ADVANCING THE SCIENCE OF ISRU. L.S. Gertsch and K.A. Morris, Missouri University of Science and Technology, Rock Mechanics and Explosives Research Center, 1006 Kingshighway, Rolla, MO, USA, 65401, GertschL@mst.edu.

Introduction: The sustainable exploration of space requires *in situ* resource utilization (ISRU). Successful ISRU depends on a solid science foundation; consequently, the planetary science landscape must include comprehensive basic and applied science investigations in support of ISRU by 2050.

Major misconceptions exist regarding the extraction and use of mineral resources in space. One is the belief that mining is a straightforward development from basic principles and can be done on an *ad hoc* basis with little preparation. Another is underestimating the profound effects of the terrestrial environment, specifically a strong unidirectional gravity vector, a thick atmosphere, and abundant oxygen and water, on mineral production practice. These, and similar, perceptions impede the effective use of space for the long-term survival of humanity.

The foundation needed for successful ISRU is not being constructed at present, so for space exploration (and planetary science) to continue to advance, that will have to change before 2050. Science in support of ISRU is science in support of sustainable minerals production everywhere, including on Earth. The effort will begin here on Earth and continue in space.

Background: Agriculture and minerals production are the enablers of civilization. Geologic materials have been produced systematically from the Earth's surface by humans for 1-2 million years (Stiles, 1998; Paddayya *et al*., 2002; Vermeersch, 2002). Means of identifying, locating, accessing, extracting, and processing these materials have been constantly evolving as technology, deposit accessibility, and human desires have changed.

These methods are direct products of the science and engineering of the times in which they were developed. The drive to extract value from mineral resources has driven technological development since before the 16th century (Hoover and Hoover, 1912); one well-known example is the invention of the steam engine (Frenken and Nuvolari, 2004).

Fields of Inquiry: Minerals production and manufacturing have drawn from all the physical sciences throughout their histories: chemistry, physics, geology, materials science, and even astronomy (*e.g.*, Brownlee *et al*., 1984) as well as from many of the non-empirical sciences: mathematics, economics, statistics, computer science, decision and game theory, and others.

Adapting the current state of the practice in these industries to space will require hypothesis-driven research to advance fundamental understanding (basic), as well as to develop the required technological capabilities (applied). Applied science and engineering require the existence of a body of knowledge created by basic science.

Basic Sciences for ISRU: Specific fields of inquiry needed for producing minerals off the Earth, at least in the early stages, include economic geology, surface chemistry, electrostatics, electromagnetics, and many topics of low-gravity condensed-matter physics. Nearly all mineral production-related inquiry to date in these disciplines has been conducted on Earth's surface, with all the biases inherent in the environment that exists there. We have discovered fundamental processes that occur throughout the space and time of the universe, but many of the details (where the devil resides) are not completely clear, especially in unfamiliar environments.

Understanding the natural processes that concentrate desired materials to levels above their natural average has been the traditional focus of the discipline of economic geology. This field needs to expand beyond a focus on finding the next orebody. For example, the theory of mineral evolution (Hystad *et al*., 2016; Hazen *et al*., 2011) enables and requires a focus well beyond Earth. Eventually, economic geology must be linked robustly to the processes active during solar system formation and evolution.

Other examples abound. Separation of the target material (*e.g.*, water) from everything else with which it is found (*e.g.*, mercury, sulfur, abrasive silicate grains) in space will require utilization of different processes than presently employed on Earth. The formation and the fragmentation of rock and cohesive soil masses are affected by the presence of thick, nitrogen-rich atmosphere. Questions regarding the constitutive behavior of these materials in space are difficult to answer on Earth's surface.

Applied Sciences for ISRU: This field is at present the most active of those discussed here, as it contains the design and development of equipment for space science and exploration (Gruntman, 2004), as well as the development and adaptation of processes and equipment to achieve industrial goals in space.

Successfully adapting terrestrial mining practices and technologies for extra-terrestrial use requires that they be disaggregated, examined, modified, and reassembled to preserve their essential capabilities. Simple technological adaptation and substitution may serve for a short time, but ultimately new mining methods (mineral production architectures) must be developed. Doing so requires fundamental understanding of the geological, technological, and economic factors involved.

Some of the environmental aspects on which terrestrial mineral production relies interact in ways that are only partially understood. On Earth they are handled in a highly empirical, labor- and/or mass-intensive fashion that will not be feasible in space.

The opportunities provided by the fundamentally different environments of space bodies, however, offer opportunities for new ways to produce mineral resources to meet human goals. These must be developed and evaluated *in situ* where possible.

Other Sciences for ISRU: History, sociology, economics, and policy studies all have played, and continue to play, important roles in planning mineral production. These sciences will be even more important to the successful development of ISRU because failure, though common in mining (Ferguson *et al*., 2011), is an even more expensive luxury in space. The impact and scope of these sciences will expand again when mineral products from space begin to rival those from Earth in terms of cost and availability on Earth.

Recommendation: The most effective approach for addressing the science needs of ISRU would be a multi-disciplinary, multi-sponsor, multi-national institute devoted to the organization, planning, and performance of ISRU-focused science investigations.

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