Dynamic and Resilient Operations in the Arctic: Cold Regions and Space Research Symbiosis. Z. J. Zody[1]
[1]United States Army Corps of Engineers, Engineering Research and Development Center, Cold Regions Research and Engineering Laboratory (USACE-ERDC-CRREL). 72 Lyme Rd, Hanover, NH 03755, zachary.j.zody@erdc.dren.mil.

Introduction: There has long been a connection between the terrestrial polar sciences and space. Although different sets of constraints and scales of operation exist, there are similarities in science and engineering challenges faced when operating in remote and extreme environments.

Valuable resources in the Arctic, ranging from newly opening shipping lanes to deposits of rare earth elements, will likely result in the Arctic becoming an active frontier going forward [1]. This is reinvigorating (or renewing) a focus on science and technology (S&T) needs in the Arctic from a national security perspective [2]. The ability to operate dynamically and with resilience is critical to maintaining an effective and responsive presence in this domain.

S&T, as it pertains to the Arctic region, is occurring in parallel with renewed interest in space and in-situ resource utilization (ISRU). Similar to ensuring resiliency in operations in the Arctic and other extreme cold regions, successful extraterrestrial mining operations need to be responsive and able to sustain themselves. This parallel evolution of S&T needs presents significant opportunity for collaboration across disciplines to the benefit of both fields.

Here three axioms illustrate the opportunity for symbiotic developments between fields:

1) ISRU as a concept is a novel and useful paradigm for cold region operations.
2) Differences in priorities and constraints mean the domain expertise and institutional memory for similar problems is different, and this is useful.
3) Data-based modeling and discovery is outpacing our ability to make decisions based on fundamental physical knowledge, and lessons learned deploying in extreme environments on Earth have relevance in space.

The U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) executes on a research portfolio that demonstrates the axioms purported here. There are many existing efforts relevant to ISRU and opportunities for ISRU applications in polar regions. This presentation focuses on existing efforts relevant to ISRU and an initial look at possible ISRU paradigms in cold regions, Arctic, research.

Arctic and Space Research Symbiosis: Domain awareness and resilient operational capabilities are critical to success in the Arctic domain. While not as harsh as the lunar surface, conditions and terrain in the cryosphere can be very difficult and dangerous, which makes many of the capabilities similar to those needed in extraterrestrial mining operations.

Applying CRREL Research to Space. The range of research that goes into enabling these capabilities is broad and encompasses many different discplines, much like ISRU research. Table 1 shows examples of recent or ongoing projects at CRREL that have relevance to ISRU with selected output referenced.

Table 1: Example CRREL Projects Relevant to ISRU Operations

Project / research theme	*Description / relevance to ISRU*
Ice adhesion and chemical properties	Comparative climatology with lake sulfate minerals, Europa drill fiberoptic cable icing, general material and chemical behavior of water-ice [3].
Vehicle mobility in frozen and thawing terrain	Modeling, experimental testing, and field testing of different vehicles, tires, and treads in multiple frozen and thawing terrains [4], military vehicle autonomy [5]
Operational energy – microgrids, controls, batteries	Experimental testing of microgrid subsystems in cold conditions, prototype low-temperature battery technologies, cold specific control considerations.
Permafrost and cold regions hydrology	Permafrost-Mars analogs [6], study of permafrost tunnel in Alaska, civil engineering in permafrost areas.
Antarctic research	Rodwell [7], utilization of ice/snow in pavement runways [8], autonomous navigation and mapping of ice masses [9].

Much of this is enabled by unique research facilities and access. Figure 1 shows the permafrost tunnel in Fairbanks, Alaska (top) and the Frost Effects Research Facility (FERF) in Hanover, New Hampshire (bottom). The tunnel is a cave network giving in situ access to the permafrost and the FERF allows for large scale testing of frozen soil and pavement layers.

Figure 1: Permafrost Tunnel and FERF, utilized for internal and external studies

ISRU as a Concept in the Arctic. ISRU is not a paradigm in Arctic research, but many current practices and projects could be classified as ISRU. Like space, the Arctic is remote, harsh, and unforgiving. A sustained presence in the Arctic benefits greatly from ISRU, as overreliance on supply lines creates significant fragilities. Advancement of ISRU in the Arctic as a concept can be beneficial to sustainable and equitable development of the Arctic if local stakeholders are consulted. For space research, Arctic development may give economic cases for field testing of technology intended for extraterrestrial purposes. Table 2 shows some relevant themes for ISRU in the Arctic.

Table 2: Example Relevant ISRU Paradigms in the Arctic

Domain	*Example Technologies*
Energy	Hydrogen fuel production from in situ ice, geothermal, wave, wind, solar, gas hydrates.
Surface material utilization	Additive manufacturing using regolith, runways and roads from water-ice, induced permafrost as building support.
Natural engineering	Coastal erosion prevention (sea ice, permafrost), cold storage.
Data collection and monitoring	Leveraging in-situ data as a resource is crucial for awareness and decision making.

Data-based Modeling and Prediction in Cold Environments: In many cases in operations the ability to reliably act and make decisions outweighs a more intimate understanding of governing processes. While modern technology provides effective and incredible capabilities in this domain, the potential pitfalls associated with faulty decision making and analysis are greatly exasperated in extreme and hard to access environments like the Arctic and space. Additionally, data-based methods will outpace laboratory methods for understanding the fundamental physics of such unfamiliar environments. Knowledge transfer between disciplines, design of algorithms and architectures effective in multiple environments, and an understanding of operational tradeoffs will be critical.

Case Study: Artificial Intelligence for Prediction of Frost Depth Penetration: Trade-offs between decision making capability and accuracy can be illustrated via recent study of data based methods for prediction of frost depth penetration. This is a long studied problem for consideration into design of pavements for roads and runways. Our research shows recurrent neural network (RNN) modeling to be an effective and fast predictor relative to finite methods if given the appropriate input data and architecture. This is not without tradeoffs, as assumptions in physical parameters (e.g. such as soil type) can alter predictions in negative ways if not accounted for. RNNs will likely be widely utilized in Arctic and space research, as prior research indicates they are effective prediction tools for time series governed by complex spatiotemporal systems [10]. These are not the only types of models that will rapidly be adopted, and there is significant space for consideration of best practices and optimization of hybrid physics-data models.

References:

[1] National Strategy for the Arctic Region. (2022) *The White House.*

[2] DoD Arctic Strategy. (2019) *Office of the Under Secretary of Defense for Policy.*

[3] E. Asenath-Smith et al. (2022) *ERDC-CRREL, TR-22-3*

[4] S. Shoop et al. (2021) *ERDC-CRREL, MP-21-28*

[5] S. Vecherin et al. (2020) *ERDC-CRREL, MP-20-1*

[6] T. Douglas and M. Mellon (2021) *ERDC-CRREL, MP-21-13*

[7] S. Hoffman et al. (2020) *NASA/TP-20205011353*

[8] E. Asenath-Smith et al. (2019) *ERDC-CRREL, TR-19-2*

[9] S. Arcone et al. (2021) *ERDC-CRREL, MP-21-29*

[10] P. Vlachas et al. (2020) *Neural Networks, 126,* 191-217.

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