar south pole PSR water–ice as an example (i.e. determining a probability distribution of recoverable water–ice quantities based on known and estimated real world parameters). A simple, baseline equation used to describe the amount of exploitable water–ice in a given volume of regolith in km^3 is outlined, and is used in the Monte Carlo simulation below as follows:

$$Ice_{(exploitablevol.)} = A \times D \times P \times RecEff,$$

The variable A is the area of the resource in sq. kilometers given by the range of 324 craters identified in the LROC Permanently Shadowed Regions Atlas and Reduced Data Record (RDR) products data base (Colaprete et al., 2010; Speyerer et al., 2013). The variable D is the vertical depth below the surface containing the expected resource deposit, and herein used a minimum of a centimeter from the surface to a maximum of 7 m in depth (Mazarico et al., 2011). The water-ice purity (P) for a given volume of regolith is assumed and discussed below, but future ground truth data could enhance the fidelity of this variable, changing it by determining and removing all the non-ice components specifically, e.g. ($P_{Ice} = 1\text{-}(Dr + Po + Co)*100$), where Dr would be the percentage of the volume being dry regolith, Po the percent volume of the void space or porosity (depth dependent), and Co the percent volume of any contaminants present in the ice that would later need to be removed to make the water a usable commodity. Much of the ground truth information is tentative at present, for example the average porosity (e.g. the void space in regolith) can be assumed to be 83.3% based on Apollo sample analysis (Hapke and Sato., 2016), but actual PSR regolith porosity remains an unknown. Likewise, a compilation of potential contaminants might be estimated from the LCROSS impact spectral analysis (Colaprete et al., 2010). In this model, though, the unknowns are omitted for the calculated PSR regolith volumes by simply using the measured ice-water content, spectrally estimated form the LCROSS impact plume. Colaprete et al. (2010) estimated a water–ice content of roughly 5.6% by mass, yet due to a lack of in situ regolith measurement the purity variable is assumed to be distributed between nearly zero and about 12% by volume using ice and regolith densities of 0.92 g/cm^3 and 1.5 g/cm^3 respectively. Recent spectral modeling has indicated pixel level (~280 × 280 m) water–ice content as great as 30 wt % (Li et al., 2018; Li and Milliken, 2017), but this estimation is a single, unrepeated data point and this value is not used in this model. The final variable shows that an understanding of the technology needed to extract expected volumes of resources is imperative and depends on the environment and technology of choice. Zubrin (2018) and others have assessed a range of methods for extracting ice (e.g. thermal mining) and a reasonable water recovery efficiency (RecEff) range could be between 80 and 98%. Ultimately, to get volumes of water, a conversion factor is needed given that the volume of liquid water at room temperature increases in volume by about 9% after freezing. This conversion is left to the reader and analysis results remain in km^3 ice. All variables were addressed using a uniform distribution as currently there is insufficient data regarding actual distributions in the subsurface environment.

Figs. 3a and b show the chance of recovering a volume of water–ice within the prescribed Reserves sublevel definitions of *Proved, Probable and Possible*. Fig. 3a shows a single analysis across the full PSR atlas (Cisneros, 2018) range of crater area sizes. Fig. 3b shows the analysis for four individual crater sizes in the same data base (smallest, average, highest (of main data range), and maximum (i.e. two largest outlier craters, Haworth and Shoemaker). In Fig. 3a, the geological likelihood for extracted quantities should equal or exceed either the low or high

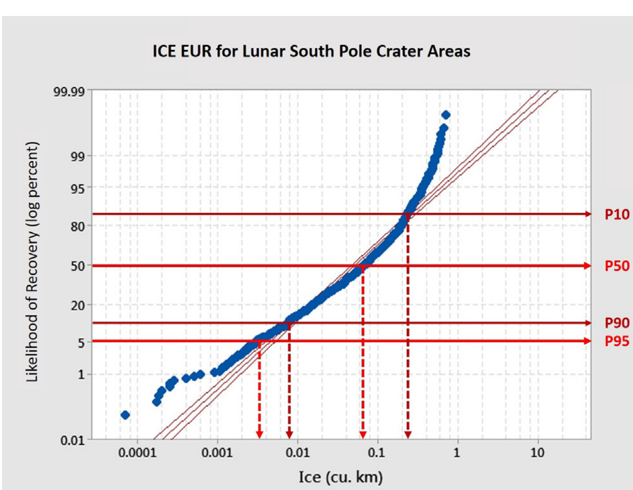

Fig. 3a. Example Ice EUR Monte Carlo simulation indicating probability (i.e. chance of exceedance values) for recoverable volumes of water–ice included across the full range of south pole crater PSR areas (Cisneros, 2018).

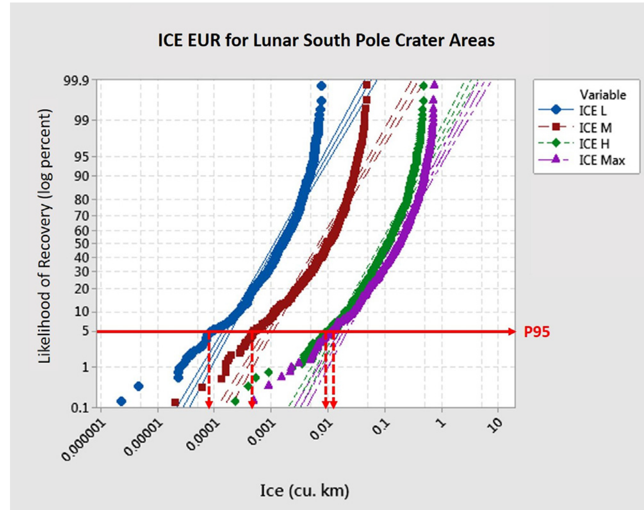

Fig. 3b. Ice EUR Monte Carlo simulation indicating probability of recoverable volumes of water–ice for four south pole PSR craters areas spanning the LROC PSR Atlas list (Cisneros, 2018). The atlas PSR ID feature and area in km^2: (1) Scott E, L = 10; (2) Ashbrook Crater, M = 62; (3) Faustini Crater, H = 663; and (4) Shoemaker crater, Max = 1075. Crater areas rounded to the nearest whole number. The 95% chance of exceedance volumes are indicated for each crater size.

PRMS estimate categories. Three of the horizontal lines in Fig. 3a demonstrate the three traditional volume probabilities as follows: the "Possible" level is given as a 10% (P10) chance of exceeding ~0.25 km^3; at the "Probable" level there is a 50% (P50) of exceeding ~0.07 km^3; and at the "Proved" level there is a 90% (P90) chance of exceeding ~0.008 km^3 of ice. In our PRMS model. Our "Proved" level was made even more stringent at the 95% chance level due to the overall complexity regarding human spaceflight, resulting in even more restricted volumes of ~0.003 km^3 of ice. The cutoff between the Probable and Possible level remain at the defined demarcations. At the P95 level for small, 10 km^2 PSR craters, using full recovery efficiency and depth range, the water–ice content estimation of the regolith would need to be at least 1.92% by volume to achieve prescribed levels of extraction.

It is important to remember these volume estimations are based on the collection of all PSR surface area ranges in the LROC PSR Atlas, and the current resolution of the data. Actual ice volumes and distributions will drive volumes that will be somewhat different (i.e. likely much lower) once enhanced ground-data has been acquired. Li et al. (2018) also importantly noted that only about 3.5% of cold traps identified in their analysis actually exhibited ice exposures, and such a limitation is not accounted for in this EUR as a support tool in selecting landing sites. Therefore, the likelihood is high that few PSRs will be suitable for ISRU, which directly speaks to the need to rapidly and economically gather as much ground-truth data as possible before sending humans to a site potentially barren of desired resources.

2.3. Contingent resources

Defined as those estimated volumes of resources that are potentially recoverable but not yet considered mature or understood enough for commercial development due to outstanding technological or commercial business case hurdles (e.g. lacking long-term financial support). In other words, this category involves resource volumes estimated based on a given date as potentially recoverable from known resource accumulations, but which are not yet currently considered to be "commercially" viable or recoverable because the commercial or technical abilities are not considered mature enough to proceed. The probability for the Contingent Resources to become economically recoverable is significantly lower than for proven, probable or possible reserves (i.e. volumes are highly speculative).

This definition is standard within the terrestrial community, and it is within this category that almost all extraterrestrial resource volume or accumulation data and estimates presently reside. Though instrumentation resolution and analytical techniques are advancing, the vast majority of data comes from imagery (i.e. geomorphological), which have foot-print resolution in meters to kilometers per pixel. Remote sensing spectral data has similar spatial resolutions, and only resolves the chemistry of the very top few centimeters of the surface at most. Other instrumentation, like ground penetrating radar (GPR) and gamma ray spectrometers (GRS) provide deeper subsurface information, but resolution and interpretations vary. Only through enhancing all data sets and cross verification between physical parameters (i.e. ground truth) can a resource move out of this category.

2.4. Prospective resources

Those volumes of resources, estimated on a given date, to be potentially recoverable from undiscovered accumulations and deemed as the potentially recoverable portion of Undiscovered Resources (Initially-in-Place) on the basis of indirect evidence (i.e. remote sensing). Every identified or theoretically proposed object in space (e.g. asteroids), especially through cursory optical or spectral techniques, fits into this category.

2.5. Range of uncertainty

Uncertainty is the driver for categorization and is a measure of the technical factors impacting the volume's ultimate producibility. Any level of certainty should reflect the adequacy of the geologic, geochemical, and geophysical data available, and a level of confidence as to how well the specific resource type being evaluated is understood. Any estimation of resource volumes (Proved, Probable, Possible, Low, Best and High; see Fig. 2) for a given resource accumulation is subject to technical, government and commercial uncertainties, and should be quoted as a range that closely approximates the volumes that will actually be recovered from the accumulation. The use risk here is primarily associated with the classification of quantities of resources (i.e. volumes) and is a measure of the certainty of a mining endeavor (or project) progressing to production. For space resources, uncertainty categories need to be defined even more precisely than on Earth (possibly before "prospecting" even starts) in order to mitigate and reduce risks prior to mission and hardware design, and during operations (i.e. directly affecting survivability, sustainability and architecture cost structures and requirements).

In all cases the actual uncertainty will depend on the amount and quality of data that is available for any given volume/accumulation. As more data becomes available for a specific accumulation, probabilistic methods should be used, and the range of uncertainty for that accumulation should be reduced and redefined as needed.

2.6. Additional standard model definitions

- *Total Resources Initially-in-Place*: that quantity of resources that is estimated to exist originally in naturally occurring accumulations. It includes that quantity of resources that is estimated, as of a given date, to be contained in known accumulations prior to production plus those estimated quantities in accumulations yet to be discovered (equivalent to "total resources").
- *Discovered Resources Initially-in-Place:* that quantity of resources that is estimated, as of a given date, to be contained in known accumulations prior to production.
- *Undiscovered Resources Initially-in-Place*: that quantity of resources estimated, as of a given date, to be contained within accumulations yet to be discovered.

Once a fully developed and working PRMS framework for defining the probability of success in extraterrestrial resource extraction is accepted across the human spaceflight and exploration community, it will set the path for the precise definition, development and deployment of prospecting resource investments, spacecraft and measurement devices, allow for the identification of useful resource volumes and ultimately provide the final criteria for selecting landing sites for sustainable and self-sufficient human bases and settlements.

3. Truth in "selling" lunar commodities and end-user market in-space needs

In order to realistically apply any ISRU implementation decision system to economically, sustainably and viably advance the human species off Earth, a clear understanding of many interrelated cycles (e.g. financial, decisional, emotional, educational), variables, uses and users, and technological capabilities must be clearly disseminated throughout the community and industry. Failure to do so promptly will likely prolong reasonable advancement. Additionally, providing the public and government with reliable reasons and sales points will inevitably bear out the value of such goals and endeavors. It is also important to bear in mind that the probability that resources mined on the Moon, or elsewhere, being used for anything other than lunar or in-space consumption is rather small (i.e. due to orbital dynamics, and entry, descent and landing (EDL) constraints). This section will hopefully stimulate awareness and discussion regarding proposed methodologies in assigning importance towards community awareness in achieving the short-term goal of returning to the Moon permanently.

Furthermore, it is important to make a cautionary observation regarding human cognition and behavior that often influences human endeavors, including the promotion and desire for space resources, and yet may be unnoticed when considering currently proposed goals. At a high level, things seem to make perfect sense. Such cognitive processes are exemplified through the precepts of the Prospect and Loss-aversion theories (Kahneman and Tversky, 1979; Tversky and Kahneman, 1992). The marketing of anything, including space resources, can be analyzed under the precepts of Prospect Theory, which assumes that losses and gains are valued differently, and thus individuals will make decisions (i.e. adopt or promote a program or goal) based on perceived gains instead of perceived losses. Also known as Loss-aversion Theory, the general concept is that if two choices are put before an individual, both equal, with one presented in terms of potential gains and the other in terms of possible losses, the former option will most likely be chosen (i.e. sold to a receptive audience via the precept, you could lose out of you don't "act now!"). Such states could be associated with too rapid a push to accomplish something, thus creating the first link in an eventual failure chain. In this case, not correctly exploring or prospecting for needed resources prior to selecting a landing site could, given many contributing variables, including high costs, result in the waste of money or cancellation of programs.

In order to make a clear presentation to all stakeholders of the reasons behind any extraterrestrial endeavor using resources as an argument and selling point, a clear understanding of those items must be established. This understanding guides mission design, vehicle designs, operations and growth projections. Herein we examine four specific variables or cases relating to resources, prospecting, exploration and settlement, primarily in furtherance of lunar ISRU, and explain their relevance and validity in designing program goals and capabilities, mission architectures, and requirements. Examples and reasoning behind lunar ISRU arguments considered as "over sold" or items not *currently* usable or available, and therefore should not be used to tout space resource development. Two arguments fostered in the lunar and spaceflight communities, as well as the public, include the acquisition of Helium-3 and spacecraft propellant production. On the other hand, two resources, water and the lunar regolith/-soil, have often been "mis-sold or under-sold" or not addressed sufficiently as to prove their pragmatic *near-term* relevancies and usefulness to commercial communities (e.g. requiring massive shifts in industry standards). It also is important to keep in mind the tie between the propellant and water resource sales-pitch. More precise communication of full cycle usage and development of these resources in the broader community will facilitate better goal development, and ultimately help to facilitate the advancement of lunar mining and ISRU. Examining these resource cases in light of our PRMS shows that the first two fall into the PRMS category of "Prospective Resource" due lack of usefulness, users or business case shortcomings. The other two resource types, water and regolith, also likely within the "Contingent Resources" category, as a result of a lack of volumetric knowledge and technology extraction unknowns; yet, some slight exceptions regarding mechanical and compositional considerations may have already risen them into the "Reserves" category.

3.1. Over-sold as potential resources due to low commercial likelihood of near term availability, need or usage.

3.1.1. Helium-3 (He-3): An resource before its time

Helium-3 has long been considered as a potential source of fuel for nuclear fusion (Oliphant et al., 1934; Schmitt, 2006). This resource though had not been linked to the Moon until 1985 when lunar soil sample #75501, brought back by Apollo 17 in 1972 (Wittenberg, 1986; Conway, 1988), provided the first indications of its distribution in the lunar regolith. Since then all Apollo soil samples have been found to contain, single digit ppb range, solar-wind implanted He-3 (Fegley and Swindle, 1993) and global maps have been produced (Kim et al., 2019) indicating sparse heterogeneous distributions with greatest content ranging between 16 and 24 parts per billion. Yet, current predictions indicate that it will take another 20–30 years, assuming sustained and uninterrupted funding and research, for safe, economic and reliable fusion reactors to first become available for public power production (National Academies of Sciences, Engineering, and Medicine, 2018). And this further assumes that He-3, as opposed to deuterium–tritium (DT), will be the preferred fuel source. Given these significant constraints, He-3 provides a poor argument for proceeding with any exploration or settlement of the Moon, and therefore should not be currently used to drive any arguments supporting lunar exploration, settlement, site selection or resource economics. Additionally, to consider He-3 as a resource, many other questions must be addressed before He-3 becomes part of the lexicon for lunar mining, including proving the techniques and technologies associates with its mining, processing and transportation in mass, all of which remain unanswered to this day (see Crawford, 2015).

3.1.2. Propellant production (or in situ propellant productions (ISPP))

The need to derive local propellants off Earth has been espoused since the very beginning of human flights into space (McDougal et al., 1963). Propellants remain one of the heaviest and thus costly components of space flight, and their production in space may become the most important enabling endeavor known (Siegfried and Santa, 2000). The problem with presently using propellant as a sales point or driver for human (or robotic) lunar exploration and settlement is multifaceted and adheres to proverbial "cart before the horse" principle. Lunar propellant production and associated resource mining has historically focused on and assumed cryogenic liquid propellant species of oxygen and hydrogen (i.e. for developing highly sustainable ISPP architectures), whether or not this is explicitly stated in any given treatise (Klemetson et al., 1985; Palaszewski, 1994; Zubrin, 1994; Duke et al., 2003; Spudis and Lavoie, 2011; Sowers, 2016; Gat and Talon, 2017; Zubrin, 2018; Kornuta et al., 2019). An extensive review of the literature from 1985 to 2019 bears out this assertion by showing that at least 39 out of 43 resource related papers referred or alluded to cryogenic propellant species. All of these works basically assume that natural water (ice) abundances are high, easily accessible and economically viable (Anand et al., 2012), irrespective of current geological understanding or data fidelity. Otherwise, lunar oxygen alone (Joosten and Guerra, 1993; Sacksteder and Sanders, 2007; Lee et al., 2013) considered as both a propellant and as a life-support consumable, would support only a partial ISPP/ISRU sustainable architecture as a spacecraft would need to carry its own fuel supply. Therefore, the ISPP sales arguments could be slightly modified given models which use only lunar oxygen at 80% the mass volume combined with other hydrocarbon based fuels transported (20% mass volume) in full to and from planetary surfaces.

Key high-performance, main and reaction control, cryogenic liquid propellant rocket engine systems and components supporting deep-throttling, multi-use, long-duration, refurbishable, for in-space and surface-to-orbit transportation remain to be developed (Brown and Nelson, 2005) to support and therefore require ISPP initiatives. Additionally, cryogenic processing, storage, transportation, refueling and standardized propulsion components, mostly low TRL, all need to be developed (Meyer et al., 2012), and used in quantity in order to support and drive ISPP/ISRU. Currently no spacecraft designed for using in-space cryogenic propulsion systems (pump or pressure fed) between 100 and 5000 kgf (220–11000 lbf) exist on the shelf, and any such development efforts, given historical technology development processes, will require a multiyear ramp-up in design, testing and production. A few large cryogenic engine projects exist such as the United Launch Alliance (ULA) Advanced Cryogenic Evolved Stage (ACES), which having been on paper for over a decade is now in various stages of testing (far from being ready to require planetary mined resources). Additionally, the only low thrust level propulsion components being developed for in-space and surface landers are under the same program (e.g. ACES and XEUS (Experimental Enhanced Upper Stage; LeBar and Cady, 2006; Sowers, 2016). Recently Blue Origin has added another, rather large, BE-7 LOX/LH2 (4535 kgf (10,000 lbf)) lunar ascent/descent motor to the list of in work cryogenic tools. Other fully unresolved or undemonstrated challenges include in-space storability, propellant transfer, power and transportation technologies, all of which are continuously being researched (Notardonato et al., 2012). Yet, issues regarding efficiency and energy requirements remain formidable, and thus make selling propellant production, at this time, as a driver for initial site selection and ISRU endeavors overly premature.

Likely the second best propellant combination that has ISRU relevancy, especially to Mars exploration and settlement, is cryogenic methane (CH_4) and oxygen (Zubrin, 1994). Some prototype work on such propulsion systems has occurred over the years, and many companies and programs have ceased development while others forge ahead or simply include them in project goal statements (e.g. XCOR & ATK in 2008; Aerojet in 2010; NASA's Morpheus Project in 2015; NASA's Integrated Cryogenic Propulsion Test Article (ICPTA) in 2017; Morehead et al., 2017; Intuitive Machines in 2018; Landspace's TQ-12 in 2018). Currently SpaceX and Blue Origin have recently designed, built and tested high thrust methane bipropellant engines called Raptor and BE-4, respectively (SpaceX, 2019; Blue Origin, 2019). Overall little or no information has yet been released on any related smaller, in-space propulsion components, potential users or space storage capabilities. Ultimately, in relation to the Moon, this would presently be a highly unsustainable propellant combination because the expected amounts of carbon in the environment, estimated in the parts per million range (C in lunar regolith/soil < 0.5 g/kg), makes reclamation extremely difficult (McCubbin et al., 2015) and ISPP unsustainable. A question instead might then be, are there other sources of carbon? How many lunar settlement inhabitants would be needed to produce enough capturable CO_2 to enable a productive methane Sabatier production cycle? The alternative, again being, carry it all with you all the time from its terrestrial source.

Lastly, other potential propellants like ionic liquids or fuels based on various metals are possible (Rosenberg, 1985; Hepp et al., 1994; Zhang and Shreeve, 2013; Morrison and Robinson, 2018), but our understanding and current technology levels remain low enough that it could take decades or more of dedicated research just to bring them into the realm of candidacy. Therefore, they seldom appear in the literature as drivers for lunar ISRU.

Ultimately, the current state of in-space cryogenic propulsion systems makes them untenable as arguments for indulging in ISRU and mining operations on the Moon right now, though propellant production will remain the most important driver for the viability and economy of long-term, growing, lunar exploration and habitation. It is likely that the only way lunar propellants will prove commercially viable is if focused efforts are made, from scratch, towards adopting and standardizing, and making shelf-ready in-space cryogenic propellant systems for the majority of future space vehicles. This further includes refillable satellite systems, adding propellant depots and developing safe and efficient transfer and refueling capabilities. Otherwise, for the near future of lunar exploration, well understood and characterized space-storable propellants (e.g. hypergolic bi-propellants) shall remain the preferred modus operandi.

3.2. Mis/inaccurately-sold and under-sold resources due to pre-established scientific interpretations or incorrectly marketed as a result of limited or inaccurate data.

3.2.1. Water: Human and commercial needs and relevancies to mission design

Water is and will be the most useful and versatile resource needed to insure human survival off Earth. Mars is the only habitable world which has observed and quantifiable volumes of water ice, and therefore makes destination choices clear. Water had already become one of the most important tenets of Mars program goals by the late 1990′s, as a scientific goal to explain both surface morphologies as well as in the search for life off Earth. Yet, Mars has again been relegated to the proverbial “20 years from now” or longer with the resurgence of lunar exploration (even given the selling point of being a stepping stone). Water, within the lunar exploration community consciousness, has only over the past ten or so years increased in visibility as the most important and necessary extraterrestrial resource, for both human habitation and exploration, as well as its implications regarding planetary science (Saal et al., 2008). Water is the most intrinsically useful consumable humans will ever need, as well as being economically enabling. Beyond the tie to propulsion production and usage listed previously, water provides water, and can provide oxygen for air (life-support), which are, especially in cases of survival and comfort, the most highly used consumables and often the least likely marketed in relation to ISRU. Additionally, given that all human habitats are “leaky,” having ready access to sufficient supplies of local water, habitat architects and designers will not need to delay or force designs to unreasonable standards of fully closed-loop efficiency.

The suggestion of lunar surface volatiles, and ice specifically, began to take form in the early 1960′s (Watson et al., 1961; Arnold, 1979), and remains in contention (Lanzerotti et al., 1981; Siegler et al., 2015). A fleet of spacecraft from Clementine to the Lunar Prospector to Chandrayaan-1 and beyond have collected a vast volatile data repository. The 1996 Clementine, bistatic radar observations have been used to assert that upwards of 135 square kilometers of icy material could exist in the bottom of perminently shadowed regions (PSRs) near the Moon’s south pole (Nozette et al., 1996). Ice lifetimes within these “cold-trap” craters have been estimated to be on the order of billions of years (Hodges, 1991; Paige et al., 2010) given that temperatures are expected never rise above 100 K (−173 °C). The Lunar Prospector’s 1998 neutron spectrometer results indicated potentially large hydrogen, and therefore presumably water-bearing, regions at the lunar poles (Feldman et al., 2001; Miller et al., 2012). Expanding on these results, the Chandrayaan-1 spacecraft, launched in 2008 carrying the Moon Mineralogy Mapper (M3) and Mini-SAR, examined extremely cold dark areas (i.e. < 110 K) providing putative estimates on volatile distributions, including water ice, which could be present in some, yet to be determined quantity (Calla et al., 2015; Milliken and Li, 2017; Li and Milliken, 2017; Banfield et al., 2018; Li et al., 2018). Launched in 2009 and still returning data, the Lunar Reconnaissance Orbiter (LRO) detected hydrogen (Mitrofanov et al., 2010; Litvak et al., 2012; Miller et al., 2012; Hayne et al., 2015; Sanin et al., 2017; Livingood et al., 2018) in shadowed crater regions using the Lunar Exploration Neutron Detector (LEND) (see Fig. 4). Analogously, extensive data for Mars was received from the 2001 Mars Odyssey spacecraft gamma-ray spectrometer (GRS) neutron instrument, providing good correlations between extensive geomorphological, radar and visible identifications of ice, supporting the efficacy of this techniques and technology. The LRO Lunar Orbiter Laser Altimeter (LOLA) and Diviner Lunar Radiometer has also

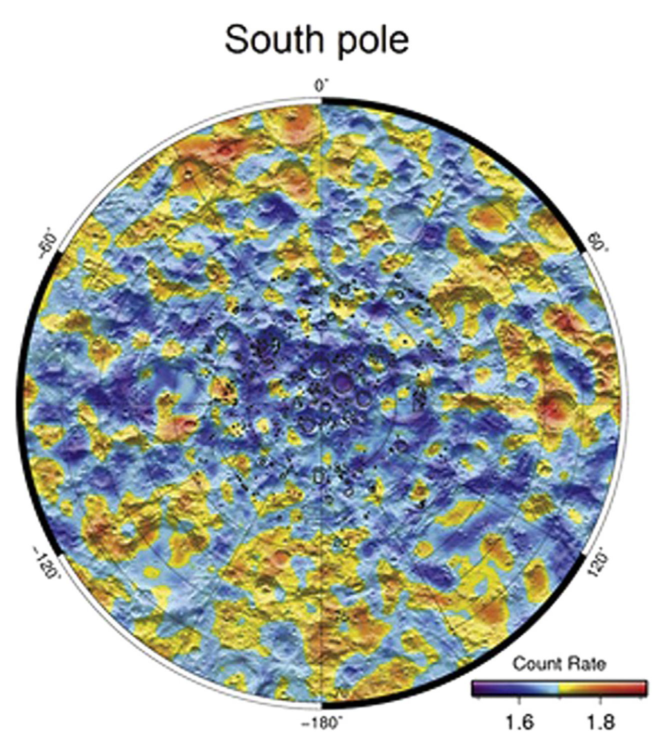

Fig. 4. LRO LEND south pole epithermal neutron counting rate variations showing enriched hydrogen content within the polar PSRs indicating water by proxy (Sanin et al., 2012, Litvak et al., 2012).

been used to assess surface reflectance in the search for water–ice (Fisher et al., 2017). The LRO sister experiment, the Lunar Crater Observation and Sensing Satellite (LCROSS) impacted Cabaus crater emanating an impact plume containing a 5.6 ± 2.9% water by mass (Colaprete et al., 2010). Additional LRO neutron data analysis has demonstrated that the Moon's spin axis had been perturbed and that apparent hydrogen deposits at each pole had been displaced accordingly showing an evolution of such deposits over time (Siegler et al., 2015). Work using this data has continued with the derivation of water-equivalent hydrogen (WEH) content maps (e.g. Sanin et al., 2017; Livengood et al., 2018). Theoretical modeling also indicates that water–ice could exist on the Moon, especially in the PSR craters at the south pole (Arnold, 1979; Ingersoll et al., 1992; Vasavada et al., 1999; Bussey et al., 2003; Hurley et al., 2012). It is also important to remember that should PSR ice exist in quantity, it does so at temperatures < 100 K (Andreas, 2007; Fisher et al., 2017), making technological access and extraction complex and therefore directly influences the full extraction efficiency cycle (i.e. the RecEff variable in the EUR model above).

Though this body of data provides the best indicator for the potential existence of water ice in the near surface regolith, little or no quantitative knowledge of volumes exists, and significant ground truth and verification is needed to sell this as a viable resource. The substantial uncertainty surrounding lunar hydrogen and water signatures, and therefore locations, true volumes, and producible quantities of easily accessible and extractable lunar ice or water remains to be resolved prior to human landing site selection.

3.2.2. Lunar regolith/soil: The most ubiquitous resource on the surface

The lunar regolith/soil, is a multifaceted resource; one that contains easily extracted and managed construction materials (i.e. unconsolidated regolith devoid of bedrock or large boulders), and a complex chemistry. This article is not meant to provide a comprehensive review of either the full utility or distribution of any specific resource, but given the ubiquity of the lunar regolith and its potential uses there is a greater need to elevate the visibility of this resource. For a good accounting of this resource see Anand et al. (2012). Understanding the mechanics of sintering, mining, transporting and processing this resource (Boles et al., 1997) may initially be the most import hurdle to establishing permanent human presence. According to our PRMS model, the lunar regolith is the only resource that presently has the potential to be categorized as a "Proved Reserve" when regarded as a bulk material for usage in sand-bagging or burying habitat structures (e.g. to protect inhabitants from the lunar surface radiation environment; Miller et al., 2009). But this simple mechanical usage explanation does not begin to address the wider potential contained within the soil's complex chemistry that drives additional forms of usage such as construction (e.g. sintering landing pads and roadways), beneficiation, elemental reduction and chemical extraction. There are a plethora of 3D printing/sintering (Meurisse et al., 2017) and construction (Bell et al., 1992) investigations designed to use the regolith that require detailed mapping of the aerial distribution of the varying mineralogy and chemistries in order to advance its precise thermodynamic and thermo-mechanical understanding. In situ sintering of such material, for example, would prove useful in constructing landing pads, foundations and structures. Additionally, production and in situ usage of solar cells has been highly touted (Landis and Perino, 1989).

On the other hand, the lunar regolith is a vast repository of potentially useful elemental species (Anand et al., 2012; Crawford, 2015), which will only grow as technology and capability advance. Lunar terrain with higher concentrations of glassy material may also contain a relatively wider array of elemental abundances useful to enhance sustainable human habitation. Given production line processing and extraction, the regolith can be heated (thermally reduced) to further extract and separate volatiles, metals and silicates (Schwandt et al., 2012; Schreiner et al., 2016). The regolith has also been considered as a source of water (Reiss, 2018) but actual reclamation remains mired in the theoretical realm, and may require destructive testing on actual lunar samples. The problems of identifying chemistries, mining, transporting, sorting and reducing remain and keep this resource in the "Contingent Resources" category.

4. The growth of a human user-base

The only way to develop a useful and growing space resources industry is to develop a *destination*, a location where a growing population and infrastructure require the development and use of in situ resources. Fig. 5 demonstrates a four-year timeline showing three simple architectures for lunar settlement sustained population growth including some associated observations and requirements.

The numbers regarding consumable usage and needs per person and mission for the three architectures are easily derived (Hanford (2004); Lopez et al. (2015). Yet, as can be seen from this rudimentary timeline, it would take hundreds of years in our traditional (sequential) spaceflight architectures and approaches to even reach the average summer working population of the McMurdo Antarctic station, which has averaged roughly 1200 between 1997 and 2017. This may currently be our best analogue for all off Earth exploration and settlement endeavors (Klein et al., 2008; "Secretariat of the Antarctic Treaty," 2019). Increasing the passenger manifest by 10 times in the second flight design (i.e. to 40 per flight), reduces this timeline to 50 years, and in the last case, using a postulated SpaceX high population transportation model, would take just about 20 years. For comparison the International Space Station (ISS) has flown 20 years continuously carrying

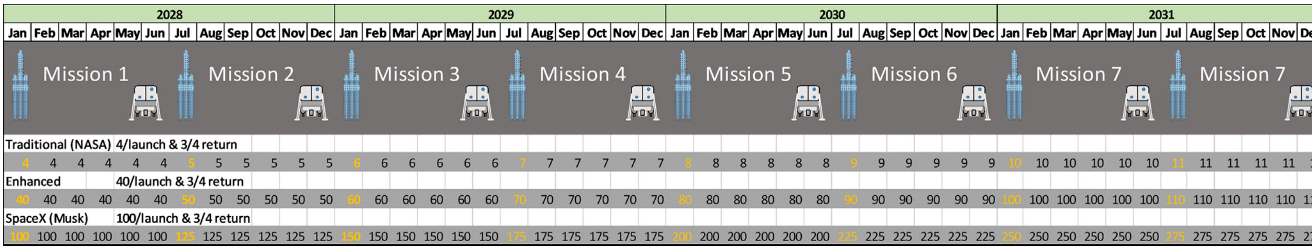

Fig. 5. A 4-year mission timeline showing the geometric growth rate of a lunar population based on a ¼ launch capacity crew rotation rate for three classes of ferrying-capacity piloted spacecraft. The first two show traditional and augmented NASA crew capacities, and the last is an aspiring SpaceX large capacity vehicle. Also assumed is a sustained flight rate, growing surface infrastructure, and detailed evolution and division of labor.

between a 3 and 6 person "permanent" crew with minimal overlapping populations, and therefore has had no net growth rate as of yet. It is also noted that population growth is only expressed in terms of humans transiting and does not account for the possibility of natural in situ growth. This would be less likely in the case of the two cycling class architectures due to crew training and shorter durations on world, and might even need to be curtailed in the last case until studies have proven the viability of human pregnancies in low-gravity high-radiation environments.

All spaceflight endeavors have yet to fly any vehicles capable of holding more than 8 passengers, the record for the largest crewed launch and return to date was set on the Space Shuttle, flight STS-61A, in 1985 with 8 souls onboard. Obviously running a growth oriented space endeavor by keeping and expanding in situ populations much longer before rotating out would also require substantial growth in funding to insure the feasibility and safety of such operations. Given that there are no established user communities in space, traditional "commercial" markets will likely not evolve to fill such a slowly evolving timeframe with one or limited customers. This has been made clear in human spaceflight simply by the lack of "commercial" endeavors in or away from LEO for the past 50 years (i.e. seven space tourists visited the ISS in 21 years).

An example tying resource usage to population size is useful. Using the P95 extraction estimate levels, from Section 2.2 above, a lifetime estimate of water can begin to be assessed for a McMurdo size base harboring 1200 full time residents. Fig. 6 shows the lifetime of water deposits that need to be identified per the stringent P95 level for landing site selection. Three different usage rates affect those supplies are used as examples: Average US user, McMurdo base usage and human spaceflight guidelines ("Human Integration Design Handbook (HIDH)", 2014), and as expected, higher usage rates result in reduced supply availabilities over time. The Average US and McMurdo are all inclusive water figures (i.e. all daily water used by an average US citizen, and full daily water usage at McMurdo divided by 1200 users). The spaceflight values from the HIDH are the sum of human only needs, i.e. hydration, food rehydration, hygiene and flush. Adding all other potential water users (e.g. conversion in ISPP or ISRU, life support, farming, cleaning, experimentation, radiation shielding, recreation and so on) will significantly raise this usage rate and decrease the supply lifetime. These values also do not take into consideration waste or recycling, which directly impact initial architectural designs regarding structural leakage.

Lastly, it is important to highlight that there are many more interrelated and unaddressed aspects of resource development that needs to be considered as populations increase, including the development of new, large capacity spacecraft, landing pad facilities (i.e. developing additive manufacturing and sintering technologies), accepting higher-ongoing risk, routine and uninterrupted flight schedules, planned growth in infrastructure, environmental planning, bulk resource mining, storage and transportation, social structures, job categorization, and so on. A similar quandary exists for any other developing space-platform or world, though some interesting differences arise regarding assumed sustainability or how distant the locations are from the Earth. The growth of populations further shows the need to efficiently identity and acquire in situ resources on clearly defined and quantified scales so as to fit our definition of sustainability and human site selection criteria. Population growth dependent variables, given that the Moon is only a few days from Earth, likely also provide the single most important and relevant piece of transferable knowledge to enacting the human settlement of Mars.

5. Discussion: The "cart before the horse" problem – Humanity off Earth

Commercialism has been a growing sales point for all aspects of spaceflight, but as can be seen by its lackluster advancement regarding human spaceflight for over 50 years, there remains certain unsurmountable obstacles regarding the creation of the profit necessary to drive the development and advancement of a thriving commercial market. In-space resource acquisition and utilization is a prime example of this "cart before the horse" quandary.

Spaceflight remains within the proverbial realm of "rocket science" with regards to transportation and risk, and this is especially true with regards to launching and

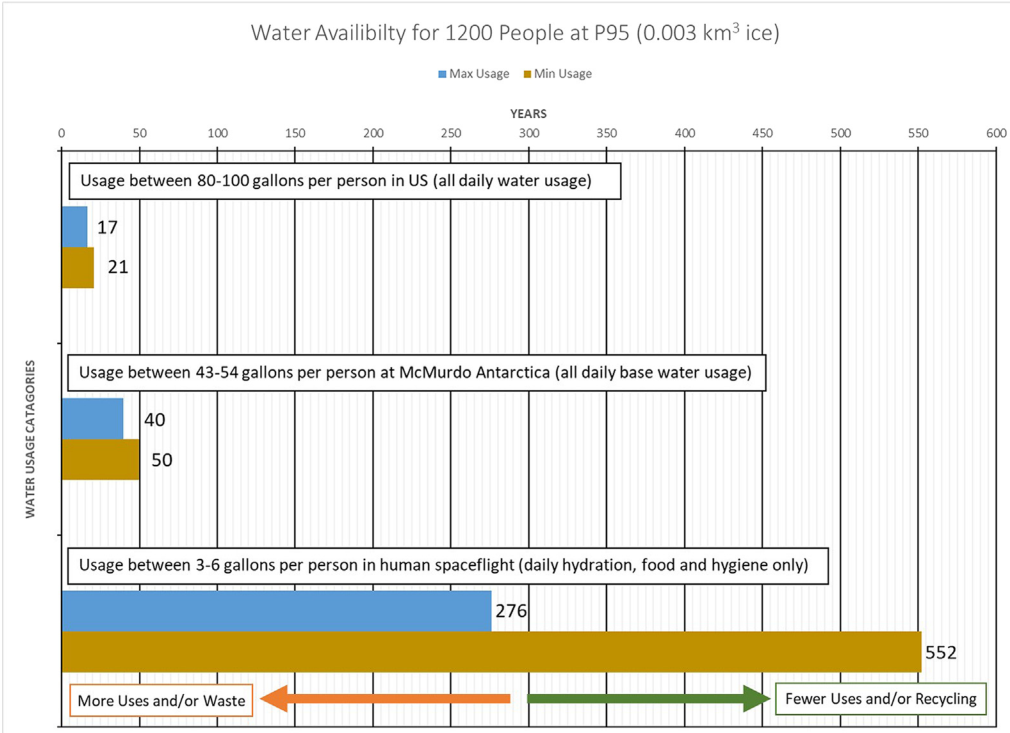

Fig. 6. Water supply comparison for three usage rates for the P95 estimated 0.003 km^3 of ice.

landing massive machines on any planetary body. Propulsion systems arguably stand out as the longest tent poles in the process of spacecraft development and production, especially with new systems. The time needed, costs and hurdles involved are historically large and cyclic, beginning from the first architectural proposals to the point of proven flight (i.e. multiple successful flights). SpaceX provides a modern case study of this process starting with the its 2011 public announcement of the first recoverable launch stage, followed by the first successful demonstration in December 2015. Another example is the unveiling of the Falcon Heavy, again in 2011, and with the first launch not occurring until early 2018 and the second over a year later. And these are examples of unpiloted vehicles. Therefore, to use ISPP as a reason for space resources requires developing an appropriate propellant customer base through the standardization of deep-space or orbital propulsion systems. Such a driver would need to be advanced in parallel of a rapidly advancing ISPP program or well in advance of a tentatively supported program; else no proven need exists for ISPP resource acquisition, and the risk to a program selling it only increases over time.

Even before usage is addressed, a pragmatic means of acquiring data and information is required to feed a PRMS type resource viability and landing site tool. In order to minimize the potential for one-off human surface landings and the potential waste of associated infrastructure components, a dedicated large-scale parallel prospecting campaign is needed (as opposed to traditional sequential mission architectures). Such an effort would require significant up-front costs, similar to those put into opening any new business or terrestrial resource exploration campaign. Should space exploration efforts remain working on a sequential path, then it will take decades to find the best resource locations or greater risk will need to be accepted in choosing any single location based on limited, unquantified resource information. As an example, the current Artemis 2024 effort will likely land at a site unsuited for resource acquisition, infrastructure development and therefore follow on landings. Currently there are no precursor resource prospecting missions scheduled that could assess *all* of the potential PSR locations so that the optimal human landing site could be chosen for development. Only a single viable and dedicated water prospecting mission for the end of 2022 is being developed, NASA's Volatiles Investigating Polar Exploration Rover (VIPER), and it is designed to traverse only a few kilometers within a single region over its 100-day lifetime. This mission is analogues to an upstream petroleum company drilling a single or couple exploratory wells in west Texas, and assuming they will strike producible oil.

Science as a spaceflight goal was a fortunate outcome of a fledgling space program that was almost an afterthought to a nationalistic ego race occurring between the US and USSR in the middle of the last century. Science in space was also spurred on by growth in communications technologies and even from the science fiction (e.g. Star Trek) of the day. This brings into question exactly *why* we should go to the Moon or any other location, and exactly *what* people will be doing once there as this is directly tied to population growth. Are we in another race? Are we going just to do scientific research? If the only goal is research and scientific return, can we create and sustain, at a minimum, a McMurdo size settlement? As has been seen in Antarctica for the past 70 years, such a model is tenuous, especially with regards to growing commercial endeavors or anything beyond the sustainability of the current facilities, operations and goals (notwithstanding the limitations due to Antarctic Treaty constraints and human environmental impacts associated with tourism).

NASA's exceptional history regarding space science over the past 50 years has hampered its ability to change course to a path that might significantly advance humanity off Earth. Only a dedicated shift to a paradigm of settlement and growing resource extraction and usage, moving science to the back-seat, will noteworthy commercialization efforts and populations off Earth be expanded. Current adhesion to catchy programmatic guidelines such as "*science enables exploration, and exploration enables science*" are cogent and yet because of the actual meanings conveyed by these words their long-term effects belay any significant advancement of humans off Earth. As mentioned it is desirable to change goals from science to permanence and settlement because scientific exploration and research will never drive sufficient populations off Earth needed to develop a true space economy. Science as a philosophy is not a physical thing but a cyclic process of observation, theorization and reevaluation that is bound by statistical validity and reliability. Similarly, the word meaning and concept of "exploration" is transient and does not imbue the meaning of a fixed goal, and therefore leaves the reader with an ambiguous result and conclusion. Understanding the cognitive aspects of words and concepts is important. Therefore, the desire to change the diction and verbiage of future human space efforts, assuming there is a desire to make humanity a multi-world species, should focus on long-term measured sustainability across all levels. And given such a transition, scientific advancement will inevitably benefit and grow to an even greater extent than if science alone remains the singular goal; this line of thought is partially predicated on the premise that "if you build it they will come."

It is also important that the communication of space exploration goals be clear and concise in order to assure that mission developers, financial stake holders, and the public (assuming public funding sources are to be used) have a clear understanding of exactly what can and should be the focus in order to attain an economically viable and successfully growing outcome. Perpetuating erroneous expectations within the human spaceflight community, the public or government regarding goals and capabilities only add to the short-term problem of advancing to any point of actualization. Unfortunately, as these and many other events and efforts occur under finite or limited financial or programmatic support, commercial or governmental, the inevitability of incurring a nonstarter, delay or cancelation are to be expected.

Since human spaceflight has the problem of having to create, outfit and populate any destination off Earth safely and with sufficient resources and infrastructure, and only governments have funded anything related or of scale as yet, it is easy to see why no true advancement has occurred towards commercial development (i.e. extremely high startup costs and no foreseeable turnaround to achieve profit). Using current mindsets and flight rates, it will take half a century at best to populate the Moon with as many people who summer at the largest Antarctic base today. Another forward looking question regarding growing populations on the Moon or any other off Earth location, which has little been addressed historically, has to do with exactly *what* these populations will be doing on a daily basis.

If human spaceflight goals are redefined towards a non-science first, pragmatic, growth oriented, resource identification and usage paradigm, combined with unalterable lines of support and appropriate funding to carry out said goals, then advancement could occur much faster even given our current state of technology (i.e. no need to wait on the next best technological upgrade to make a process slightly more efficient – as the enemy of good is better). Yet, a cautionary observation and cloud hangs over all said endeavors. Continually growing terrestrial populations and the resulting resource, pollution, climate and conflict issues will increasingly require resources to simply mitigate all related effects, and will ultimately decrease available funds and support to advance all off Earth human efforts. This may require redirection of said efforts sooner than later as a proverbial "window of opportunity" wanes or closes.

6. Conclusion

The following bulleted list, in no particular ranking, are proposed in order to insure the development of off Earth human advancement in population, scientific knowledge, technological capability and resource needs towards attaining self-sufficiency and sustainability.

- Human spaceflight goals need to change from "science" to "prospecting, production and settlement" if timely and permanent human advancement off Earth is to occur, and then, in parallel scientific advancement will happen naturally.
- A rigorous, parallel (i.e. multiple site), prospecting only paradigm needs to be initiated to provide resource identification for human settlement and commercial development off Earth in a timely manner.
- A PRMS type model methodology, highly rigorous and strictly adhered to, helps to assure sufficient quantities of resources are discovered, available and accessible prior to selecting human landing sites for settlement and exploration – no chance of drilling a dry hole (once landed hardware likely cannot be moved to a new location).
- To insure long-term, growing and successful human exploration and settlement off Earth, sufficient local resources must be accessible to insure a predefined level of sustainability, which will ultimately drive down the

costs related to further design and development, and grow a surplus that may be used to fully develop an off Earth economy.
- Since all space resources will be used in-space, for the foreseeable future, both population increases and systems designed to use said resources need to be grown in parallel, and rapidly before changes in terrestrial conditions threaten achieving a self-sufficiency break-point.
- The way the spaceflight, science and technology communities promulgate and promote concepts, language and desires to use space or lunar resources, in a bid to reduce costs, must be accurately communicated and insure that all variables are viable and accounted for in advance (i.e. resource types and amounts, user groups and technologies, timelines, infrastructure, extraction capabilities, etc.).
- The concept of "sustainability" and its component parts are directly related to the probability of success in the development of resources as well as permanent habitation off Earth, and need to be addressed formally when designing any goals and programs.
- One approach that might be considered should water deposits become viable, is to transfer "raw" water to a *cis*-lunar orbital platform for storage and processing into cryogenic propellants and other consumables, removing the requirement to move related processing and storage mass to the surface.
- Without precise PSRs volatile volume assessments the current Artemis 2024 effort, and beyond, will likely land at sites unsuited for resource acquisition and infrastructure development. Currently there are no precursor resource prospecting missions slated to assess all of the potential PSR locations so that the optimal human landing site can be chosen.

Space resources should eventually advance humanity off Earth. The pace of this expansion, though, may require as little as a few decades or may require centuries depending on the dedicated focus of the goals and actions implemented today. In the end, it is the speed at which such a redirection of efforts is made that will determine whether humanity will ever become a multi-world species, removing some of its "eggs" from the terrestrial basket, and possibly ensuring that all that is noble about our species survives.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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