NASA's EGS Program Technology Demonstrations and Risk Reduction for Sustainable Surface Operations

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***Abstract*—This paper discusses NASA's Exploration Ground Systems (EGS) Program Technology Infusion Strategy and the results from EGS technology demonstration projects, including Integrated Health Management capabilities for Condition Based and Predictive Maintenance, conservation of cryogenic fluids, and logistics management/commonality of maintenance equipment, tools, and consumables. The paper also discusses how technologies and capabilities implemented for ground systems (i.e. automated/autonomous operations and maintenance) can be leveraged to help reduce risk for sustainable lunar surface operations.**

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1. INTRODUCTION

As NASA works towards fulfilling the Artemis Program's goal of landing the first woman and first person of color on the Moon, using innovative technologies to explore more of the lunar surface, and establishing sustainable lunar exploration for the first time, NASA's Kennedy Space Center (KSC) Exploration Ground Systems (EGS) Program is at the forefront of developing the ground systems that will enable mission success. The existing ground infrastructure has been modified from the legacy manned spaceflight programs to support the new vehicle in its assembly, launch, and recovery. However, major challenges and cost drivers still exist in ground and launch processing operations. These can be addressed with technological innovations in capabilities, infrastructure, and processes to prepare, assemble, validate, execute, support, and maintain activities and operations, on Earth and on other planetary surfaces to address risk, decrease operations and maintenance costs, and increase safety and mission availability. Optimization of infrastructure (the facilities, resources, commodities, and support systems necessary to perform NASA missions) can decrease infrastructure complexity, reduce operations and maintenance (O&M) costs, increase safety and reliability, and enable multi-customer utilization to provide the best balance between required functionality, efficiency, flexibility and life-cycle costs. New technologies and concepts for assembly, integration, and launch can realize dramatic increases in responsiveness and mission availability. Technologies that enhance mission success and reduce long-term risk to NASA Programs can impact the ability to fulfill NASA's mission and provide low cost access to space and sustainable surface operations.

To help address these challenges, the EGS Program is committed to exploring the infusion of mature technologies that require little to no development and/or are being used throughout the industry. These technologies will be evaluated for reducing development, production and operations cost, while improving efficiency and safety. The EGS Technology Infusion Strategy involves assessment of EGS capability gaps to support Moon to Mars architectures and requirements with the potential to enhance mission success. From this assessment, EGS will identify associated technology investment strategies that will benefit not only NASA's ground systems engineering and operations but also commercial space industry multi-user customers. Along with identifying and incorporating mature State-Of-The-Art (SOA) technologies, EGS will actively solicit new technological innovations in capabilities, infrastructure, and processes through an annual Technology and Innovation Call to identify opportunities that could benefit the Program in the areas of system maintainability, cost and schedule risk

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reduction, increased mission availability, and safety enhancement. This strategy also leverages ground technologies and capabilities that can be extensible to the operations and maintenance of infrastructure and systems on other planetary surfaces.

2. Use of New Technology Within EGS

NASA programs rely heavily on highly skilled technical personnel to perform O&M activities. O&M cost reductions can be realized through technologies that increase launch flexibility and capacity. These include using smaller operations teams and new technologies to reduce recurring and non-recurring maintenance tasks, recovering waste streams, improving situational awareness, and more efficient logistical support. Safety improvements can be achieved by improving real-time situational awareness, reducing errors and rework, new developments in personal protective equipment, and improving ground safety tools.

The current limitations with the existing methodologies, infrastructure, and ground and launch support systems that execute NASA's spaceflight activities heavily influence and constrain operations concepts and mission designs. New technologies to transform how to prepare for, test, and execute NASA missions will mitigate long-term risk to NASA Programs, infuse innovation into capabilities across the Agency, and significantly lower the costs associated with fielding and maintaining the systems that enable NASA missions.

Within the EGS Program, "technology" is defined as the practical application of knowledge to create the capability to do something entirely new or in an entirely new way. When investments are made in a particular technology, it begins to mature--a process of testing and analysis that progressively reduces the programmatic risk of selecting that technology for an application and increases the readiness of that technology for use in a mission. Technology may be described in terms of the maturity within a scale of Technology Readiness Levels (TRL), as defined in Appendix E of NPR 7123.1 NASA Systems Engineering Processes and Requirements that reflect the extent to which the technology has been proven in a realistic situation [1].

Due to the unique operational nature of the program, EGS encourages the use of technologies with the highest possible TRL. It is understood that some technologies may not be as advanced as others, and will require further development and maturation to raise their readiness level prior to evaluation for implementation into the ground systems program. EGS will provide advocacy and program support for technology development investments through other NASA, Government, industry, and academic programs, in which the transition to ground operations and launch processing systems is the ultimate targeted implementation.

The majority of EGS technology insertion will occur at the intersection of TRL-6 (Engineering feasibility fully demonstrated in actual system application) and the successful completion of a subsystem 30 percent design review or subsystem Preliminary Design Review. However, with a program that is designed to evolve over time, technology development and implementation throughout the entire life of the Program is paramount for success and should not be limited to insertion only during the preliminary design phase. This strategy ensures technology investments are traceable to baselined requirements and mission needs.

3. EGS Technology Infusion Strategy

The EGS Technology Infusion Strategy is centered around the evaluation of mature capabilities for ground systems implementation. Mature capabilities can encompass a wide range of technologies, as long as they are at a TRL of 6 or higher, and include one of the following: SOA technologies utilized in the space industry or other industries, market available technologies, which can take the form of Commercial Off The Shelf (COTS) or modified-COTS products, and/or mature technologies that resulted from previous Center or Agency-level technology development activities.

EGS Technology Implementation Approach

The technology implementation approach includes the following three phases: demonstration, validation, and transition/implementation.

Demonstration—Technology advancements should be demonstrated in a parallel "shadow" mode, on a non-interference basis with critical processes or operations. Demonstration of new technology performance must be stable and repeatable, thereby demonstrating that the result is not spurious or transient. Modeling of the new technology demonstration must be consistent with the demonstrated result, thereby establishing that the behavior is thoroughly understood.

Validation—To validate the efficacy of new capabilities, technology demonstrations should result in overall performance that is at minimum equivalent to that of current systems and processes. Ideally, these demonstrations will result in an improved capability to augment current O&M tasks. This could entail the simplification of these tasks, a reduction in required manpower and/or operational costs, or an improvement in safety and/or reliability/availability. Testing should include verification that the technology capability meets the specified system requirements and specifications and also validation and acceptance that the new capability meets the operational needs of the Element/Stakeholder.

Transition/Implementation—Successfully demonstrated mature technologies at a proof-of-concept level will be transitioned to the specific EGS element design and operations stakeholders for larger-scale implementation into the EGS architecture (i.e. systems and processes).

4. EGS STRATEGIC TECHNOLOGY INITIATIVES

The EGS Technology Infusion Strategy is aligned with the Program Strategic Plan to strengthen the EGS Program by optimizing investments in technology to inform decisions and enable mission success. This is accomplished primarily through the management and execution of three strategic technology initiatives, including EGS Quick Response Tools and Capabilities, an annual EGS Technology and Innovation Call, and EGS Capability Gaps Assessment.

EGS Quick Response Tools and Capabilities address operations, element, and engineering concerns and challenges (i.e. to augment the closure of engineering and/or performance gaps).

The annual EGS Technology and Innovation Call actively solicits new technological innovations in capabilities, infrastructure, and processes that could benefit the Program in the areas of system maintainability, cost and schedule risk reduction, increased mission availability, and safety enhancement (i.e. to address EGS High Priority Capability Gaps for exploration missions).

The EGS Capability Gaps Assessment identifies and prioritizes capability gaps based on upgrades to Elements within EGS to support Moon to Mars architectures and requirements with the potential to enhance mission success, which informs the technology investment strategy to infuse the enabling technologies required (i.e. to augment the closure of technology and/or development gaps).

EGS Technology Management and Innovation Team

The EGS Technology Management and Innovation (TM&I) Team is responsible for executing the EGS Technology Infusion Strategy. The TM&I Team strives to manage and execute the three strategic technology initiatives, and has developed an overarching vision and mission, along with a core tenet that binds the three initiatives:

Vision—Lead innovation and technology infusion within EGS to reduce overall production and operations (P&O) costs.

Mission—Promote technology implementation and maturation that strategically aligns with the EGS Program.

Core Tenet—TM&I activities will not impact critical path operations of the EGS Program.

Quick Response Tools and Capabilities

The EGS Program is developing the necessary ground systems, infrastructure and operational approaches to process and launch the next generation of rockets and spacecraft in support of NASA's exploration objectives. The existing legacy ground infrastructure has been upgraded and modified through Design, Development, Test and Evaluation (DDT&E) and Verification and Validation (V&V) in the form of Subsystem, Element, and Multi-Element level testing to support the operational phase of a Program with robust, safe, and reliable systems. Sustaining engineering maintains the design of EGS facility systems and Ground Support Equipment (GSE) so that it fulfills its original design intent and is compatible with the intended operational use. When engineering issues arise, they can be addressed through design modifications, upgrades to the original performance capabilities through product improvement redesign for more cost-effective operations, and incidental modifications resulting from approved requirement changes.

The EGS Technology Infusion Strategy provides support and funding for Quick Response tools and capabilities (e.g. development of shop aids, special test equipment/fixtures, and prototypes) and technical discipline subject matter expertise for analysis of the status quo system performance versus current market SOA technologies. Subject Matter Experts (SMEs) provide experience, knowledge, insight, analyses, consultations, assessments, recommendations, and feedback to address operations, element, and engineering concerns and challenges. The program SMEs provide a broad knowledge base for tackling challenging technical problems and have access to collaborate with other Technical Discipline Team experts from across the Agency that can be called upon to participate in an assessment. The SMEs provide technical consistency through inputs to O&M Requirements and Specifications (OMRS), maintain cognizance of the current technology SOA across spaceflight and commercial industry sectors, and also typically have many years of ground and launch operations experience.

These technology infusion projects are coordinated with the appropriate EGS Stakeholders, including design, system, and operations engineers, and funded for up to one-year for proof-of-concept demonstration of mature capabilities and technologies and/or analysis and assessment to provide recommendations for operational considerations and design improvements.

Technology and Innovation Call

The EGS Program solicits innovative ideas from across the Agency in an annual Technology and Innovation Call relating to one or more of the following Strategic Thrust Areas of interest for the Program: reduction of schedule risk, decrease in O&M cost, improvement in reliability and mission availability, and improvement in safety and health. Ideas submission should also align with at least one of the EGS High Priority Capability Gaps areas identified for ground operations and launch systems processing supporting the Agency's exploration mission architectures. The EGS Capability Gaps assessment process, prioritization, and development of High Priority Capability Gaps is detailed in the following subsection.

A crowdsourcing platform is utilized to solicit ideas and collaboration from across the entire NASA community to solve challenges and competitions related to the Agency's mission. In this manner, EGS can leverage the immense background, diversity, and full breadth of expertise and talent

of all employees across the Agency to share knowledge and innovative ideas to address EGS Strategic Thrust Areas. This approach also helps garner more exposure to a broader audience than traditional networking approaches or relying only on local knowledge to solve problems and issues as they arise. This crowdsourcing technique therefore produces multiple solutions to the same problem for the Program to evaluate for the maximum benefit and return on investment.

The EGS Technology Infusion Strategy provides support and funding for the Call to enable the evaluation of mature capabilities for ground systems implementation. EGS wishes to find new ways of tackling engineering and operational challenges, even if new solutions leverage existing technologies. Furthermore, use of COTS products or modified-COTS is actively encouraged. The EGS Technology and Innovation Call provides investment for project ideas and concepts that have the highest potential to improve capabilities, augment and simplify O&M tasks, and reduce the high recurring costs associated with current ground and launch processing operations.

The EGS Technology and Innovation Call is set up as a multi-step challenge including Phase 1 concept submission and vetting, down-selection of concepts to submit invited proposals, and Phase 2 proposal vetting and project selection.

Phase 1 Concepts—includes an open solicitation for ideas via a NASA-hosted crowdsourcing website, collecting ideas and concepts throughout the solicitation period, closing the solicitation, initial pre-screening of concepts for compliance with the call requirements, and vetting of the Phase 1 concepts using technical subject matter experts. Concepts are evaluated based on benefit and relevance to the program, technical feasibility, and infusion into ground and launch systems. Phase 1 vetting determines which ideas have the most potential for continuing through the "multi-step" process.

Phase 2 Proposals—includes proposal development, vetting of the invited proposals, proposer presentations to the EGS Management Review Team, and final project selections. The proposals are meant to provide additional information from the initial concept submission, including a summary of the objective (nature and importance of the problem, performance issue or opportunity gap and the proposed solution), technology current SOA, applicable EGS areas that will be impacted, budget request, technical approach to solve the problem, return on investment strategy, and project schedule. Proposals are evaluated based on technical merit, return on investment, and potential for implementation into the EGS program. Phase 2 vetting determines which proposals have the highest potential for project success and benefit to the program. Final disposition and approval of project funding is provided by the EGS Program Control Board.

2019 Technology Call Results—The first annual EGS Technology Call, held in 2019, received fifty two (52) ideas and concepts from across Kennedy Space Center during the open solicitation period. Six projects were selected for project execution in Fiscal Year (FY) 2020, with extension into FY2021 due to the COVID pandemic.

2020 Technology and Innovation Call Results—The 2020 Technology and Innovation Call received forty nine (49) ideas and concepts from across the Agency during the open solicitation period. Eight projects were selected for project execution in FY2021.

2021 Technology and Innovation Call Results—The 2021 Technology and Innovation Call received twenty four (24) ideas and concepts from across the Agency during the open solicitation period. Three projects were selected for project execution in FY2022.

Lessons Learned—Each year, the EGS TM&I team looks for ways to improve the Technology and Innovation Call. The team explores different methods of advertisement for participation, refining the proposal vetting process, and communication with and assistance for participants to help maximize their potential for project consideration and selection. Additionally, the team gathers information on what projects were discontinued or did not generate the anticipated results and beneficial return on investment. The information is used to refine the proposal vetting process and have subsequent proposals address previously identified challenges for infusion into the EGS architecture. Implementation hurdles include Information Technology security, radio frequency or electromagnetic interference around flight hardware, maintaining rapidly evolving and advancing industry hardware and software, and integration into established work control procedures and systems for O&M tasks.

EGS evaluates proof of concept demonstrations of mature capabilities for ground systems infusion (≥ TRL 6) and ultimately system implementation. Concepts requiring Technology Development (< TRL 6) to demonstrate feasibility of the technology itself will be recommended for other technology proposal calls. Concepts are demonstrated and tested within an EGS system or process to evaluate successful and beneficial outcomes. The project results and performance data will be used by the program to make an informed decision regarding subsequent implementation of the capability into the element architecture.

Capability Gaps Assessment

The first two EGS strategic initiatives are framed around technology infusion projects, with quick response tools and capabilities to address engineering concerns or performance challenges, and the technology and innovation call to solicit ideas to reduce overall Production and Operations costs of the Program. The third EGS strategic initiative provides an assessment of the EGS Capability Gaps based on upgrades needed to support the exploration mission architectures, identification of key technologies that could potentially augment the closure of these gaps, and a path forward for prioritizing top technology investments that the Program

should be making to reduce risk, add capability, and meet the requirements of flight/ground project elements.

Assessment of NASA's exploration program mission architectures, manifests, Concept of Operations (ConOps), and requirements for ground systems and launch processing provided the basis for identifying the modifications and upgrades needed for EGS Elements to prepare, design, develop, and implement the necessary operational capabilities. The current EGS Capability Gaps Assessment is framed around the anticipated changes to EGS Element architectures to support specific exploration mission ConOps (i.e. the Artemis missions). Key technologies are identified from the 2020 NASA Technology Taxonomy for Ground, Test, and Surface Systems (TX-13) and previous 2015 NASA Technology Roadmap for Ground and Launch Systems (TA13) [2] [3]. These technologies are linked to the specific EGS Capability Gaps that stem from the anticipated Element upgrades and modifications and then leveraged to address closure of capability gaps that exist in the EGS architecture.

A requirements-driven approach is used to determine EGS's technology needs, gaps, and areas where expanded performance and capability can augment (simplify, reduce costs/manpower) current O&M tasks. This strategy ensures that EGS technology investments are traceable to baselined requirements, validates the mapping of technology investments to mission needs, and reduces technical and Programmatic risks. EGS will endorse and place high priority on those technology projects that are necessary to meet Program-level requirement objectives.

The EGS capability gaps are prioritized based on impact (the importance the capability may have towards achieving the goals of a mission or minimizing program risk), urgency (gap closure to meet specific decision and review dates), and trend (high when gap closure is not being addressed and low when the gap is expected to be reduced or even go away due to the efforts of others). The eight EGS High Priority Capability Gaps are listed below:

(1) Low-Loss, High-Efficiency Storage, Distribution, and Conservation of Cryogenic Fluids and Commodities through Passive, Active, and Vacuum Jacket Means

(2) Cryogenic/Non-Hazardous/Toxic Fluids Leak and Fire Detection and Mitigation

(3) Corrosion Prevention, Detection, and Mitigation

(4) Integrated Systems Health Management (ISHM)

(5) Precision Automated Alignment and Positioning Systems

(6) Advanced Ground Crew Work Instructions and Procedures Display

(7) Helium Usage Reduction Technologies

(8) Health and Safety Systems for Operations

The assessment will be reviewed periodically to ensure that the EGS High Priority Capability Gaps list is up-to-date and in line with the latest mission manifest and EGS Element upgrades.

5. Alignment with Agency Strategic Technology Initiatives

NASA engages in a variety of technology development activities to enable NASA missions by broadening knowledge of and capabilities in aeronautics, science, and space. To manage and communicate this extensive and diverse technology portfolio, NASA uses a technology taxonomy. This taxonomy identifies, organizes, and communicates technology areas relevant to advancing the Agency's mission. The taxonomy is a foundational element of NASA's technology management process. NASA's Mission Directorates reference the taxonomy to solicit proposals and to inform decisions on NASA's technology policy, prioritization, and strategic investments.

The 2020 NASA Technology Taxonomy provides a structure for articulating the technology development disciplines needed to enable future space missions and support commercial air travel. The 2020 revision is comprised of 17 distinct technical discipline based Taxonomies (TX) that provide a breakdown structure for each technology area. The taxonomy uses a three-level hierarchy for grouping and organizing technology types and includes an example technologies section that provides a non-exhaustive sample of relevant technologies [2].

Of particular relevance to EGS is the 2020 NASA Technology Taxonomy for Ground, Test, and Surface Systems (TX-13). This taxonomy includes technological innovations in capabilities, infrastructure, and processes to prepare, assemble, validate, execute, support, and maintain aeronautics and space activities and operations, on Earth and on other planetary surfaces to address risk, decrease O&M costs, and increase safety and mission availability. This taxonomy leverages ground technologies and capabilities that are extensible to the O&M of infrastructure and systems on other planetary surfaces. Several other NASA Technology Taxonomy areas with broad applicability for EGS include TX08 Sensors and Instruments, TX10 Autonomous Systems, TX11 Software, Modeling, Simulation, and Information Processing, TX12 Materials, Structures, Mechanical Systems, and Manufacturing, and TX16 Air Traffic Management and Range Tracking Systems.

6. EGS Technology Demonstration Project Results

This section describes several of the completed EGS technology infusion activities, detailing the project goals, results, and benefits for the EGS Program. Each technology innovation implemented into the EGS Program is evaluated on a case-by case basis for potential technology transfer and

public release of the scientific and technical information to maximize benefit for commercial applications and partnerships.

Aerogel Bulk-Fill Insulation System for Mobile Launcher (ML) Cryogenic Piping

Goal—Provide a new aerogel-based insulation technology option and simplified operational process for ~80 Mobile Launcher (ML) field cans as an alternative to traditional methods (e.g. wrapping with multilayer insulation and lengthy evacuation process to achieve high vacuum). The aerogel particles can be loaded in any pipe orientation to fill all the crevices and recesses within the field joint; the system is backfilled with carbon dioxide (CO2) at ambient pressure to provide partial vacuum inside the field can during cryogenic flow operations.

The ML Cryogenic Piping field joints were exposed to the elements for years uncovered, and many are contaminated with rainwater, dirt, frogs, etc. Due to the geometry and inhospitable placement of some of the joints, it is difficult to clean them sufficiently to ensure a good vacuum can be achieved and maintained once the cans are welded on. Backfilling them with aerogel and CO2 eliminates the need to pull vacuum at all, and substantially reduces the burden of cleaning them before welding on the cans.

Result—The KSC Cryogenics Test Laboratory (CTL) provided a demonstration for NASA and contractor operations and engineering personnel on how to install a bulk-fill aerogel insulation system for field cans (welded vacuum enclosures) connecting the vacuum-jacketed sections of Liquid Hydrogen (LH2) and Liquid Oxygen (LO2) piping on the ML. The contractor performed the installations after further collaborations with CTL to refine the procedure. This demonstration was completed in May 2019 and can be viewed at the following YouTube Link [4]: https://www.youtube.com/watch?v=yXE9kHyg6jI.

Custom Aerogel Filter for Space Launch System (SLS) Liquid Hydrogen Umbilical System

Goal—Design a custom "Heckle Filter" for the protection of the Hazardous Gas suction lines connected to the LH2 Umbilical Insulation Can as part of the SLS cryogenic propellant loading system.

Result—The KSC Cryogenics Test Laboratory built 3 three kits for use on the umbilical system, which included an insulation system with aerogel blanket and aerogel bulk-fill materials. The new particle-trapping type filter unit was successfully tested through a long-duration LH2 flow and will be implemented within the EGS architecture as a standard fixture on the umbilical system. This demonstration was completed in October 2019.

Launch Pad 39B LH2 Storage Tank Technologies

Goal—Implement two technology options in the construction of the new 1.4 Million gallon LH2 storage tank – glass bubbles insulation and an Integrated Refrigeration and Storage (IRAS) Heat Exchanger Assembly [5].

Result—Incorporation of glass bubbles insulation (in lieu of perlite power) to increase tank thermal performance with an estimated 46% reduction in boil-off losses; and an IRAS heat exchanger assembly inside the tank, which when paired in the future with an external refrigerator can enable new capabilities with enhanced operational flexibility. The installation of the heat exchanger assembly was completed in June 2020. The installation of the glass bubbles bulk-fill thermal insulation into the annular space between the inner and outer tank spheres commenced in December 2021.

Mid-Infrared Fire Detector False Alarm Field Limiting Cones

Goal—Develop a capability to mitigate the multiple occurrences of false alarms experienced by the new Pad Mid-Infrared (IR) fire detectors during testing from flare stack hydrogen flame reflections.

Result—The KSC Applied Physics Lab designed, tested, and fabricated cones for attachment to the Pad mid-IR (hydrogen) fire detectors, that did not alter the capability of the IR fire detectors to detect a flame, to limit their field of view. The cone attachments were installed on the new Pad Mid-IR fire detectors. During a flare stack field test many of the fire detectors still false alarmed indicating that the field limiting cones helped but did not solve the problem (false alarm issues still existed). NASA and contractor engineering and operations personnel worked with the vendor to modify the sensitivity and performance of the instrumentation with firmware updates and APL delivered more cones for all the Pad fire detectors.

A field pressure test was performed on the Launch Pad 39B Liquid Hydrogen storage tank to verify and validate that the field limiting cone attachments could mitigate/limit the Mid-IR fire detector false alarms. The Pad flare stack test resulted in one alarm and one high IR fault. NASA engineering stated that the problem was corrected and was pleased with the significant reduction provided by the field limiting cone attachments.

This capability will limit/mitigate the multiple occurrences of Mid-IR fire detector false alarms experienced during testing to improve reliability and performance for leak detection/monitoring during hazardous operations. The testing was completed and final documentation provided in February 2021 for approval to implement at the launch pad.

Acoustic Emission System

Goal—Use the KSC Applied Physics Laboratory (APL) Acoustic Emission System to locate the source of an unknown "popping" sound heard during rotation, accompanied by visible vibration, in the ML1 Crew Access Arm (CAA).

The KSC APL has a rapid response acoustic emission system Non-Destructive Evaluation (NDE) capability, which can

locate sound sources in large extended mechanical systems. The system locates noises caused by sudden changes in pressure, temperature, or load. This capability can reduce schedule time and limit the possibility of taking equipment out of service trying to locate/search for noise concerns and issues so that engineering teams can locate, analyze, and implement corrective action/design changes.

Acoustic Emission (AE) sensors detect the sound waves that are propagating through material and convert the disturbance into an electrical charge by the piezoelectric effect (electrical charge generated by a mechanical stress). By examining the timing of the initial peaks in the sound waves received by the AE sensors, a determination can be made to which sensor the origin of the sound is nearest to.

Result—Demonstration of the system was provided to NASA and contractor operations and engineering personnel and the system was delivered for field testing. The AE sensors were placed at key locations on the CAA support assembly to help triangulate the origin of the sound. The setup ruled out the ML structure as the source. The AE system performed as expected and was very effective at determining where the sound originated. This data was used to help the CAA team determine the path forward for Artemis-I and a possible redesign for Artemis-II and ML2. The testing was completed in April 2021.

Multiphysics Prediction Capability for Launch Environment (2019 EGS Technology Call Selection)

Goal—Develop a multi-physics prediction capability to accurately model the effects of the water-based Ignition Overpressure and Sound Suppression (IOP/SS) System in the prediction of the launch acoustic environment, to assess the risk of damage to the KSC ground systems and launch infrastructures. The previous design analysis for prediction of loads on the Mobile Launcher (ML), Tower, and Flame Deflector was based on high-fidelity multispecies fluid simulations of the launch ignition overpressure and acoustic pressure waves generated by the SLS Core Stage liquid engines, Solid Rocket Boosters, and air gases, but without including the effects of the water sound suppression system. This new capability will enable the Exploration Ground Systems to reduce schedule risks, operations and maintenance cost, and most importantly improve the safety of future launches.

Result—A collaborative team from the KSC and Ames Research Center utilized novel and robust high-order methods to develop diffuse interface multi-fluid models for solving the multicomponent and multiphase flow conditions, including water [6]. Technology maturation was systematically achieved through numerical method development for multiphase flow with water; implementation of the multiphase simulation capability into the Launch, Ascent, and Vehicle Aerodynamics (LAVA) CFD solver; verification and validation against canonical test problems from compressible multiphase literature; validation against flight and experiment data to test the solver for actual launch environments; and subsequent application of the full-scale simulation to SLS/EGS/ML2/Pad 39B launch environments.

The technology infusion of full-scale, high-order, time-accurate multiphase simulations to accurately predict the launch environment acoustic performance in the presence of rocket exhaust plumes and a transient water flow will help assess IOP/SS water flow rate performance requirements, reduce risk and add clarity during design of ground equipment or certification of launch vehicles, and significantly contribute to achievement of the NASA Mission. This new launch acoustics predictive capability will enable EGS, other NASA Programs, and commercial launch providers to increase mission safety, reduce design conservatism, and hence reduce operational cost of launch systems. Final project results were presented to Program Stakeholders in June 2021, including the next steps for application to the EGS/ML2/Pad 39B launch environments, with consensus that this was a very good return on the investment for EGS, NASA, and commercial space.

Integrated Health Management (IHM) Remote Monitoring of EGS Components

Current Maintenance Operations—Preventive maintenance is planned or scheduled maintenance performed at intervals specified by the manufacturer or maintenance personnel, even when machines or the systems are in complete functional mode, to prevent breakdowns or future issues. This approach leads to high maintenance costs due to performing unnecessary maintenance and risk of unintended damage during maintenance, as well as longer downtimes and unexpected failures on under-maintained systems. Corrective maintenance, often referred to as Reactive maintenance, is when maintenance/repair occurs after a malfunction is detected.

Improved Maintenance Operations—A Condition Based and Predictive Maintenance approach utilizes real-time sensor measurements to monitor and help determine the condition of system components and equipment, and when predetermined and preset conditions are reached, maintenance is scheduled. The sensor data (continuous observations) and analytics (health, status, trending) are utilized to provide early detection of potential future maintenance events (i.e. failures, breakdowns) and determine the most cost-effective time for maintenance.

Goal—Develop an implementation approach for a Proof of Concept capability to perform Condition based maintenance on demand, utilizing real-time sensor measurements to remotely monitor and determine the condition of EGS subsystem components and data analytics to provide early detection of potential future maintenance events (i.e. failures, breakdowns) and determine the most cost effective time for maintenance. The project leverages multi-user IHM capabilities developed for a flexible, scalable, reusable Architecture framework and analysis tools for anomaly detection, fault isolation, prognostics, and physics modeling with sensor data.

Result—The initial Phase I of the project was completed in September 2020, and included the following: selection of EGS subsystem components to demonstrate the technology; selection of instrumentation including sensors, thermocouples, tachometers, and data acquisition hardware; and the development of a plan for predictive analytics, data transmission, system configuration, data collection and storage requirements, design review process, documentation, and O&M support, all to be executed in Phase II of the project. The components selected for demonstration of this technology were two Launch Pad Environmental Control System blower/motor skids which provide conditioned air and are operationally used frequently and sufficient to gather information required to properly demonstrate the IHM technology. This project is currently ongoing and will complete the installation of instrumentation hardware at Launch Pad 39B to begin remote monitoring and data collection in Oct 2021.

Potential benefits of this project include increased asset operational availability (asset will operate satisfactorily when called upon), decreased downtime, optimized personnel and property safety (injury to personnel or damage to property due to catastrophic failure), reduced cost (repairs coordinated with scheduled maintenance), minimizing unnecessary testing and maintenance, and optimizing components usage and repair/replace during operations by predicting their Remaining Useful Life (RUL) and replacing them before they fail (End-of-Life).

Silicone Ablative Material Qualification (2019 EGS Technology Call Selection)

During launch of SLS, the Mobile Launcher (ML) will be subjected to extreme temperatures. In order to protect the structure and components of the ML, heat and blast protection coatings are utilized in accordance with KSC-SPEC-F-0006B Specification for Heat and Blast Protection Coating Materials and Application Methods [7]. These ablatives are effective top-coats for corrosion protection and also act as a sacrificial coating that is easily reapplied after launch. Most of the products from the current qualified products list (QPL) are commercially unavailable for purchase or no longer being manufactured. Silicone ablatives are used over many different areas, so it is crucial to have enough different types of ablatives available and applicable for different places. More qualified silicone ablative materials provide opportunity for use of commercially available and less expensive ablative options for the specific and appropriate launch pad applications and mitigates costly labor to replace and repair steel or coatings due to corrosion or heat related damaged.

Goal—Perform the necessary qualification testing of heat-resistant silicone ablative materials for use on steel launch structures and Ground Support Equipment, update the Qualified Products List, and modify the qualification procedure of KSC-SPEC-F-0006B. More options will be added on the QPL that are lower cost, have longer shelf life, and are more commercially available.

Qualification tests are required to characterize commercial off-the-shelf (COTS) coatings prior to use on the ML including adhesion (peel strength), hypergolic propellant compatibility, flexibility, rocket engine exhaust, and flammability.

Rocket Engine Exhaust Testing—Specification requirements for the rocket engine exhaust test are antiquated, since this test was performed on the Mobile Launcher Platform during launch of the Space Shuttle. NASA's Marshall Space Flight Center developed a new solid rocket motor simulation test method to qualify heat resistant coatings using a plasma torch and alumina particles to simulate Solid Rocket Motor plume impingement. This will allow for cheaper and quicker evaluation of products for qualification since the coatings would not have to be tested during a launch on the ML itself.

Flammability Testing—NASA's White Sands Test Facility performs the Upward Flame Propagation Test per NASA-STD-6001 Flammability, Offgassing, and Compatibility Requirements and Test Procedures to determine if a material, when exposed to a standard ignition source, will self-extinguish and not transfer burning debris, which can ignite adjacent materials [8]. The test specimen is mounted vertically in a test stand (with a paper sample mounted adjacent to it), ignited at the bottom by an ignition system and allowed to burn until it self-extinguishes. Burn length, linear distance of consumed specimen, and whether ignition of paper occurred by transfer of burning debris is recorded.

Result—Qualification Tests were completed for silicone ablative materials including adhesion (peel strength), rocket engine exhaust, and flammability. In addition to testing COTS coatings, a new sprayable ablative coating developed specifically for use on launch pads was provided to KSC for evaluation and qualification testing. Test report documentation was completed in October 2021 for updating the QPL and qualification procedure of KSC-SPEC-F-0006.

7. SUMMARY

EGS has established the strategic technical management approach and standardized process for technology infusion within the Program. Since the EGS Program is designed to evolve over time, cost saving initiatives, including investment in technology development and implementation (throughout the entire life of the Program) are paramount for sustainability and enabling mission success.

To dramatically transform future space operations, with significant improvement in ground operations and launch processing life-cycle costs, assessment of capability gaps and technology investment strategies will be needed in the following areas:

Infrastructure Optimization (of the facilities, resources, commodities, and support systems necessary to perform NASA missions)—to decrease infrastructure complexity, reduce operations and maintenance (O&M) costs, increase

safety and reliability, and enable multi-customer utilization to provide the best balance between required functionality, efficiency, flexibility and life-cycle costs.

Test and Qualification Environments—to validate the performance of flight vehicles, components, and ground/surface systems, including the methodologies and capabilities associated with test and qualification performance.

Assembly, Integration, and Launch—to dramatically increase responsiveness and mission availability of the facilities, equipment, processes, and skills that move components through the receiving and inspection process, assembly and test of subsystems, integration into the final launch configuration, and final launch sequence activities.

Mission Success Technologies—to collectively enhance mission success and reduce long-term risk to NASA Programs (e.g. ascertain and forecast system health and configuration and improve real-time situational awareness).

The EGS Technology Infusion Strategy involves the evaluation of mature capabilities (TRL 6) for ground systems implementation. The Technology Implementation Approach, utilizing three strategic initiatives (quick response tools and capabilities, Technology and Innovation Call, and capability gaps assessment), includes demonstrating technology advancements in parallel "shadow" mode with current processes/operations, validating equivalent performance and/or improved capability to augment (simplify, reduce costs/manpower) current O&M tasks, and implementing (successfully demonstrated) mature technologies into architecture (systems and processes).

The EGS Technology Demonstration project results highlighted in this paper showcase the impact these infusion activities are having for reducing overall P&O costs over the lifecycle of the Program. Technology infusion for supporting ground and launch systems processing of lunar and Mars mission architectures also provides risk reduction for lunar surface systems sustainability and supportability, including surface operations, cryogenic storage and transfer of commodities, inspection, maintenance and repair, redundancy, resilience, logistics spares, and reusability.

Strategically identifying human/automation roles and tasks and infusing automation and autonomy practices early in a system's lifecycle (using the ground systems program as an analog for surface operations) is essential for achieving the mission objectives for a sustainable human lunar presence, improving performance and mission effectiveness, reducing operations costs and reliance on humans to perform tasks, and accommodating ground communication delays. Standardization of interfaces, components, simulation and modeling tools, processes and procedures, and tools and repair kits can reduce costs while providing common frameworks for implementing autonomy across an entire exploration mission.

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BIOGRAPHIES



Philip J. Weber *received a B.S. in Mechanical Engineering from Montana State University in 1985. Mr. Weber has worked at NASA's Kennedy Space Center (KSC) in Florida for over 36 years and currently serves as the senior technical integration manager for NASA's Exploration Ground Systems (EGS) Program, responsible for technical decisions and approving the program technical baseline. The EGS program oversees the planning and development of required facilities, ground systems, test and verification strategy logistics, and prelaunch, launch and recovery operations for NASA's Space Launch System and Orion multi-purpose crew vehicle, as well as of the multi-user infrastructure to support commercial and other government spacecraft and launch providers. Mr. Weber serves as the Launch Project Engineer for Artemis I, in charge of the integration console in the prime firing room, leads the technical integration and problem resolution of all flight and ground systems during launch countdown, and provides the final technical "go" for the launch control team. Throughout his NASA career, he has contributed to major NASA programs, including Space Shuttle in the mechanical and project engineering divisions, Constellation as the senior technical integration manager and chief engineer for the Ground Operations Project Office, and Ground Systems Development and Operations. He was the operations team chair on the Crew Exploration Vehicle (Orion) Source Evaluation Board, launch integration chief engineer for the Orbital Space Plane, and led an interagency spaceport and range technology development initiative from KSC.*



Nancy P. Zeitlin *received a B.S. in Aeronautical Engineering from Embry Riddle Aeronautical University, Daytona Beach in 1989 and a M.B.A. from Florida Institute of Technology, Melbourne in 1995. Mrs. Zeitlin has worked at NASA's Kennedy Space Center in Florida for over 31 years and currently serves as the Technology Management and Innovation Lead for NASA's Exploration Ground Systems (EGS) Program, responsible for the infusion of technological solutions and innovative processes/practices aimed at mitigating EGS Program risks and closing gaps in NASA's ability to perform ground/surface operations to meet the exploration mission goals. Mrs. Zeitlin has substantial experience in technical program/project management with a strong engineering background in launch processing and ground operations (8 years in the Space Shuttle Program as a mechanical systems engineer and program integration manager) and 23 years of experience managing innovative technology development projects for multiple technical disciplines. Her technical strengths include solid rocket propulsion systems, ground and launch systems processing, propellant storage and transfer systems, thermal management systems, materials for life cycle optimization, and exploration habitation and life support systems.*



Breana P. Staton *received a B.S in Space Systems Engineering from Morehead State University (MSU), Morehead, Kentucky in 2021. Ms. Staton currently serves as a Technology Infusion Engineer for NASA's Exploration Ground Systems Program at the Kennedy Space Center in Florida. She also previously served in this role as a NASA Office of STEM Engagement (OSTEM) intern during the summer of 2020. In this role Breana supports ongoing technology innovation and infusion efforts within the EGS Program that target high priority capability gaps and reduce schedule risk, decrease operations and maintenance cost, improve reliability and mission availability, and improve safety and health. For her undergraduate studies at MSU, the Space Systems Engineering Program was a unique aerospace engineering program that focused exclusively on astronautical engineering - the engineering of spacecraft and space systems. Ms. Staton attended MSU as a first-generation college student holding the annual Tier 1 Merit Scholarship as well as an Excellence in Mathematics scholarship. During her time at the university, Breana also worked as a planetarium operator and as a founding member and recruitment chair for MSU's first chapter of the international club the Society for Women in Space Exploration (S.W.I.S.E), which promotes diversity and inclusion in STEM fields and provides community outreach.*



Ashish S. Patel *received a B.S. in Aeronautical Engineering and M.S. in Astronautical Engineering from Purdue University, West Lafayette, IN in 2017 and 2020, respectively. Mr. Patel currently serves as a Launch Site Integration Engineer for NASA's Exploration Ground Systems Program at the Kennedy Space Center in Florida. Ashish works with the Advanced Planning and Payload Integration team to manage requirements and the mission dependent equipment utilized in payload integration for the Artemis Program missions. He also supports EGS studies to resolve any potential future integration issues, as well as future planning studies for*

exploration and science missions. Previously, Mr. Patel worked with the EGS Technology Management and Innovation team to provide technical integration and management support for funded technology projects. He also actively participated in the development of the EGS technology infusion strategy and Strategic Technology Infusion Management Plan. Through his experiences at NASA, Mr. Patel has cultivated knowledge in Program strategic planning, project integration, technical resource management, and systems engineering.



Zachary M. Cameron *receieved a B.S. in Electronics Systems Engineering from Thomas Edison State University, New Jersey in 2021. Serving six years active duty for the United States Air Force at Joint Base McGuire Dix Lakehurst from 2015-2021 as a Pharmacy Supervisor, he reached the rank of Staff Sergeant. Mr. Cameron distinguished himself by leading projects outside of the pharmacy for the Medical Group's IT department, fitness, and vehicle programs. Mr. Cameron received the Air Force Acheievement Medal for leading pharmacy operations for Beyond the Horizon Humanitarian Mission in 2019 and the Air Force Commendation Medal for meritorious service in 2021. Currently interning with NASA through the DoD SkillBridge Program, he is supporting NASA's Exploration Ground Systems Program at the Kennedy Space Center as a Technology Infusion Engineer. Throughout the internship, Mr. Cameron has acquired knowledge in project integration, systems engineering, and technical resource management.*