A CASE FOR EXTRATERRESTRIAL WATER RESERVES AND RESOURCES

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Introduction: Language takes chaos and makes it into things, which only then can be understood. The unnameable cannot be properly addressed and coped with, it is thus better without exception to name a thing. This paper brings the attention to the problem of extraterrestrial water resources, which so far have been a field of scientific study but now their industrial potential emerged and may be properly defined, categorized and characterized. Those definitions are created in assumption that it is necessary for the development of space resources industry to have clear standards for resources characterization at every stage of operations (Figure 1.) in order to plan, develop and execute such operations (both in case of non-profit and for-profit operations) but also to increase their pace. Newly established standards connect every stakeholder with the same language, allowing them to collaborate effectively. The significance of addressing this issue is both psychological and organizational. With that in mind, multi-feedstock extraterrestrial water resources have been named and the problem of their estimations has been addressed.

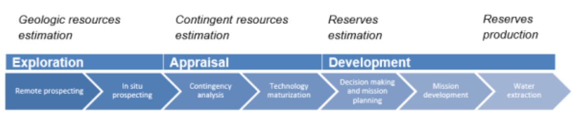

Figure 1. Phases of extraterrestrial water resources development.

General classification of extraterrestrial water resources: By drawing analogy from terrestrial framework of petroleum reserves and resources classification and estimation [1] and its translation to space environment through a lens of past ISRU studies, e.g. M-WIP [2] we may obtain new general categorization for extraterrestrial water resources with definitions for (1) reserves, (2) contingent resources, (3) prospective resources and (4) geologic resources, as well as their (I) technical and (II) commercial recoverability.

Reserves should be defined as:

Technically and commercially recoverable production input feedstocks, which have been discovered and are still in-place.

This framework diverges water reserves through probabilistic approach into proved (P90), probable (P50) and possible (P10) reserves.

Contingent resources are those discovered feedstocks for water production that currently are not technically and/or commercially recoverable.

Prospective resources are those undiscovered feedstocks for water production that are currently technically and commercially recoverable.

Geologic resources are every discovered and undiscovered feedstocks for water production currently in-place.

Until any actual production operations have taken place but also until production operations are set to market-based conditions, this framework should also define technical and commercial recoverability terms for the production process.

Technical recoverability should be defined as:

Use of a set of state of the art methods, devices and their interfaces for given water production feedstocks that has been tested in Earth-based analog conditions and obtained highest performances.

Commercial recoverability should be defined as:

Mission-driven use of a set of state of the art methods, devices and their interfaces for given water production feedstocks that has been tested in Earth-based analog conditions, resulted in lowest mission risks, and resulted in equal or lower mission costs (by mass, energy and volume) than alternative mission with no in-situ water utilization.

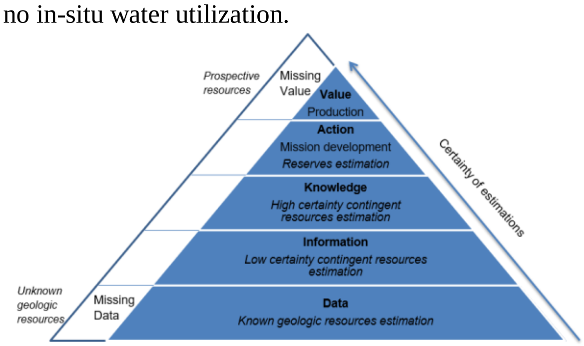

Figure 2. Hierarchy in resource estimations.

Feedstock-based resources: Feedstock-based approach to extraterrestrial water resources may be an optimal alternative to general resources-based approach due to many different sources of water that may be utilized, for which utilization of different methods and interfaces is needed. Each category of feedstock should be a subject of separate resources estimations.

Given this, we may separate water resources based on their origin feedstock into:

1) ***Refractory resources*** – feedstocks requiring high temperatures, chemical substrates and catalysts to extract oxygen out of oxygen-rich minerals to produce water in an exothermic reaction with hydrogen, or those requiring high temperatures to ex-

tract chemically bound water from hydrated minerals.

2) ***Volatile resources*** – feedstocks requiring phase change and/or phase stabilization mechanisms to produce water out of ice tables, or natural or artificial water reservoirs.

Reserves estimation: As it was mentioned before, reserves are those feedstocks for water production that are recoverable. ‘Mission-driven’ component of commercial recoverability is a major factor for reserves estimation, meaning that reserves may be estimated only if extraterrestrial water production mission is planned, developed or in progress in given extraterrestrial locations. This framework however would not define how a water utilization mission is properly designed and executed, and what factors are taken into account within it, but rather proposes that water reserves are evaluated only for missions in planning, development and execution itself. Those factors that a mission developer is taking into account – such as specific mission risks, regulations, planetary protection, mission goals, etc. – and ways of their evaluation may differ with various entities, however eventually if a mission developer puts forward a water utilization mission for execution it is assumed that commercial recoverability issues are fulfilled and thus reserves may be evaluated accordingly with a utilization mission capability.

Reserves estimations require the most data acquired in order to properly characterize them relatively to other general classes of resources (Figure 2.). That said, the higher certainty of water resources estimations is required, the more complex and certain a dataset has to be analysed. The value (physical resource) that is a result of a process of estimations has a certain size but it is necessary to note that value could be higher only if more data could be processed.

The main parameters to be used in resources estimations should be categorized as:

- *Geologic*, i.e. those related to feedstock concentrations in place, their properties and their spatial distribution, such as regolith porosity, depth of feedstock, thermal properties of regolith, mineral composition, etc.;
- *Technical*, i.e. those related to technical recoverability of this feedstock, such as range of effective extraction, excavation possibilities, etc.;
- *Mission/commercial*, i.e. those related to commercial recoverability of this feedstock, such as reusability of equipment, mobility, redundancy, regulatory capabilities, etc..

In order to evaluate resources, we could use standardized parameters, which draw analogy from terrestrial resources industry. That said, Water-in-place and Estimated Ultimate Recovery are herein volumetric estimations of water resources in an artificially formed reservoir, natural reservoir or ice table and should be used for estimations of **volatile resources**. The former (WIP) considers geological water resources currently in place that are in reach of existing state of the art technologies and takes into account purity and concentrations of ice (C_{vol}), its depth and reachable depth of a certain technology (z), area of potential resources recovery and volumetric factor that shows difference between volume of water in place and volume of water phase to be stored (B_w). The latter (EUR) downgrades water-in-place estimation by the recovery factor (RF), which may include all main parameters and in theory should be a number from 0 (no recovery) to 1 (maximum recovery).

Excavation and processing of **refractory resources** on the other hand could use an analogous type of resource evaluations, with water equivalent in-place estimations (WEIP) targeting recoverable volumes of minerals, which may be translated into useful water resources after stages of processing. Such estimations should be then downgraded using Recovery Factor that takes into account overall efficiency of processing (nominally resulting in ratio of recovered end-product water to maximum obtainable water from extractable minerals).

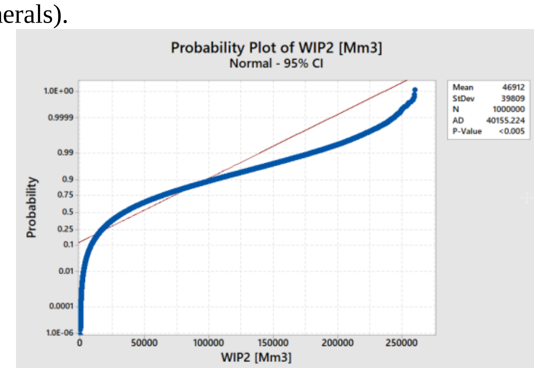

Figure 3. Estimation example of volatile contingent water resources in Martian Western Utopia Planitia (40ºN80ºE:50ºN90ºE) based on SHARAD data [3]. Probability refers to uncertainty of estimation.

References:

[1] SPE. (2001). Guidelines for the Evaluation of Petroleum Reserves and Resources. Richardson, TX: Society of Petroleum Engineers.

[2] Abbud-Madrid, A., Beaty, D., Boucher, D., Bussey, B., Davis, R., Gertsch, L., . . . Zbinden, E. (2016). Mars Water In-Situ Resource Utilization (ISRU) Planning (M-WIP) Study. California Institute of Technology: NASA.

[3] Stuurman, C. M., Osinski, G. R., Holt, J. W., Levy, J. S., Brothers, T. C., Kerrigan, M., & Campbell, B. A. (2016). SHARAD detection and characterization of subsurface water ice deposits in Utopia Planitia, Mars. Geophysical Research Letters 43, 9484-9491.