**Developing Resource Exploration Strategies for Lunar Polar Volatiles.** S. Casanova[a]*, C. Espejel[bc]*, A.Dempster[d], R.C. Anderson[e], S. Saydam[a], [a] *School of Minerals and Energy Resource Engineering, UNSW Sydney, Sydney, Australia.* [b] *ispace Europe, Luxembourg, Luxembourg.* [c] *Faculty of Science, Technology and Communication (FSTC), The University of Luxembourg, Esch-sur-Alzette, Luxembourg.* [d] *Australian Centre for Space Engineering Research (ACSER), UNSW Sydney, Sydney, Australia.* [e] *Jet Propulsion Laboratory/California Institute of Technology, Pasadena CA, USA.* * Corresponding Authors: s.casanova@unsw.edu.au; c-espejel@ispace-inc.com

**Introduction:** In order to expand our current robotic and human capabilities in space there is a need to find low-cost energy solutions to meet the anticipated in-space resource demands. The Moon, Earth's closest celestial neighbor, is known to possess abundant raw minerals and volatiles that could potentially be extracted to meet these demands. The production of hydrogen and oxygen derived from water, in particular that from water ice, is of great interest in the near-term due to the lower energy requirements for extraction and separation from the host rock. The ~1.5° tilt of the Moons rotation axis with respect to the ecliptic results in permanently shadowed regions (PSRs) at the Lunar poles which have long been suspected to act as potential cold trap reservoirs for water ice and other volatiles [1]. Numerous studies, using data collected by orbital spacecraft, have identified enhanced hydration signatures within PSRs. Supporting evidence for the presence of water ice was provided by the Lunar Prospector Spacecraft [2, 3] as well as the results of the NASA Lunar Crater Observation and Sensing Satellite (LCROSS) mission, which impacted Cabeus Crater, located in lunar south pole and measured a water ice concentration of ~5.6 % ± 2.9% [4]. Further support was provided by space and earth based radar [5, 6] and more recently by re-examination of IR spectral absorption data [7]. Our current understanding of the characteristics of these putative water ice deposits on a scale relevant to determining the resource potential is limited, due to the resolution of available data. Current interpretations suggest that these deposits are likely to be highly heterogeneous in terms form, concentration and spatial distribution both in vertical [2, 8, 9] and lateral [10-13] sense. In the near future exploration missions are likely to be sent to the Moon to better determine the nature of lunar polar volatiles and the controls on its spatial distribution and form. Given the interest in utilisation, the collection of data that can be used to estimate available quantities of extractable water ice will also be required. This study examines the current state of geological understanding and interpretations of the Lunar PSR environment, the processes which formed and preserved the prospective deposits of water ice and the proposed methods of extracting and developing them for use. This is undertaken in order to provide recommendations for robotic surface resource exploration and evaluation activities. The primary focus of this study is to identify the key geological parameters that will need to be assessed in order to develop a resource estimate. The processes outlined here can equally be adapted to the exploration and evaluation of surface and subsurface water ice deposits on Mars. Although a formal code or standard for resource estimation and classification of space resources does not yet exist it is hoped that this study will provide some guidance for developing such standards when evaluating ice deposits on the Moon and Mars.

**Space Resource Field Exploration:** Greenfield or frontier exploration are terms commonly used in terrestrial extractive industries to describe a field where there has been no previous mining or production activities and data availability is poor. Exploration targets in fields such as these are by their nature, even in a terrestrial environment with our current understanding of how economic accumulations develop, high risk ventures. For the Moon where there remains significant uncertainties as to presence and many of the fundamental processes that would have led to the deposition, accumulation and preservation of water ice, in addition to a paucity of data needed to interpret these aspects, the geological, technological and economic risks are very high. Resource exploration seeks to reduce this risk through activities which search for, identify and evaluate viable mineral deposits / volatile reservoirs, determine their geological characteristics and estimate the volume of accessible resources within a defined area. Resource exploration for space resources will begin with a reconnaissance or prospecting stage which will identify targets of interest using data collected by orbital spacecraft and develop a preliminary geological model of the exploration target of interest referred to as a prospective resource model. Once a target has been selected in-situ field exploration will be required to further reduce uncertainties related to resource presence, resource volume-in-place as well as the feasibility of extraction and eventual development of a specific target. Space resource field exploration activities will involve four to five key stages (dependent upon the extraction method being used) these include: geophysical / ground survey analysis, target drilling, resource evaluation, production testing / appraisal (if required) and feasibility studies.

***1. Geophysical / Ground Survey Analysis**:* Initial investigation should begin with ground survey and geophysical data collection to assist exploration program planning and identifying areas for more detailed analysis.

***2. Target Drilling:*** the next stage is aimed at successfully intersecting (using a drill and sample approach) a viable deposit / reservoir (*i.e.* in this case direct sampling of water ice on the lunar surface or near subsurface). Activities also include the testing and analysis of the drill and sample data to determine key geological properties (i.e. water form, content, depth, thickness etc.). The results will inform decisions regarding whether or not to proceed with more detailed investigations of a site and assist in design of fit for purpose extraction methods.

***2. Resource Evaluation*****:** This stage aims to provide estimates of volume-in-place. The focus should be on achieving a good understanding of the spatial extent, continuity and variability of geological characteristics of the resource. This data will inform the development of a static geological resource model.

***3. Appraisal and Pilot Testing:*** Some extraction methods for water ice on the Moon propose techniques which directly heat a water ice deposit/reservoir inducing in-situ sublimation of the ice. In this case it will be necessary to undertake an appraisal phase. Pilot production testing, which involves small scale recovery tests can be used to quantify the likely deliverability of water, in particular the production rate and the **estimated ultimate recovery (EUR)** from the reservoir. This data will be used to inform dynamic resource models.

***4. Feasibility Studies:*** This final stage of evaluation involves a feasibility study, a desk-top due-diligence assessment of all factors relevant to the making the decision to proceed with development and the construction of a development plan.

**Static and Dynamic Modelling:** If water exists in the form of pore ice it will likely be highly mobile. Disturbances to a water ice reservoir as a result of some of the proposed extraction methods are likely to result in changes to the recoverability of the ice over time. Thus two types of resource models are required. A static model which represents the resource as it occurs in its stable equilibrium state before production and a dynamic model which models changes to the original state as a result of production.

***Static Geological Resource Model:*** The estimate of the total water present within a reservoir, referred to here as the **Original-Water-In-Place (OWIP)** is an important estimate to inform development decisions. It will also be important to reference the state of the water product (i.e. solid, liquid or gas) and form (i.e. ice, adsorbed water or mineral) *i.e.* if the estimate is for the total amount of available water ice within a reservoir we can refer to this resource estimate as **Original-Water-Ice-In-Place** (**OWIIP)**. As part of this study we examine methods of obtaining OWIP and/or OWIIP and the key parameters that would be required to build this estimate *i.e*. reservoir area and thickness, volatile form, net pay, gas content, density, porosity and permeability, reservoir pressure and temperature. Developing a scientific instrumentation payload which is capable of evaluating each of the properties is essential. In addition to the parameters to build the static resource model logistical and geotechnical parameters will also need to be collected as part of the exploration process which will be used in feasibility assessments *i.e.* surface temperature, available sunlight, overburden thickness and rock properties, slope, terrain roughness and trafficability,

***Dynamic Modelling:*** If required, changes in productivity and production decline within a given area of influence can be modelled using reservoir simulation techniques built from results obtained from pilot testing or, if available, production results from analogous fields. As production of a given field matures and greater production data is made available more sophisticated reservoir simulation methods can be introduced to better predict the behavior of a particular water ice reservoir as a result of production.

**Conclusions and Future Work** There is still much that is unknown about Lunar PSR water in particular the present day form, spatial distribution, water content and depth which impairs our ability to design fit for purpose extraction equipment and development plans. Our understanding of the processes which control the deposition, preservation and concentration is also not yet well-developed, which makes identifying locations that have the greatest chance of successful resource extraction challenging at this time. This study identifies some of the key parameters required for evaluation and techniques for developing geological models to better inform resource exploration planning and decision making.

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