**Advancements in Crosscutting Capabilities to Enable Science & Exploration**. K. K. John[1], K. Somervill[1], N. Werkheiser[1], A. J. Sanchez[1], M. Ching[1], B. E. Troutman[2]. [1]NASA Space Technology Mission Directorate. [2]NASA Johnson Space Center.

**Introduction:** As NASA looks beyond Human Lunar Return and towards Foundational Exploration, there are several crosscutting capabilities necessary to achieve these goals. NASA's Space Technology Mission Directorate (STMD) has worked with internal and external stakeholders to make advancements in the areas of dust mitigation, extreme environments, extreme access, interoperability, and lunar simulants.

To enable and ultimately push the limits of lunar science, instrumentation will rely on development in these crosscutting capability areas.

**Dust Mitigation:** Any hardware going to the lunar surface needs a lunar dust mitigation strategy. STMD has spent the last several years putting out guidance to assist hardware owners. In 2021, STMD released version 1 of NASA-STD-1008, Classifications and Requirements for Testing Systems and Hardware to be Exposed to Dust in Planetary Environments [1]. The purpose of this NASA Technical Standard is to establish minimum requirements and provide effective guidance regarding methodologies and best practices for testing systems and hardware to be exposed to dust in dust laden and generating environments. The intent is to facilitate consistency and efficiency in testing space systems, subsystems, or components with operations and missions in dusty environments. In 2023, STMD released Lunar Dust Mitigation: A Guide and Reference (First Edition) [2]. STMD funded several testing efforts and advanced the Technology Readiness Level (TRL) of key dust mitigation technologies, including some that have been or will be demonstrated on the lunar surface. Through various programs in STMD, several small businesses and universities developed dust mitigation technologies that continue to show promise. The toolkit for dust mitigation continues to grow, however, this is still very much an area in need of innovation, ideas, and contributions.

NASA's Moon to Mars Programs in NASA's Exploration Systems Development Mission Directorate (ESDMD) have also advanced certain dust mitigation technologies. They have also performed tolerance testing of various subsystems and have funded the study of the behavior of dust in relevant environments (e.g. adhesion). Some of this data will be presented at the conference.

**Extreme Environments:** Each visit to the surface teaches us more about the many hazards associated with the Moon beyond the harsh regolith. To guide hardware owners, a new document has been released by NASA STMD and the NASA Engineering and Safety Center (NESC) called the Guidebook to Environmental Testing for Lunar Surface Technologies [3]. Other material is also being provided to educate the community on the effects on hardware and astronauts from various lunar environments including radiation, thermal, surface charging, micrometeroids, dust and regolith, ultraviolet, moonquakes, vacuum, illumination, reduced gravity, and terrain.

NASA's Moon to Mars Program is working to release guidance on induced environments between elements. The document for guidance on the natural environments is the Cross-Program Design Specification for Natural Environments (DSNE) [4].

**Extreme Access:** As we venture to new and challenging places with humans and robotic systems, the crosscutting capability area of extreme access becomes key. Considering needs of autonomy and hardware while navigating the rough and unknown terrain presents new challenges to be solved. Tapping into expertise across the Agency, industry, academia, and beyond, the community is coming together to find innovative solutions to access and operate in extreme locations.

**Interoperability:** As more partners enter the lunar economy, it is more important than ever to enable interoperability to ensure interfaces are accessible. Developing standards for lunar infrastructure today will enable collaboration tomorrow.

**Lunar Simulants:** At the center of most tests for lunar surface technologies are relevant lunar simulants. Selecting the appropriate simulant (e.g. geotechnical versus geochemical) is essential.

**What's Next?** Studies and analyses are underway to advance these crosscutting capability areas and to identify gaps in the existing guidance. To enable science and exploration, it is essential to work with the community to continuously learn about the environment such that we can operate for sustained periods of time. When we envision Lunar Infrastructure with Foundational Technologies such as Excavation & Construction, Surface Power, and In-Situ Resource Utilization, advancements in crosscutting capabilities will be needed.

[1] NASA-STD-1008, Classifications and Requirements for Testing Systems and Hardware to be Exposed to Dust in Planetary Environments. [2] NASA/TP-20220018746, Lunar Dust Mitigation: A Guide and Reference (First Edition) [3] Guidebook to Environmental Testing for Lunar Surface Technologies. [4] Cross-Program Design Specification for Natural Environments (DSNE).