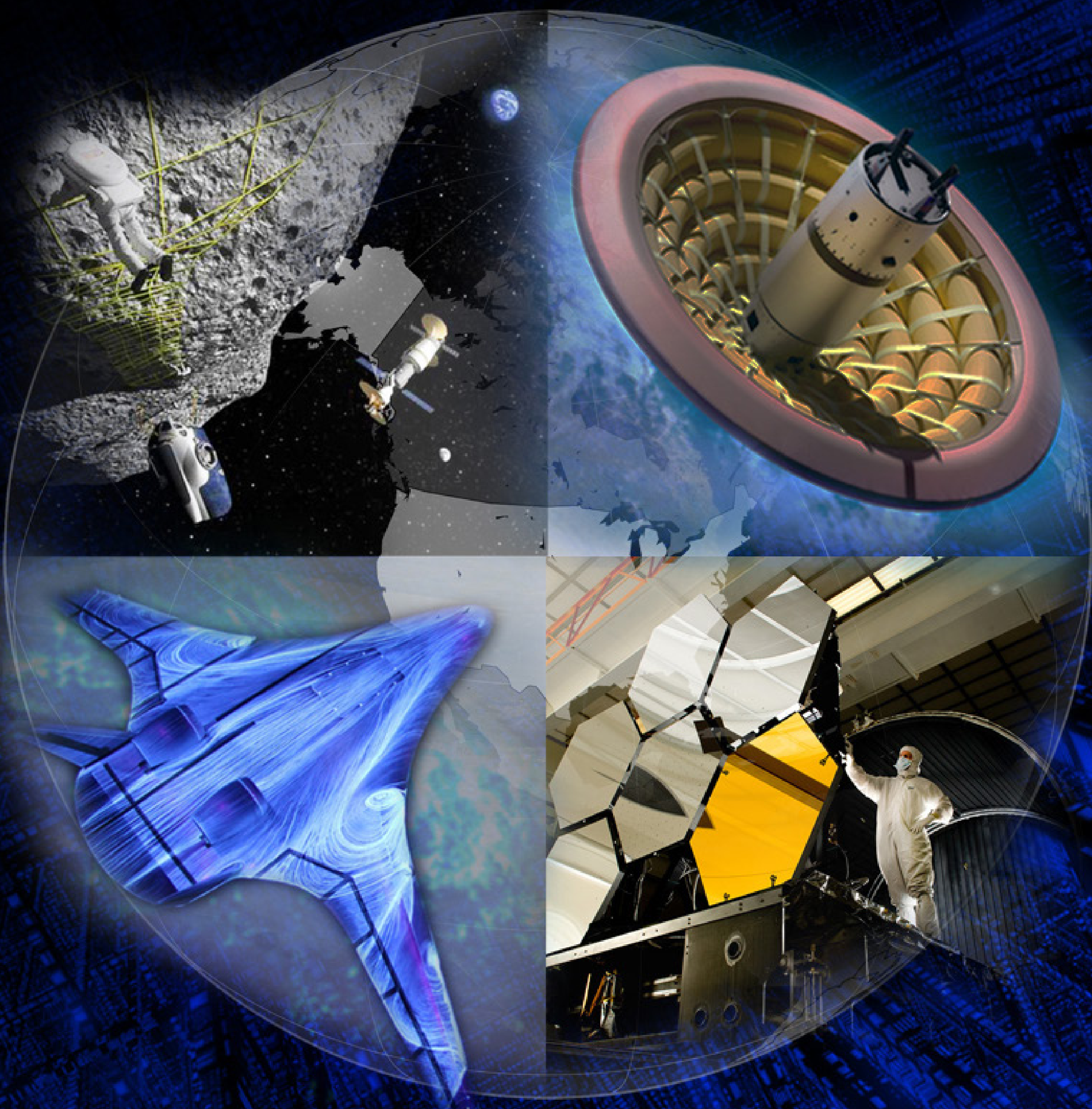
National Aeronautics and Space Administration

NASA Technology Roadmaps

TA 13: Ground and Launch Systems



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Foreword

NASA is leading the way with a balanced program of space exploration, aeronautics, and science research. Success in executing NASA's ambitious aeronautics activities and space missions requires solutions to difficult technical challenges that build on proven capabilities and require the development of new capabilities. These new capabilities arise from the development of novel cutting-edge technologies.

The promising new technology candidates that will help NASA achieve our extraordinary missions are identified in our Technology Roadmaps. The roadmaps are a set of documents that consider a wide range of needed technology candidates and development pathways for the next 20 years. The roadmaps are a foundational element of the Strategic Technology Investment Plan (STIP), an actionable plan that lays out the strategy for developing those technologies essential to the pursuit of NASA's mission and achievement of National goals. The STIP provides prioritization of the technology candidates within the roadmaps and guiding principles for technology investment. The recommendations provided by the National Research Council heavily influence NASA's technology prioritization.

NASA's technology investments are tracked and analyzed in TechPort, a web-based software system that serves as NASA's integrated technology data source and decision support tool. Together, the roadmaps, the STIP, and TechPort provide NASA the ability to manage the technology portfolio in a new way, aligning mission directorate technology investments to minimize duplication, and lower cost while providing critical capabilities that support missions, commercial industry, and longer-term National needs.

The 2015 NASA Technology Roadmaps are comprised of 16 sections: The Introduction, Crosscutting Technologies, and Index; and 15 distinct Technology Area (TA) roadmaps. Crosscutting technology areas, such as, but not limited to, avionics, autonomy, information technology, radiation, and space weather span across multiple sections. The introduction provides a description of the crosscutting technologies, and a list of the technology candidates in each section.

Table of Contents

Executive Summary

This is Technology Area (TA) 13: Ground and Launch Systems, one of the 16 sections of the 2015 NASA Technology Roadmaps. The Roadmaps are a set of documents that consider a wide range of needed technologies and development pathways for the next 20 years (2015-2035). The roadmaps focus on “applied research” and “development” activities.

Ground operations and maintenance are significant contributing factors to the high rate of success associated with NASA’s missions. NASA developments in TA 13 Ground and Launch Systems technology candidates enable new and more frequent exploration missions and reduce the costs associated with operations and maintenance through application of automation, conservation, and situational awareness tools. A small sampling of these technologies includes self-learning planning systems, self-healing coatings, self-repairing systems, additive manufacturing of spare parts, helium waste stream recovery and reuse, robotic assistants for assembly, unmanned aerial vehicles (UAVs) for range operations, networked weather stations, anti-icing cryogenic couplers, and counterfeit part countermeasure processes.

Goals

The primary goal of ground and launch system technologies is to provide the launch capability required to enable exploration while reducing operations and maintenance costs by 50%, and achieving a 50% reduction in ground safety mishaps, process escapes, and close calls. Operations and maintenance 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 (PPE), and improving ground safety tools.

Ground and launch systems are highly dependent upon flight hardware design and servicing requirements. To the greatest extent possible, technologies should be jointly developed with launch vehicle, spacecraft, and payload developers. Technology goals for ground and launch systems are divided into four categories (Level 2 TAs): Operational Life-Cycle, Environmental Protection and Green Technologies, Reliability and Maintainability, and Mission Success.

Table 1. Summary of Level 2 TAs

13.0 Ground and Launch Systems	Goals:	Provide the launch capability required to enable exploration while reducing operations and maintenance costs by 50%, and achieving a 50% reduction in ground safety mishaps, process escapes, and close calls.
13.1 Operational Life Cycle	Sub-Goals:	Reduce waste, commodity costs, operations crew size, and servicing times through conservation, automation and improved logistics.
13.2 Environmental Protection and Green Technologies	Sub-Goals:	Reduce maintenance costs and extend the life of launch infrastructure, reduce the environmental impact of legacy systems, and provide new green technologies to remediate potential environmental contamination.
13.3 Reliability and Maintainability	Sub-Goals:	Reduce operations and maintenance costs, improve ground safety, and improve the efficacy of maintenance tasks, by reducing human error opportunities.
13.4 Mission Success	Sub-Goals:	Reduce operations and maintenance costs and reduce ground safety mishaps, process escapes, and close calls.

Benefits

The clearest benefit from improved TA 13 technology candidates are reduced ground operations and maintenance costs to NASA programs at major launch sites, as well as the off-site test venues and command centers that support launch campaigns. The savings could be used for new and more frequent exploration missions. In addition to reduced costs, applied technologies that infuse automation, conservation, and ground operations team situational awareness will result in improvements across a broad range of activities. These improvements include reduced costs of propellants and other fluids; reduced logistics costs; reduced times required for ground processing and launch; reduced mission risk; reduced hazards exposure to personnel; reduced areas cleared for launches; increased flexibility, capacity, safety, and security for launch and range operations; reduced launch vehicle weights; reduced levels of flight hardware contamination; reduced levels of environmental contamination; reduced levels of carbon in the ecology; increased likelihood of mission success due to reduced levels of contamination on exploration flight hardware; and full protection from contamination from return of extraterrestrial samples to Earth.

In addition, many key technology candidates can help the U.S. achieve its national priorities in energy conservation; improving healthcare; protecting our environment and our national interests; improving and protecting our information, communication, and transportation infrastructure; and strengthening science, technology, engineering, and mathematics education. Examples of this are: clean energy storage; medical diagnostic devices; environmental clean-up from gas stations, dry cleaning operations, and chemical manufacturers; and studying climate changes on NASA field centers to develop models and approaches to mitigating carbon dioxide effects on natural vegetation.

Many of the areas proposed for development in TA 13 can have far-reaching commercial applications, which can ultimately lead to the development of new consumer products. Examples include: low-loss cryogenic systems for liquid natural gas or hydrogen-fueled vehicles; non-intrusive radio frequency identification wireless sensors for detecting water leaks within walls or room-to-room carbon monoxide interrogation systems for homeowners; smart, environmentally friendly, and self-healing corrosion-protective coatings and paints for automobiles, highway bridges, gas and liquid transmission pipelines, ships, and port infrastructure; smart, self-healing wire insulation for commercial and military aircraft; and custom-fitted, lighter-weight personal protective equipment (PPE).

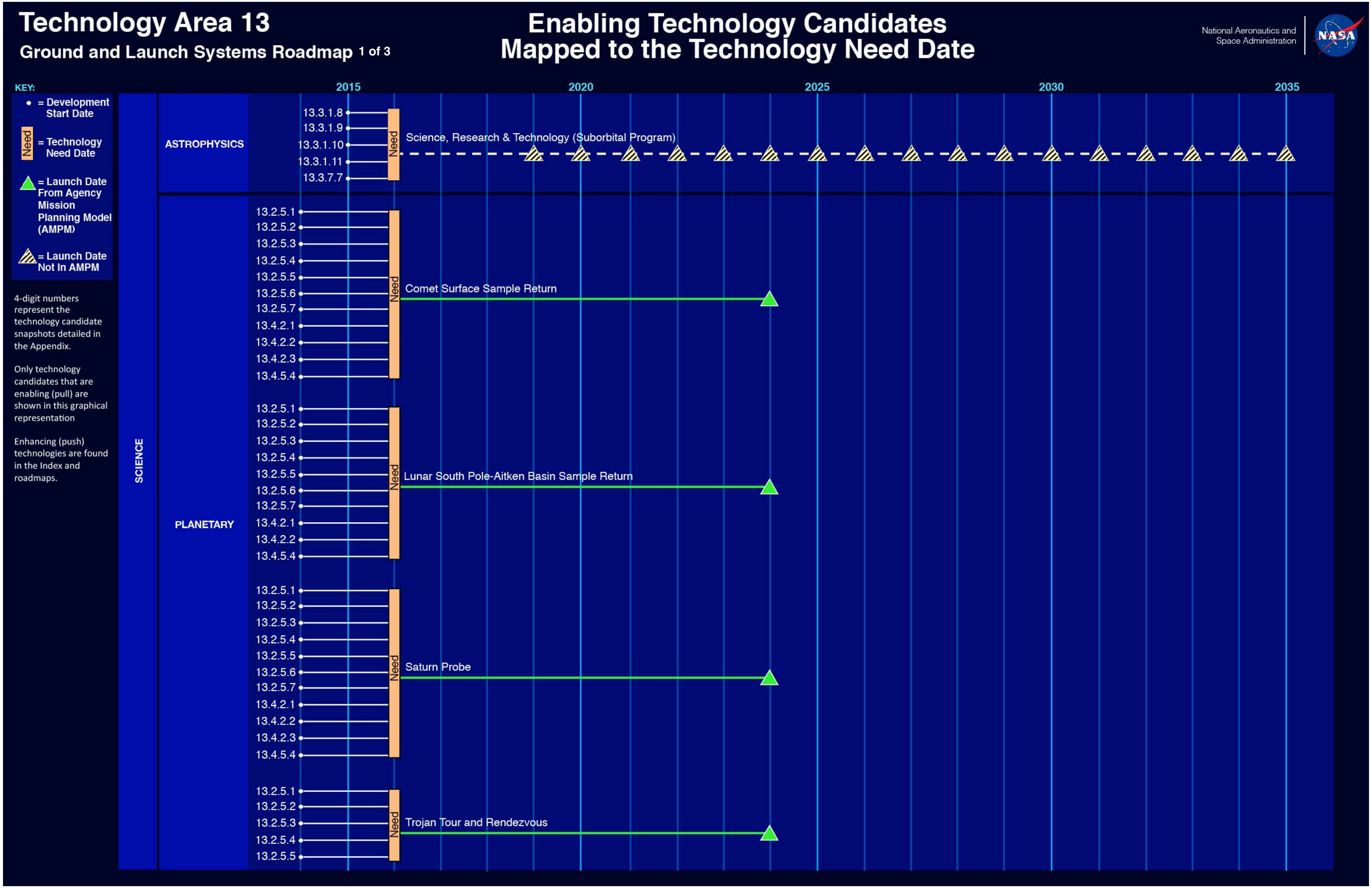

Figure 1. Technology Area Strategic Roadmap

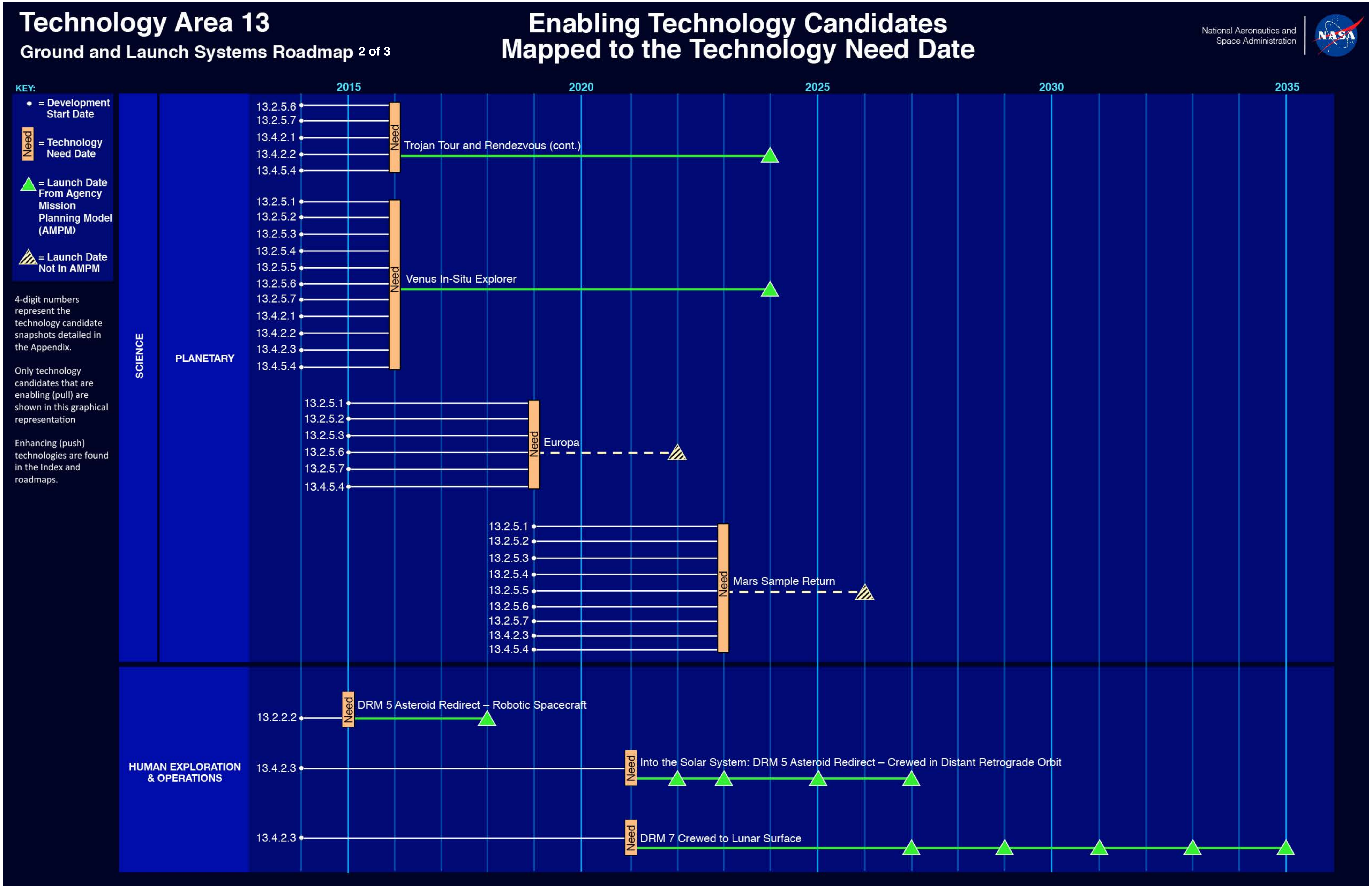

Figure 1. Technology Area Strategic Roadmap (Continued)

Technology Area 13
Ground and Launch Systems Roadmap 3 of 3

Enabling Technology Candidates Mapped to the Technology Need Date

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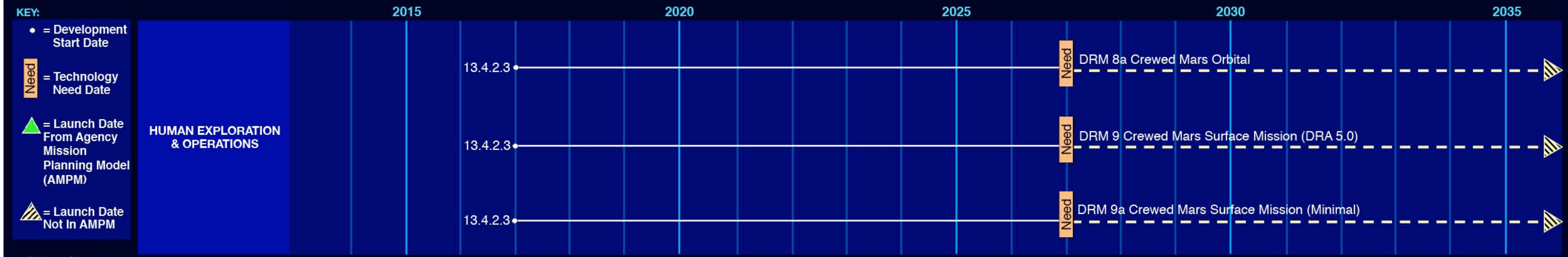


4-digit numbers represent the technology candidate snapshots detailed in the Appendix.

Only technology candidates that are enabling (pull) are shown in this graphical representation

Enhancing (push) technologies are found in the Index and roadmaps.

Figure 1. Technology Area Strategic Roadmap (Continued)

Introduction

The scope of this technology area includes technology candidates associated with Earth-based ground systems and launch. It includes instrumentation systems for wind tunnels; engine test stand support systems; ground systems for sounding rockets and high-altitude balloons; environmental remediation systems; ecological preservation systems; integration, checkout, and servicing systems for launch vehicles and spacecraft; logistical support systems; launch pad support systems; range support systems; weather prediction systems; launch control systems; communications, networking, timing, and telemetry systems; recovery support systems; and returned sample control systems.

Since some of these systems pose hazards to not only workers, but also to the public, extensive safety analysis will be needed to ensure that hazards are controlled and the risks are acceptable.

Figure 2 is the technology area breakdown structure (TABS) for ground and launch systems. As associated technological advancements are realized and new challenges, capabilities, and customers are identified, this roadmap will adapt accordingly.

Technology goals for TA 13 are divided into four categories (Level 2 TAs): Operational Life-Cycle, Environmental Protection and Green Technologies, Reliability and Maintainability, and Mission Success.

13.1 Operational Life Cycle

The NASA Systems Engineering Handbook (NASA/SP-2007-6105 Rev. 1) states that the life-cycle cost of a project or system shall include human systems integration and can be defined by its total cost of design, development, deployment, operation and maintenance, and disposal. According to the 2008 NASA Cost Estimating Handbook, costs in the operations and support phase of a program life cycle can be 50% or more of the total life-cycle cost, especially for long-duration programs. Therefore, improving technologies that address the operational phase is a very direct way to reduce costs and increase efficiencies, yielding opportunities for new and more frequent missions.

Technologies can be grouped into the following general categories:

- **13.1.1 On-Site Production, Storage, Distribution, and Conservation of Fluids:** Includes on-site, on-demand production of propellants, other fluids, and gases from the local environment; active and passive means for reducing cryogenic, toxic, and non-toxic propellant waste; recovery, reconditioning, and reuse of helium; and hyperspectral imaging for rapid identification of propellant leaks and fires.
- **13.1.2 Automated Alignment, Coupling, Assembly, and Transportation Systems:** Includes optical and non-optical systems for accurate and controlled alignment of hardware for element-to-element integration; and couplers that self-clean, quickly demate and remate, repel ice formation, self-verify their interfaces, and self-lock.
- **13.1.3 Autonomous Command and Control for Integrated Vehicle and Ground Systems:** Includes intelligent planning and scheduling systems; immersive training systems; multi-mission control rooms; automated fault detection and isolation systems; real-time data and voice loops connecting control rooms with remote operators; personal confirmation technology for system access; concurrent multi-user three-dimensional (3D) situational information environment control rooms; automatic generation of ground software and test algorithms; radio frequency identification (RFID) wireless instrumentation systems; integrated vehicle health management (IVHM) systems; advanced, deployable sensor networks for launch monitoring; temperature and pressure-sensitive paints; and sensors for ground test facilities such as Rayleigh scattering, particle image velocimetry (PIV), and advanced non-conventional Schlieren techniques.

TA 13 Ground and Launch Systems

13.1 Operational Life-Cycle

13.1.1 On-Site Production, Storage, Distribution, and Conservation of Fluids

13.1.2 Automated Alignment, Coupling, Assembly, and Transportation Systems

13.1.3 Autonomous Command and Control for Integrated Vehicle and Ground Systems

13.1.4 Logistics

13.2 Environmental Protection and Green Technologies

13.2.1 Corrosion Prevention, Detection, and Mitigation

13.2.2 Environmental Remediation and Site Restoration

13.2.3 Preservation of Natural Ecosystems

13.2.4 Alternate Energy Prototypes

13.2.5 Curatorial Facilities, Planetary Protection, and Clean Rooms

13.3 Reliability and Maintainability

13.3.1 Launch Infrastructure

13.3.2 Environment-Hardened Materials and Structures

13.3.3 On-Site Inspection and Anomaly Detection and Identification

13.3.4 Fault Isolation and Diagnostics

13.3.5 Prognostics

13.3.6 Repair, Mitigation, and Recovery Technologies

13.3.7 Communications, Networking, Timing, and Telemetry

13.3.8 Decision-Making Tools

13.4 Mission Success

13.4.1 Range Tracking, Surveillance, and Flight Safety Technologies

13.4.2 Landing and Recovery Systems and Components

13.4.3 Weather Prediction and Mitigation

13.4.4 Robotics and Telerobotics

13.4.5 Safety Systems

Figure 2. Technology Area Breakdown Structure for Ground and Launch Systems

NASA's technology area breakdown structure (TABS) is in wide use in technology organizations around the globe. Because of this, any sections that were previously in the structure have not been removed, although some new areas have been added. Within these roadmaps, there were some sections of the TABS with no identified technology candidates. This is either because no technologies were identified which coupled with NASA's mission needs (either push or pull) within the next 20 years, or because the technologies which were previously in this section are now being addressed elsewhere in the roadmaps. These sections are noted in gray above and are explained in more detail within the write-up for this roadmap.

- **13.1.4 Logistics:** Includes digital product lifecycle management, supply chain and supplier economic resilience modeling, additive manufacturing as replacement for Original Equipment Manufacturer (OEM) spare parts, light-fidelity data transmission and identification (LFID), and counterfeit part countermeasures.

13.2 Environmental Protection and Green Technologies

This area includes technologies that protect systems from environmental effects, remediate and restore the environment from effects of historical programs, preserve the environment, provide environmentally friendly cleaning techniques and energy sources, ensure protection of the destination environment, and ensure sample return containment.

Technologies can be grouped into the following general categories:

- **13.2.1 Corrosion Prevention, Detection, and Mitigation:** Includes self-healing, corrosion-protective coatings; corrosion degradation, resistant materials; self-healing launch structures; environmentally friendly corrosion preventative compounds; accurate service life prediction for materials and coatings; accurate service life prediction for legacy structures; and accelerated corrosion, material degradation.
- **13.2.2 Environmental Remediation and Site Restoration:** Includes environmental clean-up of impacted systems, environmentally friendly alternate cleaning techniques, and automated deep deployment sediment analysis tool.
- **13.2.3 Preservation of Natural Ecosystems:** Includes concrete aggregates, binders for reduced carbon emission; bio-char creation for soil improvement and carbon sequestration; and multispectral thermal, hyperspectral imaging to map evapotranspiration rates and detect disease.
- **13.2.4 Alternate Energy Prototypes:** Includes energy storage systems for backup spaceport power using flywheels, and carbon-based materials,
- **13.2.5 Curatorial Facilities, Planetary Protection, and Clean Rooms:** Includes molecular-based analysis of biological contamination, next-generation ground or in-flight spacecraft sterilization, scaled-up ethylene oxide chamber for spacecraft sterilization, extraterrestrial sample return containment, robotic assistants for spacecraft assembly, organically clean robotics for processing of extraterrestrial rocks, portable clean rooms, thermal and vacuum test facility capabilities for exoatmospheric hardware reentry testing, portable gravity offload system for ground check-out, and portable payload purge backup system.

13.3 Reliability and Maintainability

This area includes technologies that ensure the reliability and maintainability of systems for integration, checkout and servicing, and launch of launch vehicles, spacecraft, sounding rockets, high-altitude balloons, and ballistic and blended flight systems, as well as horizontal landing of reusable launch vehicles and spacecraft.

Technologies can be grouped into the following general categories:

- **13.3.1 Launch Infrastructure:** Includes intelligent crane controls, Helmholtz resonators for energy absorption of rocket engine exhaust, active acoustic source noise cancellation system, hydrogen pooling mitigation, variable-geometry flame trenches, mobile launch pad kit for nano-launchers, ground systems for sounding rockets and high-altitude balloons, and common interfaces for small launchers and payloads.
- **13.3.2 Environment-Hardened Materials and Structures:** Includes runway surface movement detection system, advanced overrun runway materials, more durable flame trench surface materials, and versatile materials and coatings for resisting electrostatic-charge build-up.

- **13.3.3 On-Site Inspection, Anomaly Detection, and Identification:** Includes integrated, multi-parameter ground-powered sensors for non-destructive evaluation (NDE) and continuous monitoring; and small robotic inspectors that can access confined or hard-to-reach spaces.
- **13.3.4 Fault Isolation and Diagnostics:** Includes embedded fault detection, isolation, and diagnosis; smart materials for leak detection; smart materials for damage detection; and non-traditional sensors for fault detection.
- **13.3.5 Prognostics:** Includes molecular agents for predictive health of fluid systems, built-in test (BIT) enhanced life forecasting, and models and approaches for remaining useful life prognostics.
- **13.3.6 Repair, Mitigation, and Recovery Technologies:** Includes self-repairing seals for fluid systems, self-repairing wiring insulation, small robots for repairs and mitigation actions, and field repair through predictive and reconfigurable components.
- **13.3.7 Communications, Networking, Timing, and Telemetry:** Includes on-demand, adaptive communications; advanced networking protocols for delay-tolerant networking; highly secure and access-controlled flexible data networking; free space optics for ground communication; model-based configuration of ground control systems; and mobile, modular, and non-persistent network and information services.
- **13.3.8 Decision-Making Tools:** Includes intelligent procedures for launch operations sequencing and system troubleshooting, and advanced ground crew work instructions or procedures.

13.4 Mission Success

This area includes technologies that ensure the success of a mission's launch, landing, and recovery as well as ensure the safety of the astronauts, ground crew, and general public.

Technologies can be grouped into the following general categories:

- **13.4.1 Range Tracking, Surveillance, and Flight Safety Technologies:** Includes space-based range surveillance assets, smart sonobuoys for range operations, unmanned aerial vehicles (UAVs) for range operations, onboard tracking for range operations, advanced telemetry systems for range operations, advanced antenna systems for range operations, steerable beam antennas for range operations, autonomous flight termination system, solid-state laser initiated ordnance for flight termination system, anti-jamming and anti-spoofing communications for range operations, and aerospace traffic control system.
- **13.4.2 Landing and Recovery Systems and Components:** Includes UAVs for ground payload recovery and UAVs for aerial recovery of reentry vehicles, first stage rockets, and suborbital rockets while under parachute or parafoil canopy.
- **13.4.3 Weather Prediction and Mitigation:** Includes weather information database for aerospace traffic management and multi-users; UAV-based meteorological sensors; three-dimensional (3D) real-time system to measure electric fields for lightning prediction; precision lightning-strike locator system; weather prediction models; and small, networked weather stations.
- **13.4.4 Robotics / Telerobotics:** see TA 4 Robotics and Autonomous Systems.
- **13.4.5 Safety Systems:** Includes virtual hazardous operations modeling; virtual range operations modeling; on-demand, custom-fitted, and lighter-weight personal protective equipment (PPE); ground safety tools for radioactive payload processing; and hazardous environment personnel monitoring system using visible light for data transmission.

TA 13.1: Operational Life Cycle

Current ground operations can be characterized as a highly successful paradigm of a very large team performing numerous tasks manually on an on-call basis. Umbilicals and couplers for flight element to flight element and flight element to ground system are connected manually with each copper path and fluid interface verified in a very time-consuming fashion. Flight elements are moved manually over the course of hours and aligned for mating with limited use of basic laser alignment tools. Command and control systems are largely custom-developed with console operators monitoring lists of parameters while automated monitoring and response is limited to critical systems exceeding their fault thresholds. Also, program logistics support has large warehouses of spare parts with fill rates based on determinations of mean time between failure (MTBF) and vendor lead times for order placing to delivery.

The primary goals of TA 13.1 technologies are to reduce operations and maintenance costs by 50% and attain a 50% reduction in ground safety mishaps, process escapes, and close calls. The 50% goals were derived as reasonable stretch goals based on projections of the collective positive impacts of technology developments in ground and launch systems. Cost reductions can be realized through smaller operations teams using technologies that reduce recurring maintenance and servicing tasks. Safety improvements can be realized through reduced errors and rework. To the greatest extent possible, TA 13.1 technologies should be jointly developed with launch vehicle, spacecraft, and payload developers.

Technologies are presented in the following four categories: On-Site Production, Storage, Distribution, and Conservation of Fluids; Automated Alignment, Coupling, Assembly, and Transportation Systems; Autonomous Command and Control for Integrated Vehicle and Ground Systems; and Logistics. The major benefit of achieving the goals in TA 13.1 is cost reduction. However, meeting these goals will also provide improved safety, reduced processing time, reduced mission risk, and increased launch and range capacity.

Sub-Goals

Goals of TA 13.1 Operational Life Cycle technologies focus on reduction in waste, commodity costs, operations crew size, and servicing times through conservation, automation, and improved logistics. Challenges specific to TA 13.1 include changing the paradigm by moving to small ground operations teams, autonomous operations where possible, and additive manufacture of parts that meet original equipment manufacturer (OEM) specifications.

Table 2. Summary of Level 13.1 Sub-Goals, Objectives, Challenges, and Benefits

Level 1		
13.0 Ground and Launch Systems	Goals:	Provide the launch capability required to enable exploration while reducing operations and maintenance costs by 50%, and achieving a 50% reduction in ground safety mishaps, process escapes, and close calls.
Level 2		
13.1 Operational Life Cycle	Sub-Goals:	Reduce waste, commodity costs, operations crew size, and servicing times through conservation, automation and improved logistics.

Table 2. Summary of Level 13.1 Sub-Goals, Objectives, Challenges, and Benefits - Continued

Level 3		
13.1.1 On-Site Production, Storage, Distribution, and Conservation of Fluids	Objectives:	Increase on-site production and improve storage, distribution, and conservation of fluids.
	Challenges:	Achieving zero boil off. Scaling up to a launch pad or engine test stand environment. Automated or autonomous cryo transfer and vehicle.
	Benefits:	Reduces on-site cost through on-site production, storage, distribution and conservation of fluids. Increases safety by reducing waste and hazard exposure to personnel. Increases likelihood of mission success.
13.1.2 Automated Alignment, Coupling, Assembly, and Transportation Systems	Objectives:	Develop automated approaches to transport, align, and connect flight elements to one another or to ground facilities.
	Challenges:	Significant modifications will need to be made to exterior roadways for applying sensors and reducing surface roughness. Ruggedizing optical and non-optical alignment systems for reliable use in launch pad or engine test stand environments. Integrate passive means through emerging materials with active means such as heaters and purges. Ensure highly reliable functionality of quick remate in the event of a pad abort scenario.
	Benefits:	Reduces ground operations times thus increasing capacity for launch and range operations. Reduces mission risk, levels of flight hardware contamination, and launch vehicle weights.
13.1.3 Autonomous Command and Control for Integrated Vehicle and Ground Systems	Objectives:	Automate complex and time critical decision making.
	Challenges:	Ensuring accuracy of the information being fed into the system and accuracy of the decisions made.
	Benefits:	Improves situational awareness resulting in safer, more efficient ground operations and reduced mission risk.
13.1.4 Logistics	Objectives:	Reduce the size of the logistics footprint, ensure timely availability of logistical support, ensure resilience of the supply chain across programs, and ensure integrity of component pedigrees.
	Challenges:	Integration and commonality across projects and programs, certification of components manufactured using emerging techniques, and unique and untamperable identification tags.
	Benefits:	Reduces logistics costs, mission risk and provides overall more efficient ground processing.

TA 13.1.1 On-Site Production, Storage, Distribution, and Conservation of Fluids

Today, production of propellants and other fluids is performed at remote locations and transported to the user using tanker trucks. Air separation plants generate oxygen and nitrogen. Natural gas processing is performed to produce helium and hydrogen. Approximately 6-10% of cryogen commodities are lost in transport due to boil-off. Approximately 0.03% of cryogens are lost per day due to boil-off losses while stored in large vacuum-jacketed storage tanks with Perlite radiation barriers. To support launch or engine test, cryogens are pressure-fed or pumped across long transfer lines that lose approximately 2.5 British thermal units per hour foot (BTU/hr-ft) and require hours of replenishment time to ensure the propellants are fully liquid. Large volumes of helium are used for purges at launch pads and engine test stands and no attempts are made to recover and reutilize. Monitoring operations for fluid leaks and fires use infrared cameras to image fires not visible by human eyes. Closed-circuit camera surveillance and mass spectrometer readouts detect increases in the percent of commodities within the total background atmosphere.

Technical Capability Objectives and Challenges

To supplement the fluids needs of current mission architectures, on-site production, storage, distribution, and conservation of fluids, technologies are focused on cryogenic, green, and toxic propellant systems. The scaling up of successful on-site, on-demand production of propellants, other fluids, and gases from the local environment could achieve a 50% reduction in commodity costs. Optimizing storage and transfer of cryogenic propellants could lead to low loss in storage, a 50% reduction in waste, and a 50% reduction in servicing times, although achieving zero boil-off will be a challenge. Optimizing distribution of green and toxic propellants could lead to 10% reduction in waste, although fluid couplers and fittings that bleed out bubbles internally without the loss of propellant need to be developed. Capturing large volumes of helium purge gas waste streams, purifying and recovering helium, and reusing helium at high pressure could result in a 40% reduction in waste; however, scaling up to a launch pad or engine test stand environment will be a challenge. Hyperspectral imaging of fluid leaks and fire detection or mitigation through real-time and accurate surveillance sensors and data processing could lead to a 50% improvement in the amount of time taken to identify spills or fires, but it will be necessary to conduct significant field testing in a relevant environment.

With the continued development of large solar electric propulsion (SEP) systems for NASA's science and human exploration missions, it is anticipated that new launch site infrastructure should include the production, storage, and transfer of xenon gas. Xenon is an inert and odorless gas that is heavier than helium. NASA has used it in ion-propulsion engines for flight demonstrations generating a thrust efficiency 10 times higher than the traditional chemical fueled rocket engines. The electric power for the ion-propulsion system can be provided by solar arrays or nuclear power systems. There may be commonalities with ongoing technological improvements for the helium systems described above. Specific technologies will be determined once the system level requirements for xenon propellant quantities are known.

Benefits of Technology

Alongside the overall safety and cost benefits discussed in the Executive Summary, on-site production, storage, distribution and conservation of fluids technologies will result in reduced costs for propellants and other fluids, reduced waste, reduced hazards exposure to personnel, and increased likelihood of mission success. Further, these technologies can be used by any future crewed or robotic mission beyond low Earth orbit (LEO), as well as commercially-provided crew or cargo access to LEO.

Table 3. TA 13.1.1 Technology Candidates - not in priority order

TA	Technology Name	Description
13.1.1.1	Production of Propellants and Other Fluids from Fresh or Salt Water	On-site, on-demand production of propellants, other fluids and gases from local environment (fresh or salt water) using emerging technologies that are mobile, modular, and more efficient.
13.1.1.2	Production of Propellants and Other Fluids from Biomass or Landfill	On-site, on-demand production of propellants, other fluids, and gases from local environment (biomass or landfill) using emerging technologies that are mobile, modular, and more efficient.
13.1.1.3	Low-Loss Storage of Cryogens Through Active Means	Enable zero loss storage and cryo below their normal boiling point to eliminate storage loss and improve flight mass density for improved rocket performance.
13.1.1.4	Higher-Efficiency Storage of Cryogens Through Passive Means	Reducing parasitic heat leak into storage vessels to reduce energy costs of maintaining them in a cryogenic state.
13.1.1.5	Higher-Efficiency Transfer of Cryogens Using Active Means	Autonomously deliver and load normal boiling point or sub-cooled propellant quality at the ground-to-vehicle interface to improve vehicle loading times and flight performance. Includes application of advanced cryo coolers and other active devices embedded throughout system.

Table 3. TA 13.1.1 Technology Candidates - not in priority order - Continued

TA	Technology Name	Description
13.1.1.6	Higher-Efficiency Transfer of Cryogens Using Passive or Vacuum Jacket Means	Deliver normal boiling point or sub-cooled propellant quality at the ground-to-vehicle interface to improve vehicle loading times and flight performance. Includes application of components having frictionless flowpaths and insulative capability embedded within components beyond having this capability in long piping runs.
13.1.1.7	Green Propellant Storage and Distribution	Optimize storage and distribution of green propellants for use on engine test stands and launch complexes. Reduce propellant waste through self-bleeding components.
13.1.1.8	Toxic Propellant Storage and Distribution	Optimize storage and distribution of toxic propellants for use on engine test stands and launch complexes. Reduce propellant waste through self-bleeding components.
13.1.1.9	Helium Waste Stream Recovery, Recondition, and Reuse	Capture large volumes of helium purge gas waste streams, purify and recover helium, and recycle to high-pressure storage. Production, storage, and transfer of xenon gas may have commonalities with the technological improvements for helium.
13.1.1.10	Hyperspectral Imaging for Cryogenic Fluids Leak, Fire Detection and Mitigation	Area surveillance to minimize number of sensors and maximize system coverage for cryogenic fluids and gases. Characterize spectral signature of propellant fires in launch pads and engine test stands through modeling and testing.
13.1.1.11	Hyperspectral Imaging for Non-Hazardous Fluids Leak, Fire Detection and Mitigation	Area surveillance capability to minimize number of sensors and maximize system coverage for green fluids and gases. Characterize spectral signature of propellant fires in launch pads and engine test stands through modeling and testing.
13.1.1.12	Hyperspectral Imaging for Toxic Fluids Leak, Fire Detection and Mitigation	Area surveillance capability to minimize number of sensors and maximize system coverage for hypergolic and toxic fluids and gases. Characterize spectral signature of propellant fires in launch pads and engine test stands through modeling and testing.

TA 13.1.2 Automated Alignment, Coupling, Assembly and Transportation Systems

Umbilical plates for past and current rockets use a combination of mechanical alignment pins, pivot feet, and collet systems where manual connections take hours. Vehicle stacking and positioning are based on manual observer-based motion and alignment with operations taking hours to perform. Mating of ground and flight interfaces of fluid connections in operational environments can introduce levels of contamination into flight hardware. To mitigate this, ground crews minimize open exposure and use wipes prior to connection. To mitigate ice formation, inert nitrogen or helium purges are used in cavities holding mated ground and flight couplers. Following coupler mate, electrical connectors are verified through conductivity checks that require control bus drops, circuitry activation, and console operator verification of feedback using break out boxes on downstream connectors. Fluid connectors require manual leak checks using a bubble soap solution, helium mass spectrometry devices, or console operator verification of feedback.

Technical Capability Objectives and Challenges

To support the integration needs of current mission architectures, it will be important to focus on automated approaches to transport, align, and connect flight elements to one another or to ground facilities. Systems that automatically transport and position vehicles, engines, and payloads in a controlled and precise manner can reduce ground operations times by 75% using embedded sensors or targets with onboard position determination.

Optical and non-optical alignment systems could reduce ground operations times by 75% by providing accurate and controlled alignment of hardware for element-to-element integration, such as payloads-to-vehicles, engines-to-test stands, vehicles-to-pads, and umbilical plates-to-vehicles. However, ruggedizing them for reliable use in launch pad or engine test stand environments will be a challenge.


Ground Transportation Systems

Couplers that self-clean and self-verify can reduce contamination in flight hardware by 50% and reduce ground operations times by 75%. The challenges will be to impact flight hardware designs and ruggedize them for reliable use in a launch pad or engine test stand environment. Self-locking lift off (T-0) couplers could reduce the weight of the flight-side umbilical plate by 50%, but the challenge will be to conduct substantial field demonstrations to verify reliability as well as to impact flight hardware design. Anti-icing cryogenic couplers could eliminate ice build-up on launch vehicles and the associated breakaway at launch with possible damage concerns. The challenge will be to integrate passive means through emerging materials with active means such as heaters and purges. Quick demate and remate T-0 couplers would allow for umbilical plates to demate prior to T-0, making launch safer by eliminating a failure mode and enabling better assured protection of ground systems. The challenge will be to ensure highly reliable functionality of quick remate in the event of a pad abort scenario.

Wireless power for interfacing elements is needed, in particular for ground and flight systems at the pad. Examples include vehicle T-0 interfaces, mobile launch platform (MLP)-pad interfaces, and payload servicing (e.g., battery charging).

The use of linear motors as a more reliable and sustainable technology for crawler transporter propulsion should be considered. Linear motors are needed as a low-maintenance, low-emission alternative to diesel-electric motors for the crawler and transporter.

As part of demonstrations in the laboratory environment, commonality with technologies maturing in-situ resource utilization (ISRU) should be considered. The laboratory test program should identify tests where common coupler component design or operational requirements can be tested.

Benefits of Technology

The major benefit of automated alignment, coupling, assembly, and transportation systems technologies is dramatically reduced ground operations times that would result in increased capacity for launch and range operations. Additionally, these technologies help reduce mission risk, reduce levels of flight hardware contamination, and reduce launch vehicle weights, all of which help to increase the likelihood of mission success for all types of government and commercial missions.

Table 4. TA 13.1.2 Technology Candidates - not in priority order

TA	Technology Name	Description
13.1.2.1	Optical Alignment Systems	Systems having lasers, cameras, and targets to align payloads to vehicles, engines to test stands, vehicles to pads, and umbilical plates to vehicles for integration of elements.
13.1.2.2	Non-Optical Alignment Systems	Systems having instrumentation and data processing to non-optically align payloads to vehicles, engines to test stands, vehicles to pads, and umbilical plates to vehicles for integration of elements.
13.1.2.3	Self-Cleaning Couplers	Ground and flight interfaces of fluid connections self-clean prior to mating in order to reduce the possibility of contamination entering flight hardware.
13.1.2.4	Quick Demate/Remate Liftoff (T-0) Couplers	Couplers that demate/remate prior to T-0.
13.1.2.5	Anti-Icing Cryogenic Couplers	Couplers that self de-ice , i.e., no ice (frozen air constituents) build up on ground-to-flight systems.

Table 4. TA 13.1.2 Technology Candidates - not in priority order - Continued

TA	Technology Name	Description
13.1.2.6	Self-Locking Liftoff (T-0) Couplers	Self-locking T-0 couplers on an umbilical plate that provides the overall locking capability of the ground plate to the flight plate.
13.1.2.7	Self-Verifying Coupler Interfaces	Following fluid, electrical ground, and flight coupler mates, leak checks are performed at the source using microdevices.
13.1.2.8	Precision, Automated Vehicle and Equipment Positioning Systems	Transports and positions vehicles, engines, and payloads where they need to go using embedded sensors, targets, and onboard position determination systems.
13.1.2.9	Wireless Power Interfaces for Ground Systems at Pad	Wireless Power Interfaces for ground systems at pad. Enables ground/flight systems at the pad. Examples include vehicle T-0 interfaces, MLP-pad interfaces, and payload servicing (e.g., battery charging).
13.1.2.10	Linear Motors as Motive Force for Crawler Transporters	Provide a low-maintenance, low-emission alternative to diesel-electric motors for the crawler/transporter.

TA 13.1.3 Autonomous Command and Control for Integrated Vehicle and Ground Systems

Scheduling systems are typically a commercially-available scheduling tool augmented by a specialized database. Command and control systems are largely custom-developed with console operators monitoring lists of parameters. Automated monitoring and response is limited to critical systems exceeding their fault thresholds. Reconfiguration to support different missions involve physical demating and remating of connectors to ensure data integrity, and developing different instrumentation processing algorithms. Training is largely classroom-based. Launch controller training is conducted at consoles using software simulation models of realistic launch countdown parameters with the training team introducing failures.

Technical Capability Objectives and Challenges

To support the control room needs of current mission architectures, autonomous command and control for integrated vehicle and ground systems must focus on command and control systems, ground operations scheduling, ground operations team training, and sensors and instrumentation. Intelligent planning and scheduling systems can optimize the use of resources during ground operations, from the execution of daily tasks to working within all constraints and requirements to plan longer-range activities, such as launch manifests and facility utilization. However, these systems must have accurate information on the availability and quantity of resources as inputs, with reliable integration and feedback loops from the shop floor.

Systems for immersive ground operations team virtual training can provide faster and more effective training for situational awareness, decision-making, and task knowledge, and proficiency that can result in safer and more efficient ground operations. However, the systems must be rapidly reconfigurable; allow for remote system operator support; accurately simulate environmental integration, such as ground operations facility and flight hardware; and have effective tactical situational awareness content.

Command and Control Systems

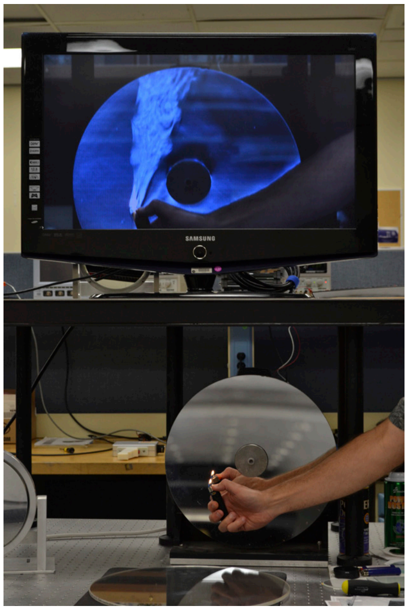
Multi-mission control centers can support ground operations for multiple types of spacecraft and launch vehicles within the same control room through commonality of data structures, data transmission formats, and intelligent decoding of data streams. The challenges include early coordination of common command and control formats across multiple users;

development of embedded metadata-based stream decoding; simple and secure co-hosting of multi-users independent of their mission criticality; and development of reusable, modular software for standard spacecraft and launch vehicle functions.

Automated and embedded fault detection, isolation, and recovery (FDIR) systems can monitor thousands of parameters using rules enabled through inference engines with very high reliability of detection, low probability of undetected faults, and low probability of detected non-faults. The challenges include successful and extensive embedding of FDIR into electronics, limitations of processor speeds, and extensive verification testing of the rules.

Systems that provide real-time control room data, voice, and commanding capability to remote users via their personal computer (PC), personal digital assistant (PDA), or wearable device allows situational support for contingency consultations and improved overall operator situational awareness. The challenges will be to ensure access security, effective voice recognition, and effective device data displays. Personal confirmation technologies can ensure only authorized system or facility access through easy verification of user identity, regardless of personal device used or location of individual within a facility. New information technology (IT) security tools and adaptive technologies are needed to identify, stop, and mitigate sophisticated cyber-attacks to corrupt or limit access to mission critical data. However, the system must have reliable voice identification; dependable, but not obtrusive location system installations; and alerts to system controllers for timely and effective action responses.

An interactive glass wall control room is a large video display wall providing a topic-specific backdrop with visually rich subject matter queues that can reduce the time required for team problem solving by 25%. The challenges are to make the data visible to multiple users and to ensure discrete user authorizations. Automatic generation of ground operations software and test algorithms allow for 100% reuse of human-interactive, automated test procedures and application code in downstream test environments and control centers. The challenge will be to develop early and well-integrated systems for analysis, production, and operations.



Advanced Leak Detection Using Schlieren Optics

A radio frequency identification (RFID)-enabled, sensing-based instrumentation system helps reduce instrumentation design complexity while reducing power requirements through passive sensing with interrogator range of hundreds of meters and 50-100 sensors. However, development is required to extend system performance to these values. Cross contamination of data from RFID-enabled sensors must be studied and tested under varied environmental conditions.

Standardized wireless data acquisition (DAQ) systems can provide a plug-and-play integration capability for multiple wireless data acquisition system deployments into a single telemetry stream, but further development is required to provide wireless integration of components from a variety of systems and integrated outputs.

Integrated vehicle health management (IVHM) can provide 25% reductions in overall operator time to identify, isolate, and correct anomalous conditions, as well as a 25% reduction in overall costs associated with performance of planned and unplanned maintenance activities. Challenges include establishing engineering processes for utilizing elements of IVHM in designs and enabling the development and use of intelligent devices that can be part of an IVHM knowledge architecture.

Advanced, deployable sensor networks for spacecraft, launch vehicle, and pad monitoring provide the ability to rapidly deploy networks of sensors to monitor the launch pad and integration environment without deploying or maintaining significant wiring infrastructures; the ability to rapidly configure sensors to monitor different conditions; and the ability to report collaboratively on their integrated observations. The challenge will be ensuring the reliability of sensor networks and their ability to support safety critical sensor readings.

Instrumentation systems for wind tunnels and other test facilities can provide wider ranges, more accurate measurements, and improved visualization through technologies such as Rayleigh scattering, particle image velocimetery (PIV), advanced non-conventional Schlieren techniques, advanced force measurement, and advanced high-speed photography or video. The challenges include ruggedizing and retrofitting existing facilities.

Temperature sensitive paint (TSP) and pressure sensitive paint (PSP) have the objectives of wider ranges and faster times to set up and perform tests. The primary challenge for TSP is providing less intrusive coatings with good survivability properties and for PSP the challenge is achieving actual pressure at the surface rather than a calculated estimate.

Benefits of Technology

Along with the overall benefits highlighted in the Executive Summary of this document, TA 13.1.3 Autonomous Command and Control for Integrated Vehicle and Ground Systems technologies infuse automation into the ground operations team, which improves situational awareness and results in safer, more efficient ground operations and reduced mission risk for all types of exploration missions.

Table 5. TA 13.1.3 Technology Candidates - not in priority order

TA	Technology Name	Description
13.1.3.1	Advanced Planning and Scheduling Systems	Planning and scheduling systems to optimize the use of resources during operations, from the execution of daily tasks to working within all constraints and requirements to plan longer-range activities such as launch manifests and facility utilization.
13.1.3.2	Self-Learning Planning Systems	Activity scheduling primarily determined through system learning (prior good answers, fuzzy logic, and dynamic rule creation).
13.1.3.3	Virtual Training	Provides immersive training that develops situational awareness and decision making within the assembly and integration, launch preparation, and launch countdown environments.
13.1.3.4	Multi-Mission Control Centers	Provides rapid reconfiguration of the Launch Control Center (LCC) to support a different launch vehicle.
13.1.3.5	Automated Fault Detection and Isolation Systems	Provides awareness and determination of faults in a complex system.
13.1.3.6	Real Time Data and Voice Loops to Personal Computer (PC) or Personal Digital Assistant (PDA)	Provides interactive communication for operators regardless of location.
13.1.3.7	Personal Confirmation Technology	Provides identity confirmation and location for operators.
13.1.3.8	Concurrent Multi-User Three-Dimensional (3D) Situational Information Environment	This is the next evolutionary step in reviewing situational data, systems, and operations in a 3D state-driven environment.
13.1.3.9	Automatic Generation of Ground Operations/ Launch Control Software and Test Algorithms	Human-interactive, automated test procedure and application code reuse in downstream test environments and control centers.
13.1.3.10	Radio Frequency Identification (RFID) Wireless Instrumentation Systems	Technology based on RFID-enabled sensing development at the device level and with the interrogator radio frequency (RF) system. An RFID-enabled sensing-based instrumentation system helps to reduce instrumentation design complexity while reducing power requirements through passive sensing.
13.1.3.11	Standardized Wireless Data Acquisition Systems	Development of wireless data acquisition systems that can integrate across vendors is a desired technology.

Table 5. TA 13.1.3 Technology Candidates - not in priority order - Continued

TA	Technology Name	Description
13.1.3.12	Integrated Ground and Flight Vehicle Health Management (IVHM)	Development in ground and flight hardware and software to provide integrated awareness of ground and vehicle system health and trending conditions.
13.1.3.13	Advanced, Deployable Sensor Networks for Spacecraft, Launch Vehicle, and Pad Monitoring	Architectures and standards to support the use of sensor networks, data fusion, wireless power and data transfer, integrated health management technologies, and optics for local, remote, portable and autonomous launch and range operations.
13.1.3.14	Rayleigh Scattering	Provides non-intrusive, seedless gas flow velocity, temperature, and density measurements in ground test facility environment.
13.1.3.15	Particle Image Velocimetry (PIV)	Provides two- or three- component velocity vectors in ground test facility environment.
13.1.3.16	Advanced Non-Conventional Schlieren Techniques	Provides 2D flow visualization of density gradients in ground test facility environment Provides seedless velocimetry by applying cross-correlation techniques to Schlieren image data in a ground test facility environment.
13.1.3.17	Temperature Sensitive Paint	Paint with temperature-sensitive properties that provide surface temperature measurements in ground test facility environment or flight.
13.1.3.18	Pressure Sensitive Paint	Paint with pressure-sensitive characteristics that provide surface pressure measurements in ground test facility environment.
13.1.3.19	Advanced Force Measurement System	Device that provides force measurements in ground test facility environment.
13.1.3.20	Advanced High-Speed Photography	Ruggedized equipment for high-speed imaging in ground test facility environment.

TA 13.1.4 Logistics

Program logistics support has large warehouses of spare parts with fill rates based on determinations of mean time between failures (MTBF) and vendor lead times for order placing to delivery. There is much reliance on the knowledge base of individual buyers and vendors. Responses to supply-chain disruptions are largely tactical down to the lower-tier suppliers as issues arise.

Technical Capability Objectives and Challenges

The primary objectives are to reduce the size of the logistics footprint, ensure timely availability of logistical support, ensure resilience of the supply chain across programs, and ensure integrity of component pedigrees. To support the multi-tiered supply chain needs of current mission architectures, the logistics discipline focuses on integrating electronic design packages for on-demand manufacturing, modeling supply chain resilience, secure manufacturing technologies, and emerging parts planning and location systems. Digital product lifecycle management can reduce logistics support costs by 25% through multi-directional integration of 3D computer aided design (CAD) drawings for expedient and repeatable manufacturing. The primary challenges are integration and commonality across projects and programs, certification of components manufactured using emerging techniques, and unique and untamperable identification tags.

Supply chain and supplier economic resilience modeling can reduce logistics support costs by 35% through early determination and objective measuring of risks associated with diminishing manufacturing sources and materials for proactive actions to resolve issues.

Additive manufacturing could be used as a replacement for OEM spare parts, reducing warehouse footprints by 50%. The challenges to this approach include extensive required development, evaluation, and deployment of efficient and flexible additive manufacturing technologies for different types of parts.

Light fidelity data transmission and identification (LFID) using high-intensity, solid-state light emitting diodes (LEDs) can reduce logistics management costs by 10% through secure wireless communication, continual real-time inventory update, and system health monitoring. The primary challenge is developing transmit identification tags and component sensors with data processing capabilities. Systems for counterfeit part countermeasures provide zero incursions of counterfeit components into the supply chain through an ability to positively identify certified parts using computer chips or nano-scale tags inside the genuine parts. The challenges are developing non-intrusive and unique transmitting identification tags and associated vendor deployment costs.

Lastly, ontological models to support planning operations can reduce program logistics costs by 5% through faster identification of problems and proactive actions to resolve issues. The primary challenge is applying this approach to the NASA-unique operational environment in regards to integration and commonality across flight hardware elements.

Benefits of Technology

The major benefits in TA 13.1.4 Logistics technologies are reduced logistics costs, reduced mission risk and overall more efficient ground processing.

Table 6. TA 13.1.4 Technology Candidates - not in priority order

TA	Technology Name	Description
13.1.4.1	Digital Product Lifecycle Management	Digital product lifecycle management, reliant on supply chain management and product data management content sourcing. The objective is a system that digitally connects all stakeholders within the extended supply chain processes and products of NASA with informational or bit-based representations of a physical or atom-based object, resulting in the harmonization of people, processes, practices, and technology.
13.1.4.2	Supply Chain and Supplier Economic Resilience Modeling	Next-generation hybrid supply chain management software application that uses programmatic and enterprise hardware demand information, as well as industry financial benchmarks, to efficiently and effectively forecast economic influences on the product and supplier viability throughout the program lifecycle.
13.1.4.3	Additive Manufacturing as Replacement for Original Equipment Manufacturer (OEM) Spare Parts	3D printing or additive manufacturing is a process of making a three-dimensional solid object of virtually any shape from a digital model. 3D printing is achieved using an additive process, where successive layers of material are laid down in different shapes. Technology creates an adaptive capability for supporting manufacture on-demand while reducing launch costs associated with the logistics footprint.
13.1.4.4	Light Fidelity Data Transmission and Identification	Secure wireless communication, continual real-time inventory update, and system health using high-intensity, solid-state light-emitting diodes (LEDs).
13.1.4.5	Counterfeit Part Countermeasures	Computer chips or nano-scale tags inside genuine parts for systems and other electronics that would identify compromised or counterfeit components and ensure zero incursions into the supply chain.

TA 13.2: Environmental Protection and Green Technologies

Launch pad and engine test stand infrastructures require extensive maintenance and repair due to corrosive environment exposure. Properties in and around launch pads and engine test stands have cases of environmental contamination by solvent and heavy metals used by legacy programs. Ecologies in and around NASA centers experience degrees of environmental impact that are due to increasing carbon levels. Banks of lead acid batteries and diesel generators are used to protect launch countdown and engine test stands during critical test timeframes. In addition, exploration flight hardware has some presence of biological contamination prior to their launch.

The primary goals of TA 13.2 technologies are to reduce operations and maintenance costs, improve safety, and ensure protection of the environment and ecosystem in and around launch facilities.

Technologies are presented in the following five categories: Corrosion Prevention, Detection, and Mitigation; Environmental Remediation and Site Restoration; Preservation of Natural Ecosystems; Alternate Energy Prototypes; and Curatorial Facilities, Planetary Protection, and Clean Rooms.

In addition to reduced costs, application of TA 13.2 technologies will result in reduced times required for ground processing and launch, reduced mission risk, reduced hazards exposure to personnel, increased capacity for launch and range operations, reduced levels of flight hardware contamination, reduced levels of environmental contamination, reduced levels of carbon in the ecology, and increased likelihood of mission success.

Sub-Goals

The primary goals of developments in TA 13.2 Environmental Protection and Green Technologies are to lower maintenance costs and extend the life of launch infrastructure, reduce the environmental impact of legacy systems, and provide new green technologies to remediate potential environmental contamination. The challenges associated with meeting these goals include scaling up emerging laboratory-scale technologies.

Table 7. Summary of Level 13.2 Sub-Goals, Objectives, Challenges, and Benefits

Level 1		
13.0 Ground and Launch Systems	Goals:	Provide the launch capability required to enable exploration while reducing operations and maintenance costs by 50%, and achieving a 50% reduction in ground safety mishaps, process escapes, and close calls.
Level 2		
13.2 Environmental Protection and Green Technologies	Sub-Goals:	Reduce maintenance costs and extend the life of launch infrastructure, reduce the environmental impact of legacy systems, and provide new green technologies to remediate potential environmental contamination.
Level 3		
13.2.1 Corrosion Prevention, Detection, and Mitigation	Objectives:	Extend the life of protected structure.
	Challenges:	Ensuring equivalent material properties on current materials, ensuring return on development, and lengthy test programs.
	Benefits:	Lowers maintenance costs, extends life of protected structures, and improves maintenance planning while decreasing environmental contamination.

Table 7. Summary of Level 13.2 Sub-Goals, Objectives, Challenges, and Benefits - Continued

Level 3		
13.2.2 Environmental Remediation and Site Restoration	Objectives:	Develop green solvents that match performance of fluorinated solvents.
	Challenges:	Develop an effective set of approaches for all possible contamination sites.
	Benefits:	More effective removal of contaminants from structures and the environment as well as reduced time to characterize contamination.
13.2.3 Preservation of Natural Ecosystems	Objectives:	Reduce carbon emissions and improving characterizations of environmental impacts.
	Challenges:	Understanding the mechanisms, scaling up for large-scale applications, and developing methods for targeted improvements in soil fertility. Integrating technologies to ensure full characterization capabilities for multispectral thermal, hyperspectral imaging.
	Benefits:	Reduces carbon emissions and improves soil fertility and other environmental elements within the ecosystem, resulting in improved environmental impact on health and safety.
13.2.4 Alternate Energy Prototypes	Objectives:	Develop alternative energy systems to supply emergency backup power for mission-critical systems as well as reduce operations and maintenance costs compared to current systems.
	Challenges:	Scale up efforts to industrial levels and assure reliability. Backup power system applications for spaceports is seen as feasible within this roadmap timeframe. Subsequent timeframes allow for primary power system applications that support a long-term vision of a self-sufficient spaceport.
	Benefits:	Significant reduction in operations and maintenance costs. Provides a sustainable exploration with less environmental impact. Solutions are transferrable to U.S. power grid applications.
13.2.5 Curatorial Facilities, Planetary Protection, and Clean Rooms	Objectives:	Meet the environmental protection needs of exploration destinations as well as the Earth.
	Challenges:	Sterilization methods that do not require high temperature. Integrating a complete solution meeting biosafety level (BSL)-4 requirements for a facility at a convenient location. Ensure system materials are compatible, ensure that robots don't damage flight hardware, and ensure that robotic observation capabilities are acceptable to quality control inspectors who will be relocated to outside of the clean room. Dexterity of robotic systems and materials compatibility.
	Benefits:	Reduces program costs through reduced ground operations crew size, schedules, and heat-resistant flight hardware components.

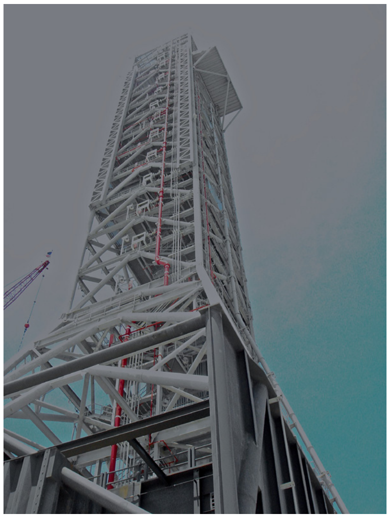
TA 13.2.1 Corrosion Prevention, Detection, and Mitigation

Launch pad and engine test stand infrastructure requires extensive maintenance and repair due to corrosive environment exposure. Corrosion prevention, detection, and mitigation efforts are underway. Corrosion-inhibiting coatings are being used widely with positive results. Preventative maintenance is performed on launch pad and engine test stand structures, including detailed periodic inspections and removal of corroded surfaces and reapplication of corrosion-inhibiting coatings or other paints. Demonstrations have been performed for emerging corrosion-resistant coatings and materials.

Corrosion Research

Technical Capability Objectives and Challenges

To support the infrastructure's need for corrosion protection on current mission architectures, methods like corrosion prevention, detection, and mitigation are focused on self-healing and corrosion-resistant coatings and materials. Self-healing corrosion protective coatings can lower maintenance costs and extend the life of protected structures, but laboratory-developed application methods must translate to field applications.



Self-Healing Launch Structures

Corrosion or degradation-resistant materials can lower maintenance costs and extend the life of a protected structure, but ensuring equivalent material properties on current materials will be a challenge. Self-healing launch structures with diagnostic, prognostic fault detection, and self-repair capabilities through triggered microcapsules and microparticles also can lower maintenance costs and extend the life of protected structures. The challenges are ensuring equivalent material properties on current materials, as well as ensuring return on development in these technologies.

Environmentally friendly corrosion-preventative compounds can be cost-effective temporary solutions when more permanent solutions are not an option, but laboratory-developed application methods must translate to field applications.

Accurate service life prediction for materials, coatings, and structures can provide improved maintenance planning. Accelerated corrosion or material degradation performed under controlled laboratory conditions would quantitatively correlate to long-term behavior observed in actual service environments. The challenge is that lengthy test programs are expected to validate the models for materials, coatings, and structures.

Benefits of Technology

The primary benefits of developments in TA 13.2.1 Corrosion Prevention, Detection, and Mitigation are lower maintenance costs, extended life of protected structures, and improved maintenance planning. Additionally, NASA can achieve significant cost savings for the space program and the nation as a whole by developing and implementing new corrosion prevention, detection, and mitigation technologies. The new technologies will provide environmentally friendly, corrosion-resistant and protective materials, coatings, and systems that last longer, require fewer reapplications, lower maintenance and inspection costs, reduce corrosion-related damage, structural failures, cost less to dispose of, and create less environmental contamination.

Table 8. TA 13.2.1 Technology Candidates - not in priority order

TA	Technology Name	Description
13.2.1.1	Self-Healing, Corrosion-Protective Coatings	Self-healing of mechanical damage in corrosion protection coatings.
13.2.1.2	Corrosion or Degradation Resistant Materials	Materials resistant to corrosion or degradation in launch pad environment, extraterrestrial environments, and human habitats.
13.2.1.3	Self-Healing Launch Structures	Provides diagnostic, prognostic fault detection and self-repair in launch pad environment.
13.2.1.4	Environmentally Friendly Corrosion Preventative Compounds	Provides cost-effective, temporary corrosion protection in launch environment.
13.2.1.5	Accurate Service Life Prediction Methods for Materials and Coatings	Methods that predict service life in launch environment.
13.2.1.6	Accurate Service Life Prediction Methods for Legacy Structures	Algorithm that forecasts structures' remaining service time.
13.2.1.7	Accelerated Corrosion or Material Degradation Methodology	Method that provides correlation between laboratory testing and launch environment.

TA 13.2.2 Environmental Remediation and Site Restoration

Properties in and around launch pads and engine test stands have cases of environmental contamination by solvents and heavy metal that were used by legacy programs, and contamination cleanup efforts are underway. Technologies and application methods are being developed that have demonstrated effective removal of heavy metals and other contaminants from water sources, soil, sediment, and structures. Current precision-cleaning practices use fluorinated solvents. Emerging environmentally friendly precision-cleaning technologies are being developed.

Environmental Clean Up

Technical Capability Objectives and Challenges

To support the environmental impact needs of current mission architectures, environmental remediation and site restoration are focused on clean-ups from legacy programs, green solvents, and tools for more effective application of remediation approaches. Environmental cleanup of impacted systems can provide more effective removal of heavy metal and other contaminates, such as polychlorinated biphenyl (PCB) from water sources, soil, sediment, and structures, but laboratory-developed application methods must translate to field applications. Environmentally friendly alternative cleaning techniques can match the performance of existing solvents. A challenge is replacing fluorinated solvents because few other solvents are able to clean fluorinated greases. An automated, deep-deployment sediment analysis tool can reduce the time required to characterize contamination in a particular location. It will be a challenge to develop an effective set of approaches for all possible contamination sites.

Sediment Analysis

Benefits of Technology

The benefits of Environmental Remediation and Site Restoration technologies include more effective removal of contaminants from structures and the environment, as well as reduced time to characterize contamination. These technologies ensure effective clean-up of launch sites and ensure environmental safety moving forward.

Table 9. TA 13.2.2 Technology Candidates - not in priority order

TA	Technology Name	Description
13.2.2.1	Environmental Cleanup of Impacted Systems	Cleanup technologies for impacted environmental systems.
13.2.2.2	Environmentally Friendly Alternative Cleaning Techniques	Environmentally friendly precision cleaning techniques for spacecraft and ground support equipment.
13.2.2.3	Automated Deep-Deployment Sediment Analysis Tool	Capability to adequately sample and analyze for contamination so that effective removal techniques can be employed.

TA 13.2.3 Preservation of Natural Ecosystems

Ecologies experience degrees of environmental impact due to increasing carbon levels. Efforts to characterize the effects are underway. Measures are being taken to have new facilities be more environmentally friendly. Government vehicle fleets are transitioning to have more fuel-efficient vehicles as well as electric vehicles. Technologies to sequester carbon are being developed.

Technical Capability Objectives and Challenges

Due to the fact that facilities associated with current mission architectures need to co-exist in their local ecosystems, preservation of natural ecosystems is focused on reducing carbon emissions and improving characterizations of environmental impacts.

Renewable-energy technologies (e.g., solar) and energy conservation technologies (i.e., low-emission windows, high-resistance insulation, etc.) are needed to retrofit current facilities and be incorporated in new construction. Development of these technologies will decrease carbon emissions, enabling preservation of natural ecosystems.

Concrete aggregates or binders for reduced carbon emission can provide alternatives to Portland-based cements that have similar curing times, strength, and cost to produce. Providing technologies that can reduce the cost to produce is the primary challenge.

Bio-char creation for soil improvement and carbon sequestration can use organic waste streams and biomass from exotic plant removal programs to improve soil fertility and sequester carbon for hundreds of years. The primary challenges include understanding the mechanisms, scaling up for large-scale applications, and developing methods for targeted improvements in soil fertility.

Multispectral thermal, hyperspectral imaging that can map evapotranspiration rates and detect disease has the objective of reducing required characterizations from weeks to days. The primary challenge is integrating technologies to ensure full characterization capabilities.

Benefits of Technology

The primary benefit of technologies for the Preservation of Natural Ecosystems is reducing carbon emissions and improving soil fertility and other environmental elements within the ecosystem, resulting in improved environmental impact on health and safety for the Nation and ensuring a sustainable space program.

Table 10. TA 13.2.3 Technology Candidates - not in priority order

TA	Technology Name	Description
13.2.3.1	Concrete Aggregates or Binders for Reduced Carbon Emission	Cement, concrete, and other composite construction materials that contain synthetic calcium and magnesium carbonate to reduce carbon emissions.
13.2.3.2	Bio-Char Creation for Soil Improvement and Carbon Sequestration	Charcoal from large-scale plant removal programs and pyrolysis of organic waste to improve soil quality and sequester carbon.
13.2.3.3	Multispectral Thermal, Hyperspectral Imaging to Map Evapotranspiration Rates and Detect Disease	Multispectral thermal, hyperspectral imaging to map evapotranspiration rates to correlate with disease detection and prediction.

TA 13.2.4 Alternate Energy Prototypes

Banks of lead acid batteries and diesel generators are used to protect launch countdown and engine test stands during critical test timeframes. The use of proton exchange membrane (PEM) fuel cells as alternative back-up power supplies has been successfully implemented. This section includes energy storage systems for backup power using flywheels and carbon-based materials. Alternate energy prototypes also include renewable power generation systems that is, systems that do not require fossil fuels.

Technical Capability Objectives and Challenges

To support the need for ground facilities associated with current mission architectures to have emergency backup power for mission-critical systems, alternate energy prototypes focus on systems that can satisfy this need as well as reduce operations and maintenance costs compared to current systems. Backup power system applications for spaceports are seen as feasible within this roadmap timeframe. Subsequent timeframes allow for primary power system applications that support a long-term vision of a self-sufficient spaceport.

Energy storage for backup power using flywheels provides the required large energy storage capability by transforming waste energy into stored rotational energy that can be transformed back to usable energy when needed, with reduced operations and maintenance costs. The challenge will be to scale up these efforts to industrial levels and to assure reliability.

Energy storage for backup power using carbon-based materials provides the required large energy storage capabilities that are robust, lightweight, flexible, and thin. The system can have rapid charging ability and high power density with reduced operations and maintenance costs. The challenge will be the significant scaling-up effort to industrial levels and assuring reliability.

Energy generation technologies are needed, particularly renewable power generation systems that do not burn fossil fuels.

Benefits of Technology

The major benefit of alternate energy prototypes technologies is a significant reduction in operations and maintenance costs. Using renewable backup power systems also provides a sustainable exploration with less environmental impact. In addition, successful solutions are very transferrable to U.S. power grid applications.

Table 11. TA 13.2.4 Technology Candidates - not in priority order

TA	Technology Name	Description
13.2.4.1	Energy Storage for Backup Power Using Flywheels	Large energy storage to serve as back-up power to safety-critical spaceport and test stand operations.
13.2.4.2	Energy Storage for Backup Power Using Carbon-Based Materials	Large energy storage using carbon-based materials to serve as back-up power to safety-critical spaceport and test stand operations with minimal lifecycle maintenance costs and hazardous waste stream production.

TA 13.2.5 Curatorial Facilities, Planetary Protection and Clean Rooms

Exploration flight hardware has some presence of biological contamination prior to its launch. This occurs despite best efforts to perform sterilization at the component level using methods like vapor phase hydrogen peroxide and isopropyl alcohol; and at the entire spacecraft level using dry heat microbial reduction. Personnel attired in clean room garments conduct assembly and test operations in clean rooms.

Technical Capability Objectives and Challenges

To support the environmental protection needs of exploration destinations with respect to samples returned, Curatorial Facilities, Planetary Protection, and Clean Room efforts focus on sterilization techniques, containment of returned samples, robotic assistants, and facility capabilities for extreme environment testing.

Increased sensitivity and faster sample results are needed for molecular-based analysis of biological contamination that provide the ability to assess biological contaminants present in spaceflight hardware either prior to launch or after return from space. The primary challenges are impacts to facilities, equipment, and training associated with moving beyond the standard culture-based assay.

Next-generation ground or in-flight sterilization that provides non-destructive penetrating and surface treatments can be more effective and less complex than current methods. The primary challenge is to develop methods that do not require high temperatures. Developing a scaled-up ethylene oxide or vapor hydrogen peroxide chamber for entire spacecraft sterilization will first require a benchmarking study of similar capabilities with respect to the ability to meet NASA requirements for flight hardware cleanliness levels and ground operations safety. The scaled-up chamber, which would be used after spacecraft assembly and prior to encapsulation and launch, can be more effective and reduce costs associated with requiring heat-resistant flight hardware components. The primary challenge is mitigating the associated ground personnel hazards.

Extraterrestrial sample-return containment can provide 100% isolation and containment facility capabilities, practices, and procedures for handling extraterrestrial samples returned from space. The primary challenges are developing and integrating a complete solution meeting biosafety level (BSL)-4 requirements for a facility at a convenient location, including containers for ultra-safe sample transport.

Using robotic assistants to assemble life detection payloads or spacecraft can reduce the number of personnel required to enter clean rooms by 50%. The primary challenges are to ensure system materials are compatible, ensure that robots do not damage flight hardware, and ensure that robotic observation capabilities are acceptable to quality control inspectors who will be relocated to outside of the clean room.

Organically clean robotics for processing of extraterrestrial rocks can provide robotic handling and minimize losses during the subdivision of rocks. The primary challenges are dexterity of robotic systems and materials compatibility.

Portable cleanrooms that are utilized wherever a payload resides, including vendor facilities, integration areas, and post-flight facilities can reduce launch and landing site costs associated with cleanroom capabilities by 50%.

Thermal and vacuum test facility capabilities for reentry testing exoatmospheric hardware can provide a reasonable approximation of the surface temperature, pressure, and the gas enthalpy found in a high-velocity, supersonic flow experienced by a vehicle on Earth atmospheric entry after returning from Mars, Venus, near Earth asteroid (NEA), or other destination. The challenges will be to trade off retrofitting existing facilities against building new ones, as well as minimizing power requirements. See TA 13.4.2 for more information.

Portable gravity offload systems that support dynamic testing of space surface system structures in lunar, martian, or other microgravity environment can be transportable, support up to three interactive test articles, and support test article weights of up to 500 pounds. The challenge will be portability and ensuring no coupled loads across test articles.

Benefits of Technology

The benefits of Curatorial Facilities, Planetary Protection, and Clean Rooms include reducing NASA program costs through reduced ground operations crew size, schedules, and heat-resistant flight hardware components. The savings could be used for new and more frequent exploration missions.

Table 12. TA 13.2.5 Technology Candidates - not in priority order

TA	Technology Name	Description
13.2.5.1	Molecular-Based Analysis of Biological Contamination	Qualitatively assessing or quantitatively measuring the presence or amount of biological contaminant.
13.2.5.2	Next Generation Ground and/or In-Flight Sterilization	Non-destructive penetrating and surface treatments (e.g., hard radiation, gas-phase chemicals, cold plasma, electron-beam irradiation, ion desorption or ablation, chemical and abrasive cleaning).
13.2.5.3	Scaled-Up Ethylene Oxide Chamber for Spacecraft Sterilization	A scaled-up ethylene oxide chamber could accommodate entire spacecraft for post-assembly full sterilization.
13.2.5.4	Extraterrestrial Sample Return Containment	Biosafety practices and procedures for handling of extraterrestrial sample return.
13.2.5.5	Robotic Assistants for Spacecraft Assembly	Robotic assistants for assembly of life detection payloads or spacecraft in an enclosed, clean environment.
13.2.5.6	Organically Clean Robotics for Processing of Extraterrestrial Rocks	Robotic systems that are organically clean for processing extraterrestrial rocks.
13.2.5.7	Portable Clean Rooms	Cleanroom that can be utilized wherever a payload resides (at vendor, integration area, post-flight) in lieu of brick-and-mortar cleanrooms at launch site.
13.2.5.8	Portable Gravity Offload System for Ground Checkout	Portable gravity offloading of space surface system structures for dynamic testing in lunar, Martian, or other microgravity environments.

TA 13.3: Reliability and Maintainability

Reduction in operations and maintenance costs, improved ground safety, and improved efficacy of maintenance tasks can be achieved through development of Reliability and Maintainability technologies. Safety improvements can be realized by developing technologies that reduce errors and rework. To the greatest extent possible, TA 13.3 technologies should be jointly developed with launch vehicle, spacecraft, and payload developers. Technologies are presented in the following eight categories: Launch infrastructure; Environment-Hardened Materials and Structures; On-site Inspection and Anomaly Detection and Identification; Fault Isolation and Diagnostics; Prognostics; Repair, Mitigation, and Recovery Technologies; Communications, Networking, Timing and Telemetry; and Decision-Making Tools. Development of these technologies will result in decreased ground operations and maintenance costs; reduced times required for ground processing and launch; reduced mission risk; increased capacity for launch and range operations; and increased likelihood of mission success.

Sub-Goals

The primary goals of these technologies are to reduce operations and maintenance costs, improve ground safety, and improve the efficacy of maintenance tasks by reducing human error opportunities. The challenges to be overcome for these technologies include scaling up and ruggedizing emerging laboratory-scale technologies for application in launch pad or engine test stand environments, minimizing up-front development costs, and extensively verifying and validating automated inspections.

Table 13. Summary of Level 13.3 Sub-Goals, Objectives, Challenges, and Benefits

Level 1		
13.0 Ground and Launch Systems	Goals:	Provide the launch capability required to enable exploration while reducing operations and maintenance costs by 50%, and achieving a 50% reduction in ground safety mishaps, process escapes, and close calls.
Level 2		
13.3 Reliability and Maintainability	Sub-Goals:	Reduce operations and maintenance costs, improve ground safety, and improve the efficacy of maintenance tasks, by reducing human error opportunities.
Level 3		
13.3.1 Launch Infrastructure	Objectives:	Increase launch throughput by allowing for quick turnaround and mobility to launch from multiple sites.
	Challenges:	Reliable performance in a launch pad or engine test stand environment. Ruggedization of materials and systems. Packaging approaches for high altitude balloons and sounding rockets. Minimize retrofit impacts to operational facilities.
	Benefits:	Increases launch throughput by allowing for quick turnaround and mobility to launch from multiple sites. Improves launch safety, reduce area cleared for launch, and increases telemetry data rates for high-altitude balloon and sounding rocket missions.
13.3.2 Environment-Hardened Materials and Structures	Objectives:	Improved safety and reduce maintenance costs resulting from extreme operational environments.
	Challenges:	Materials that provide improvements in protection while remaining durable in operational environments that include diverse propellants and weather conditions.
	Benefits:	Improves safety and reduces maintenance costs providing more frequent and sustainable exploration missions. Reduces times required for ground processing and reduces mission risk.

Table 13. Summary of Level 13.3 Sub-Goals, Objectives, Challenges, and Benefits - Continued

Level 3		
13.3.3 On-Site Inspection and Anomaly Detection and Identification	Objectives:	Reduce test set-up times and improving overall processing times.
	Challenges:	Embedding ground-powered sensors without impairing integrity of their material or structure. Ensuring effectiveness of the visualization system and ensuring the robot inspectors do not cause collateral damage.
	Benefits:	Reduces time to identify and resolve problems thereby reducing test set-up times and improving overall processing times.
13.3.4 Fault Isolation and Diagnostics	Objectives:	Significantly reduce ground operations times for fault detection and identification, improve overall throughput times, and reduce mission risks.
	Challenges:	Verifying model-based systems and scaling model-based techniques. Long-term durability of materials in a launch pad or engine test stand environment, repeatability, and accuracy.
	Benefits:	Significantly reduces ground operations times for fault detection and identification, improving overall throughput times and reducing mission risks. Reduces ground safety mishaps, process escapes, and close calls.
13.3.5 Prognostics	Objectives:	Reduce ground operations and maintenance time.
	Challenges:	Long-term durability of materials in a launch pad or engine test stand environment, repeatability, and accuracy. Miniaturizing the capability onto computer chips, reliability, and repeatability of results.
	Benefits:	Reduces ground operations and maintenance time. This provides both cost savings and overall improvements in efficiency, allowing for more frequent launches.
13.3.6 Repair, Mitigation, and Recovery Technologies	Objectives:	Reduce repair times and reduce the number of mitigation actions required.
	Challenges:	Materials compatibility, reliability, and scale-up performance for high-pressure systems. Resiliency of robots to a variety of hazardous environments while maintaining suitable dexterity and minimizing size.
	Benefits:	Reduces repair times and reduces number of mitigation actions required which in turn reduces overall ground operations and maintenance costs and improves efficiency, identification of needed repairs, mission risk and increases safety of personnel.
13.3.7 Communications, Networking, Timing, and Telemetry	Objectives:	Reduce ground reconfiguration times and improve network security.
	Challenges:	Supporting a wide range of frequencies efficiently, effectively respond to spurious events, and be highly reliable.
	Benefits:	Significantly reduces ground reconfiguration times and improves network security, which reduces overall ground operations times and reduces mission risk.
13.3.8 Decision-Making Tools	Objectives:	Reduce ground operations times, improve maintenance planning times, and reduce ground safety mishaps and close calls.
	Challenges:	Ensure effective visual and aural overlaid procedures, instructions, and reference material; and ensure effective correlation of successful work task completion to images of actions from multiple viewpoints.
	Benefits:	Reduces ground operations times significantly, improves maintenance planning times, and reduces ground safety mishaps and close calls, resulting in reduced mission risk.

TA 13.3.1 Launch Infrastructure

To support the infrastructure needs of current mission architectures, launch infrastructure is focused on crane operations, rocket engine acoustic energy abatement, launch pad hydrogen pooling mitigation, mobile and modular launch pads, ground systems for high-altitude balloons and sounding rockets, payload-to-launch vehicle integration, and advanced horizontal landing facilities.

Technical Capability Objectives and Challenges

Advanced crane controls can ensure protection of high-value spaceflight hardware during crane movements and crane availability, but the challenge will be to justify the development costs in the cost-benefit analysis.

Active and passive means to reduce acoustic energy associated with rocket engine firings can reduce area clears and reduce energy reflected upward toward launch vehicles, but the scaled-up solution must perform reliably in a launch pad or engine test stand environment.

Hydrogen pooling mitigation can reduce the presence of unburned hydrogen near a rocket engine prior to ignition, reducing the risk of explosion; however, identification of possible improvements will require complex modeling of the engine nozzle, launch pad, or engine test stand environments.

Variable-geometry flame trenches can provide optimal removal of exhaust products and heat at a multi-user launch pad, but will require complex modeling and ruggedization of materials and systems. A mobile launch pad kit can provide multi-user capability to launch anywhere at any time, but the primary challenge is to develop an on-demand and multi-user command and control system. Ground systems for high-altitude balloons and sounding rockets can improve data transmission rates, but the challenge will be the packaging approaches in the flight systems.

Common interfaces for small launchers and payloads can reduce ground operations times for integration, but the challenge will be to achieve consensus on the technical approach across payload and launch vehicle developers. Common interfaces can incorporate wireless power for on-pad electrical interfaces and payload battery charging. Such a system would reduce test time, enhance interface reliability, and improve personnel safety.

A runway surface movement detection system can enable a controller to assure cleared distances between horizontal takeoff and landing aerospace vehicles in the vicinity of active runways, but the challenge will be to minimize retrofit impacts to operational facilities.

Benefits of Technology

The benefits of developments in Launch Infrastructure technologies are to increase launch throughput by allowing for quick turnaround and mobility to launch from multiple sites. These technologies also improve launch safety, reduce area clears for launch, and increase telemetry data rates for high-altitude balloon and sounding rocket missions.

Table 14. TA 13.3.1 Technology Candidates - not in priority order

TA	Technology Name	Description
13.3.1.1	Supervisory Control System for Cranes	Protection of high-value spaceflight hardware during crane moves through development of a smaller, less complex and modular system for a parallel crane operation monitoring system compared to a custom commercial-off-the-shelf (COTS) system still having single failure points.
13.3.1.2	Collision Avoidance System for Cranes	Collision avoidance system that recognizes obstructions and possesses automated control system stops.

Table 14. TA 13.3.1 Technology Candidates - not in priority order - Continued

TA	Technology Name	Description
13.3.1.3	Crane Control Diagnostic and Prognostic System	A detailed supervisory monitoring system tailorable to specific applications and incorporate crane component diagnostics and prognostics for improved maintenance planning and reduction in unplanned outages.
13.3.1.4	Helmholtz Resonators for Energy Absorption of Rocket Engine Exhaust	Helmholtz resonators that reduce acoustic energy associated with rocket engine firings.
13.3.1.5	Active Acoustic Source Noise Cancellation System	Active source noise cancellation system that reduces acoustic energy associated with rocket engine firings.
13.3.1.6	Hydrogen Pooling Mitigation	Mitigation of hydrogen gas pooling within structures including engine nozzles for launch vehicles that use hydrogen in order to eliminate risk of explosions during engine ignition that can cause catastrophic results.
13.3.1.7	Variable Geometry Flame Trenches	Launch pad or test stand flame trenches that are reconfigurable depending on engine performance and vehicle type and that allow for reduced noise and more efficient removal of exhaust products and heat. Trench walls would reconfigure and lock well-prior to launch or engine test operations. This also provides for a multi-use capability at a launch pad or engine test stand.
13.3.1.8	Mobile Launch Pad Kit	A mobile launch pad kit with modular elements supporting a wide variety of different classes of launchers. Elements include: launch platform, flame trench, launch tower, umbilicals, propellant servicing equipment, command and control system, weather station, and range tracking station.
13.3.1.9	High-Altitude Balloon Ground Systems	Ground systems supporting high-altitude balloons include lift gas servicing system for helium or hydrogen and launch tracking system.
13.3.1.10	Sounding Rocket Ground Systems	Ground systems supporting sounding rocket missions include: launch pads, launch rails, blockhouse systems, controls, consoles, tracking systems, and telemetry systems.
13.3.1.11	Common Interfaces for Small Launchers and Payloads	Standardizing and simplifying fluid, electrical, structural, communication, and data interfaces using an open architecture or industry consensus-driven approach. Common interfaces can incorporate wireless power for on-pad electrical interfaces and payload battery charging.
13.3.1.12	Runway Surface Movement Detection System	Detects multiple vehicles on and in vicinity of active runway.

TA 13.3.2 Environment-Hardened Materials and Structures

Technical Capability Objectives and Challenges

To support the materials needs of current mission architectures' extreme operational environment, Environment-Hardened Materials and Structures is focused on runway materials, launch pad flame trench materials, and materials and coatings to mitigate electrostatic charge build-up. Advanced overrun runway materials can arrest high-velocity, horizontally-landing aerospace vehicles, but must survive long-term exposure to the environment. Advanced flame trench surface materials can reduce maintenance costs and decrease the risk of material breaking away and becoming foreign object debris (FOD) during launch. The primary challenge is overcoming the cost-benefit analysis that evaluates costs to develop and implement versus small improvements over current materials that have proven to be adequate. Materials and coatings that are resistant to electrostatic charge build-up can provide improved performance and durability. The primary challenge will be developing materials that provide improvements in protection while remaining durable in operational environments that include diverse propellants and weather conditions.

Benefits of Technology

The primary benefits of Environment-Hardened Materials and Structures are improved safety and reduced maintenance costs, providing more frequent and sustainable exploration missions. In addition, application of technologies associated with TA 13.3.2 will result in reduced times required for ground processing and reduced mission risk.

Table 15. TA 13.3.2 Technology Candidates - not in priority order

TA	Technology Name	Description
13.3.2.1	Advanced Overrun Runway Materials	Gradually slow down aircraft that have overrun the runway through use of energy-absorbing materials.
13.3.2.2	Advanced Flame Trench Surface Materials	Advanced flame trench materials that provide less degradation over time and less chance to break away and become foreign object debris (FOD) during launch that could strike vehicle.
13.3.2.3	Electrostatic Charge Build-up Resistant Materials and Coatings	Non-accumulating, discharge, and non-contaminating neutralization materials, coatings that increase the decay rate of charged materials; switchable materials that will become electrically conductive in the presence of rising electric fields and electrostatically dissipative when charge starts to develop.

TA 13.3.3 On-Site Inspection, Anomaly Detection, and Identification

On-site inspections at launch pads and engine test stands are manually performed and sometimes require temporary construction of scaffolding for personnel access. Anomalies are detected using external test equipment, such a leak detection devices, borescope inspection cameras, and checkout units that connect to electronics boxes.

Technical Capability Objectives and Challenges

To support the field inspection and monitoring needs of current mission architectures, On-Site Inspection, Anomaly Detection, and Identification is focused on non-intrusive sensor applications and small robotic inspectors. Integrated, multi-parameter, ground-powered sensors for NDE and continuous monitoring can reduce ground operations test set-up times by 50% because of the much lower requirement for portable test equipment. The challenge is that the system approach must be able to embed the ground-powered sensors without impairing integrity of their material or structure.

Small robotic inspectors can significantly reduce time to identify and resolve problems in difficult-to-access spaces as compared to inspections performed by ground operations technicians. These robotic inspectors would have the ability to navigate through highly confined spaces without damaging spacecraft or launch pad components and would provide continuous inspection via a variety of sensors to autonomously identify anomalies like leaks and deformations. The primary challenges are ensuring effectiveness of the visualization system and ensuring the robot inspectors do not cause collateral damage.

It is critical that new technology sensor data points capture information that can be readily interpreted so that human operators can correctly identify anomalies according to established standards.

Benefits of Technology

The benefit of On-Site Inspection, Anomaly Detection, and Identification technologies is a reduction in time to identify and resolve problems, thereby reducing test set-up times and improving overall processing times.

Table 16. TA 13.3.3 Technology Candidates - not in priority order

TA	Technology Name	Description
13.3.3.1	Integrated, Multi-Parameter, Ground-Powered Sensors for Non-Destructive Evaluation and Continuous Monitoring	Monitors the health and performance of actuators, instrumentation, devices, structure, connectors and wiring, and pressure vessels using smart sensors embedded directly in the materials that are powered wirelessly from ground systems.
13.3.3.2	Small Robotic Inspectors	Small, articulated robotics able to operate in highly-confined spaces and provide in-situ inspection in areas where human inspection is difficult and costly.

TA 13.3.4 Fault Isolation and Diagnostics

Most fault detection approaches use simple monitor-response mechanisms that look for symptoms of faults that have already occurred. Examples of symptoms include decreases in pressure, temperature, and volume.

Technical Capability Objectives and Challenges

To support the need to understand and assess complex ground system behavior during ground operations of current mission architectures, Fault Isolation and Diagnostics is focused on embedded technologies, smart materials, and non-traditional sensors.

Embedded fault detection, isolation, and diagnosis can detect off-nominal behavior in seconds, identify faults in minutes, and diagnose faults in tens of minutes. The primary challenges are verifying model-based systems and scaling model-based techniques.

Smart materials for leak detection, such as color-changing materials to detect and isolate a leak source, can significantly reduce ground operations times to identify and isolate leak sources in fluid systems. Smart materials for damage detection, such as color-changing materials to detect and isolate structural impacts and damage from hail strikes, FOD strikes, and occurrences during operational mishaps, can significantly reduce ground operations times to identify and isolate leak sources in fluid systems. The primary challenges for smart materials are long-term durability of materials in a launch pad or engine test stand environment, repeatability, and accuracy.

Non-traditional sensors for fault isolation can significantly reduce ground operations times to identify and isolate faults. This includes non-traditional use of radio detection and ranging (RADAR), light detection and ranging (LIDAR), forward-looking infrared radiometer (FLIR), and ultrasonic acoustic sensors to detect leak sources or triangulating a component malfunction. The primary challenges are long-term durability of materials in a launch pad or engine test stand environment, repeatability, and accuracy.

Benefits of Technology

The primary benefit of Fault Isolation and Diagnostics technologies is to significantly reduce ground operations times for fault detection and identification, improving overall throughput times and reducing mission risks. Other major benefits in TA 13.3.4 technologies include reduced ground safety mishaps, process escapes, and close calls that result in safer and more sustainable exploration missions.

Table 17. TA 13.3.4 Technology Candidates - not in priority order

TA	Technology Name	Description
13.3.4.1	Embedded Fault Detection, Isolation and Diagnosis	Launch vehicles and ground systems monitor and assess their own health to identify and repair off-nominal conditions and/or detect timing that might lead to crew abort or flight termination.
13.3.4.2	Smart Materials For Leak Detection	Smart materials such as color-changing materials to detect and isolate a leak source.

Table 17. TA 13.3.4 Technology Candidates - not in priority order - Continued

TA	Technology Name	Description
13.3.4.3	Smart Materials for Damage Detection	Smart materials such as color-changing materials to detect and isolate structural impacts and damage.
13.3.4.4	Non-Traditional Sensors for Fault Isolation	Non-traditional sensors to detect and isolate faults. Examples include radar, light detection, lidar, FLIR, and ultrasound to detect and isolate a failure in a 3D space such as "hearing" a leak source or a component malfunction and triangulating the location.

TA 13.3.5 Prognostics

Prognostics are mostly limited to an operator's knowledge of trending data. For example, an operator might conclude that the pump bearings are wearing and will soon fail based on current observation of degrading pump flow rate outputs and previous experience of the same condition.

Technical Capability Objectives and Challenges

To support the predictive maintenance needs of ground systems for current mission architectures, Prognostics is focused on embedded technologies and models. Embedded technologies include molecular agents that can monitor fluid system degradation for predictive health. These molecular agents can provide significant reductions in ground operations times to identify degradation in fluid systems for improved planning of maintenance activities. The primary challenges are ensuring the long-term durability of materials in an extreme environment, repeatability, and accuracy.

Built in Test (BIT)-enhanced life forecasting that embeds forecast life expectancy at the card and subsystem level can provide significant reductions in ground operations times for identifying degradation in electronic systems, and can improve planning of maintenance activities. The primary challenges are miniaturizing the capability onto computer chips, reliability, and repeatability of results.

Models and approaches for prognostics on remaining useful life provide the ability to estimate the useful remaining life for new and degraded components. Prognostics models can also significantly reduce ground operations times to identify degradation in systems for improved planning of maintenance activities and reduced mission risk. The primary challenge is that extensive model validation will be required, especially if component run-to-failure testing is required.

Benefits of Technology

The primary benefits of Prognostics technologies are significant reductions in ground operations and maintenance time. This provides both cost savings and overall improvements in efficiency, allowing for more frequent launches.

Table 18. TA 13.3.5 Technology Candidates - not in priority order

TA	Technology Name	Description
13.3.5.1	Molecular Agents for Predictive Health of Fluid System	Targeted, optically active contrast agents provide markers of fluid system deterioration allowing optical images to be acquired in real time with high spatial resolution to image-specific molecular targets.
13.3.5.2	Built-In Test Enhanced Life Forecasting	Assesses life expectancy of electronic boxes and systems at the card and sub systems level using active probing to estimate remaining life.
13.3.5.3	Models and Approaches for Remaining Useful Life Prognostics	Estimate the time to failure (or useful remaining life) for new and degraded components.

TA 13.3.6 Repair, Mitigation and Recovery Technologies

Repairs or mitigation actions are largely performed manually. Examples include field repair of a fluid system connection seal using a seal-polishing device, mitigation action of a structural crack by drilling out the damage and bonding doubler plates over both sides of the defect, and freezing a vertical pipe containing hydraulic fluid using liquid nitrogen and then performing a replacement of a fitting without having to drain the system.

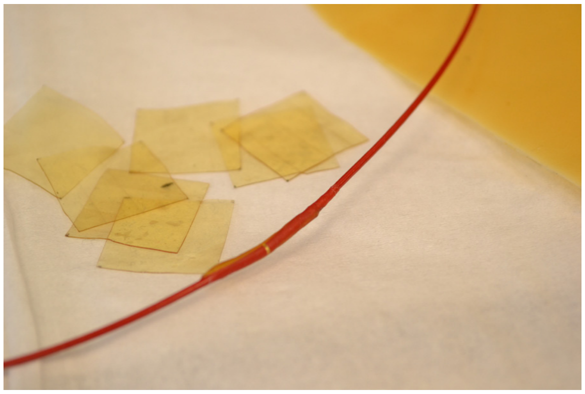
Self-Healing Materials

Technical Capability Objectives and Challenges

To support the need to perform field repairs or mitigation actions for current mission architectures, this section is focused on smart materials, small robots, and self-configuring components.

Self-repairing seals for fluid systems can significantly reduce ground operations times to identify, isolate, and repair fluid system leaks. The primary challenges are materials compatibility, reliability, and scale-up performance for high-pressure systems. Self-repairing wiring insulation can significantly reduce ground operations times to identify, isolate, and repair damaged wiring insulation. The primary challenges are materials compatibility and reliability.

Small robots can significantly reduce ground operations times to perform repairs and mitigation actions. The primary challenges are resiliency of robots to a variety of hazardous environments while maintaining suitable dexterity and minimizing size, as well as the ability to perform operations autonomously while working with hazardous products. Field repair through predictive and reconfigurable components can significantly reduce ground operations times to perform repairs and mitigation actions. The primary challenge will be constraining the set of implementable design solutions to a practical size.



Self-Healing Wiring Insulation

Benefits of Technology

Repair, Mitigation, and Recovery technologies significantly reduce both repair times and the number of mitigation actions required. This produces reductions in overall ground operations and maintenance costs, improved efficiency and allows for more frequent exploration missions. Additionally, improved identification of needed repairs reduces mission risk and increases safety of personnel.

Table 19. TA 13.3.6 Technology Candidates - not in priority order

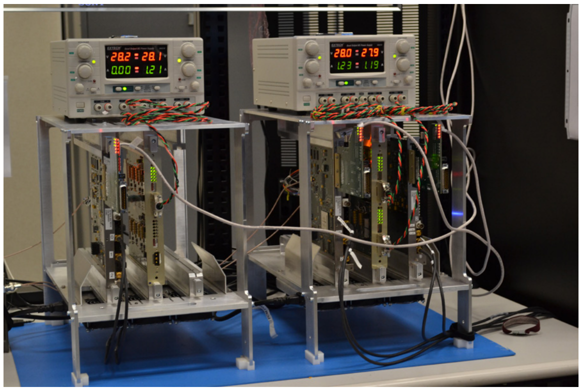
TA	Technology Name	Description
13.3.6.1	Self-Repairing Seals for Fluid Systems	Polymer or other-based seals for use in fluid systems that detect leaks and self-seal.
13.3.6.2	Self-Repairing Wiring Insulation	Polymer or other-based wiring insulation materials that detect damage and self-repairs.
13.3.6.3	Small Robots for Repairs and Mitigation Actions	Perform repairs and remediation tasks such as spill clean-ups, leak repairs, opening access panels, connecting fluid or electrical lines or foreign object debris (FOD) removal in sometimes highly hazardous or inaccessible environments (such as launch pads, engine test stand, processing facilities with hydrazine spills, etc.).
13.3.6.4	Field Repair Through Predictive and Reconfigurable Components	Real-time mitigation of failures based on local estimates of remaining capability and ability to pre-emptively replace or reconfigure components.

TA 13.3.7 Communications, Networking, Timing and Telemetry

Physically-isolated networks provide data confidentiality between a launch pad or engine test stand and the control room. An example is hardline data transmission cables for one facility that are physically routed and connected to the command and control system, having no additional data feeds, in one access-controlled control room to ensure data confidentiality. For non-isolated networks, manual configurations ensure network security policies are maintained. An example is a command and control system within a control room that has hardline data transmission cables from a launch complex with data from ground systems, the launch vehicle, and the payload, as well as external data feeds from a weather station. Cabling that is physically routed from specific signal conditioners and connected to specific consoles ensures the confidentiality of the data available at the specific consoles.

Technical Capability Objectives and Challenges

To support the needs of current mission architectures, Communications, Networking, Timing and Telemetry is focused on solutions that are adaptive, reconfigurable, delay tolerant, highly secure, mobile, and modular. On-demand, adaptive communications can reduce ground operations times to reconfigure systems for variable frequencies, modulations, and coding. The primary challenges are that the system must support a wide range of frequencies efficiently, effectively respond to spurious events, and be highly reliable. Advanced networking protocols for delay-tolerant networking can successfully respond to latencies of 30 seconds or less, node repair times of 60 to 90 seconds, and maintain node reliability of .999. The primary challenges are determining the amount of information to exchange, the frequency at which in-range devices query each other for updates, and which devices are chosen among others for information exchange.



Communication, Networking, Timing, and Telemetry

Highly secure and access-controlled flexible data networking can improve network security reconfigurations from minutes to seconds. The primary challenge is to provide the ability to handle real-time critical information, such as commands to mission-critical fueling valves, and to ensure delivery.

Free space optics for ground communications can provide highly secure and high-speed (10 Gbps) uplinks and downlinks that can support full-pad 4K video and multi-spectral sensing for hazardous gas detection. The primary challenges are overall durability and reliability in an operational environment such as a launch pad or engine test stand.

Model-based configuration of ground control systems can significantly improve ground operations times for reconfiguration of systems. Examples include pre-flight testing of spacecraft antennas that require multiple reconfigurations of ground antennas and reconfiguration of formats for command and control system data processing for sample rates and data processing algorithms. The primary challenge is to develop and validate a model of significant ground system characteristics and configurations.

Mobile network and information services can provide a fully mobile and modular non-persistent network and information services to support emerging multi-user needs, such as exploration analog test sites and launch control for nano-launchers. The primary challenge will be optimizing capabilities to fully satisfy multiple user needs.

Benefits of Technology

The benefits of Communications, Networking, Timing and Telemetry technologies are significantly reduced ground reconfiguration times and improved network security, which reduces overall ground operations times and reduces mission risk.

Table 20. TA 13.3.7 Technology Candidates - not in priority order

TA	Technology Name	Description
13.3.7.1	State Aware Monitor and Control	State aware monitor and control of ground infrastructure and flight assets by exchanging high-level states and constraints and goals on those states.
13.3.7.2	On-Demand, Adaptive Communications	Reconfigurable communications anytime, anyplace and connectivity for anything. Provide ability to quickly reconfigure ground communications equipment to adapt to a variety of different launch vehicle different frequencies, modulations, and coding.
13.3.7.3	Advanced Networking Protocols for Delay-Tolerant Networking	Networking protocols that allow launch systems to function during periods of network disconnection or disruption without losing critical information.
13.3.7.4	Highly Secure and Access-Controlled Flexible Data Networking	Securely and dynamically route information based on content rather than pushed to specific addresses.
13.3.7.5	Free Space Optics for Ground Communications	Alternative to radio frequency communication with high-speed and tap-proof optical communication systems.
13.3.7.6	Model-Based Configuration of Ground Control Systems	Rapidly and reliably configure ground support equipment and launch control systems to meet the particular needs of the vehicle being integrated or launched.
13.3.7.7	Mobile Network and Information Services	Mobile and modular non-persistent network and information services for the purpose of providing remote visibility voice, video, data, and networking for multiple users such as analog test sites and nano-launchers.

TA 13.3.8 Decision-Making Tools

Test procedures are paper or electronic and configuration controlled. Deviations like system troubleshooting procedures require several levels of approvals through signatures on paperwork and often delay resumption of operations. Reference information to assist in troubleshooting, such as schematics and specifications, are also in paper or electronic form and must be referred to separately from the controlled test procedure. Decision-making tools include evaluating overlaid trend data, such as pressure, temperature, and time using commercial-off-the-shelf (COTS) office software, laboratory analyses of flight system fluid samples like propellants and gases, and evaluating infrared camera displays.

Technical Capability Objectives and Challenges

To support the ground operations teamwork procedure and troubleshooting needs of current mission architectures, Decision-Making Tools is focused on intelligent procedures. Intelligent procedures for launch operations sequencing and system troubleshooting can significantly reduce ground operations times to identify, evaluate, and respond to launch countdown issues, as well as perform system troubleshooting. The primary challenge is to ensure reliability.

Benefits of Technology

The clearest benefit in Decision-Making Tools is to reduce ground operations times significantly, improve maintenance planning times, and reduce ground safety mishaps and close calls, resulting in reduced mission risk.

Table 21. TA 13.3.8 Technology Candidates - not in priority order

TA	Technology Name	Description
13.3.8.1	Intelligent Procedures for Launch Operations Sequencing and System Troubleshooting	Provide intelligent procedures to advise the launch control team during launch operations including propellant loading, constraints management, mission management team polling, late-in-the-launch-countdown, time-critical actions such as access arm retraction and cryogenic systems hold-times, and launch commit criteria (LCC).
13.3.8.2	Advanced Ground Crew Work Instructions and Procedures Display	Augmented reality glasses allowing ground crew procedures and instructions to be visually, aurally overlaid onto the actual work as it is being performed. Procedures monitor user actions and provide directions, or certify that the process has been performed correctly.

TA 13.4: Mission Success

The focus of this area is to protect the public, astronauts, pilots, the workforce, and high-value equipment and property during operations such as launching, flying, landing, and testing of launch or flight vehicles. This applies to all NASA centers and test facilities and all NASA vehicle programs including expendable launch vehicles, reusable launch vehicles, and unmanned aerial vehicles (UAVs), as well as any NASA-funded commercial ventures that involve range operations.

The SOA at NASA for protection involves mitigating and controlling hazards associated with range operations, such as uncontrolled vehicles, debris, explosives, and toxins. SOA instrumentation provides vehicle-positioning information for a launch site using downrange C-band radar, vehicle telemetry, and optical tracking systems. SOA telemetry also provides vehicle health and status information through its data stream. Spacecraft returning to Earth landing either on land or in water do so in specialized, restricted landing zones in remote locations with vehicle-unique handling equipment and highly trained personnel. Meteorologists use various systems to measure barometric pressure, altimeter, wind speed, wind direction, temperature, dew point, visibility, cloud ceiling, icing, lightning, sea level pressure, and precipitation accumulation. Facilities are outfitted with hazard-sensing systems, such as low-oxygen meters, infrared fire detectors, and closed-circuit television monitoring equipment. Employees select standard sizes of personal protection equipment (PPE) from available stock.

Technologies are presented in the following four categories: Range Tracking, Surveillance and Flight Safety; Landing and Recovery Systems and Components; Weather Prediction and Mitigation; and Safety Systems. The benefits of developing these technologies include reduced operations and maintenance costs, reduced times required for ground processing and launch, reduced mission risk, reduced hazards exposure to personnel, and increased capacity for launch and range operations.

Sub-Goals

The primary goals of developments in TA 13.4 Mission Success technologies are to significantly reduce operations and maintenance costs and reduce ground safety mishaps, process escapes, and close calls. The challenges to overcome include scaling up and ruggedizing emerging laboratory-scale technologies for application in launch pad or engine test stand environments, minimizing up-front technology development costs, and achieving stakeholder buy-in to evolve the restrictive, yet time-tested and highly reliable launch and range control processes.

Table 22. Summary of Level 13.4 Sub-Goals, Objectives, Challenges, and Benefits

Level 1		
13.0 Ground and Launch Systems	Goals:	Provide the launch capability required to enable exploration while reducing operations and maintenance costs by 50%, and achieving a 50% reduction in ground safety mishaps, process escapes, and close calls.
Level 2		
13.4 Mission Success	Sub-Goals:	Reduce operations and maintenance costs and reduce ground safety mishaps, process escapes, and close calls.

Table 22. Summary of Level 13.4 Sub-Goals, Objectives, Challenges, and Benefits - Continued

Level 3		
13.4.1 Range Tracking, Surveillance, and Flight Safety Technologies	Objectives:	Increase the efficiency of range operations and reduce operations and maintenance recurring costs.
	Challenges:	Integrating technologies, ruggedizing for operational environments.
	Benefits:	Significantly reduces operations and maintenance recurring costs and increases efficiency of range operations. Provides improvements in reliability and decreases system complexity thus providing improved safety and reduced mission risk.
13.4.2 Landing and Recovery Systems and Components	Objectives:	Assure recovery of valuable NASA assets.
	Challenges:	Integrating technologies for precision unmanned aerial vehicle (UAV) capture. Integrate the technologies while minimizing power requirements for test facilities.
	Benefits:	Assures recovery of assets while decreasing overall ground operations times, reducing costs and allowing more frequent exploration missions.
13.4.3 Weather Prediction and Mitigation	Objectives:	Improve the speed and accuracy of operator decision-making based on meteorological conditions.
	Challenges:	Integration issues associated with likely incompatibility of existing data systems.
	Benefits:	Significant improvement in the speed and accuracy of decision making, thereby reducing ground safety mishaps, process escapes, and close calls, providing safer and more sustainable exploration missions.
13.4.4 Robotics and Telerobotics	This section is covered in TA 4 Robotics and Autonomous Systems.	
13.4.5 Safety Systems	Objectives:	Increase safety of operations personnel by providing reduced instances of safety mishaps, process escapes, and close calls.
	Challenges:	Limitations of geographic area scans. Integrating electronics into 3D-printed articles. Integrating technologies for application in an operational environment.
	Benefits:	Increases safety of operations personnel by providing reduced instances of safety mishaps, process escapes and close calls which in turn reduces times required for ground processing and reduces mission risk.

TA 13.4.1 Range Tracking, Surveillance and Flight Safety Technologies

Instrumentation provides vehicle-positioning information for a launch site using downrange C-band radar, vehicle telemetry, and optical tracking systems. Telemetry also provides vehicle health and status information through its data stream. This data is shipped via redundant paths using secure networks to the range safety displays in range operation control centers. The data is then processed to generate flight path and predicted impact point displays. Based on predefined mission rules, the range safety officer determines risk and, if required, terminates thrust of any vehicle that violates these rules using a network of ground-based command destruct systems and vehicle-based flight termination systems.

Technical Capability Objectives and Challenges

To support the range control needs of current mission architectures, Range Tracking, Surveillance and Flight Safety Technologies is focused on land, air, sea, and space applications. A space-based range can provide a 75% reduction in recurring operations and maintenance costs, but the primary challenge is to address the non-recurring costs to develop and launch the space-based assets.

“Smart” sonobuoys for range operations can improve time and accuracy for identifying above- and below-water vessel traffic patterns and types, but the primary challenges are integrating technologies and performing extensive field demonstrations to verify performance. UAVs for range operations can improve time and accuracy for identifying vessel traffic patterns and types, but the primary challenges are integrating technologies and performing extensive field demonstrations to verify performance. Onboard tracking for range operations can provide 100% reliability in tracking and eliminating no-launch periods in which radars are down for repairs or maintenance; however, the primary challenges are integrating technologies and performing extensive field demonstrations to verify performance.

Advanced telemetry systems can provide near-zero loss of telemetry on ascent or re-entry, but challenges include integrating technologies and performing extensive field demonstrations to verify performance. Advanced antenna systems and steerable beam antennas for range operations can provide a 25% improvement in transmission performance, but the primary challenges are scaling up and ruggedizing these systems for operational environments. Autonomous flight termination systems can reduce ground systems operations and maintenance costs and provide faster response times to identify flight path deviations and destruct command transmission. The primary challenge is the expected multiple field demonstrations that will be required to validate performance.

Solid-state laser-initiated ordnance for flight termination system can improve reliability, cost, and complexity. The primary challenge is the expected multiple field demonstrations that will be required to validate performance. Anti-jamming and anti-spoofing communications for range operations may provide effectiveness in defeating intrusions, challenges include scaling up these systems for operational environments. Aerospace traffic control system may provide 100% coverage of flight profiles, handle multiple simultaneous flights, and ensure safe spacing between vehicles. The primary challenges are scaling up these systems for operational environments and determining when the systems would be required based on launch and landing manifests.

Benefits of Technology

The primary benefits of Range Tracking, Surveillance and Flight Safety Technologies are significant reductions in operations and maintenance recurring costs and increased efficiency of range operations. In addition, these technologies provide improvements in reliability and decrease system complexity, providing improved safety and reduced mission risk.

Table 23. TA 13.4.1 Technology Candidates - not in priority order

TA	Technology Name	Description
13.4.1.1	Space-Based Range	Tracks launch vehicles using space-based surveillance assets.
13.4.1.2	"Smart" Sonobuoys for Range Operations	"Smart" sonobuoys that measure sea states, detect various watercraft, both above and below water and signal processing to determine vessel type, position, speed, and bearing, and transmitting the information to range safety officers via satellite relay.
13.4.1.3	Onboard Tracking for Range Operations	Tracking systems with global positioning system (GPS)-metric tracking, Automatic Dependent Surveillance – Broadcast (ADS-B) technology, autonomous flight safety system (AFSS) and other concepts.
13.4.1.4	Advanced Telemetry Systems for Range Operations	Highly-reliable transmission capability during launch and re-entry using software-programmable radios, high-frequency transmissions, transmissions through plasma, and exhaust plumes.
13.4.1.5	Advanced Antenna Systems for Range Operations	Highly-reliable antenna technologies to increase data rates and bandwidth for sending and receiving imagery, and integrated flight antennas for range operations.
13.4.1.6	Steerable Beam Antennas for Range Operations	Steerable beam antennas will be responsive to vehicle position and attitude and conformal to the vehicle skin.
13.4.1.7	Autonomous Flight Termination System	Autonomous flight safety system (AFSS) to track a vehicle's position onboard and autonomously terminate if it deviates from the controlled corridor.

Table 23. TA 13.4.1 Technology Candidates - not in priority order - Continued

TA	Technology Name	Description
13.4.1.8	Solid-State Laser-Initiated Ordnance for Flight Termination System	Incorporating innovative lasers that allow flight termination ordnance initiation systems to be more reliable, cost less, and have less complexity.
13.4.1.9	Anti-Jamming and Anti-Spoofing Communications for Range Operations	Security measures affecting communications, information technology, networks, data storage, intrusion detection, and jamming.
13.4.1.10	Aerospace Traffic Control System	Provide aerospace traffic control system capable of monitoring, deconflicting, debris tracking, weather overlays, local and global scheduling, and rapid reconfiguration for concurrent launches, reentries, and flights of diverse flight platforms (manned/unmanned aircraft/launch vehicles/buoyant systems).

TA 13.4.2 Landing and Recovery Systems and Components

Returning spacecraft land in specialized, restricted landing zones in remote locations using vehicle-unique handling equipment and highly trained personnel. Re-entry payload recoveries require radar tracking as well as visual monitoring. Horizontal landings on runways use high-intensity lighting, landing aids, or beacons to facilitate landing accuracy. Water landings require that personnel install floatation devices and disconnect parachutes. Payload recovery from suborbital rockets and balloons require that operators monitor telemetered coordinates in land or sea chase vehicles and visually monitor landings using binoculars.

Technical Capability Objectives and Challenges

To support landing and recovery needs of current mission architectures, landing and recovery systems and components are focused on technologies for recovery of first-stage rockets, crewed and uncrewed reentry vehicles, capsules, and payloads carried aloft by sounding rockets and high-altitude balloons.

UAVs for payload recovery can reduce ground operations times to recover first-stage rockets, crewed and uncrewed reentry vehicles, capsules, and payloads carried aloft by sounding rockets and high-altitude balloons. The primary challenges are maturing sensors and developing protocols for UAV-to-UAV communications that focus the UAVs on the landing site.

UAVs for aerial recovery can significantly reduce ground operations times and have a very high success rate for aerial recoveries of first-stage rockets, crewed and uncrewed reentry vehicles, capsules, and payloads carried aloft by sounding rockets and high-altitude balloons while still under parachute or parafoil. The primary challenge is integrating technologies for precision UAV capture at a certain point in the sky at a certain time.

Arc jet, an arc-heated wind tunnel technology test capability, is an enabler for safe passage through atmospheric entry missions at hyper-velocities without which mission success cannot be assured. Arc jet is a large, fixed facility that provides ground truth to design and certify flight thermal protection systems (TPS). Arc jet testing requires a core set of technologies that provide capability for the required testing and development of new TPS materials and the flight qualification of entry hardware elements and sub-systems. Thermal and vacuum test facility capabilities for reentry testing exoatmospheric hardware can provide a reasonable approximation of the surface temperature, pressure, and the gas enthalpy found in a high-velocity, supersonic flow experienced by a vehicle on Earth atmospheric entry after returning from Mars, Venus, NEA, or other destination. The challenges will be to develop the core set of ground-based test capabilities with minimum power requirements.

Characterization of high-enthalpy facilities are necessary to anchor and build physics-based models that are used to predict aerothermal environments and TPS performance. Technologies include spectroscopic measurements of arc jet and shock tube facilities. Spectroscopic measurements may be used to characterize ablation products, shock layer chemistry, and infer mechanisms. The challenge is that spectroscopic capabilities exist but are not incorporated into high-enthalpy facilities.

Benefits of Technology

Landing and Recovery Systems and Components technologies assure recovery of valuable NASA assets while decreasing overall ground operations times, reducing costs, and allowing more frequent exploration missions.

Table 24. TA 13.4.2 Technology Candidates - not in priority order

TA	Technology Name	Description
13.4.2.1	Unmanned Aerial Vehicles for Payload Recovery	Recovering payloads from re-entry, suborbital rockets, or balloons by providing coverage of the entire recovery area, then autonomously focusing on smaller areas based upon shared tracking and remote-sensing data, targeting the landing site.
13.4.2.2	Unmanned Aerial Vehicle Aerial Recovery	Utilize global positioning system (GPS) data communicated from a payload to the unmanned aerial vehicle (UAV) recovery aircraft to develop enhanced aerial recovery techniques for payloads from balloons, sounding rockets, first-stage rockets, and small orbital vehicles.
13.4.2.3	Arc Jet Test Capabilities for Thermal Protection Material and Systems Development and Flight Qualification for Mission Assurance During Atmospheric Entry	Arc jet capabilities that provide a reasonable approximation of the heat flux, pressure, shear and the gas enthalpy experienced by a vehicle during hyper-velocity atmospheric entry into Earth, Mars, Venus, Titan and outer planets including Saturn.
13.4.2.4	Ablation Spectroscopy	Measure spectroscopic signatures during arc jet, shock tube or ballistic range testing. Laser induced fluorescence, optical emission spectroscopy are used primarily for atomic species characterization. Characterization is expanded to include ablation materials.

TA 13.4.3 Weather Prediction and Mitigation

Meteorologists use the Automated Weather Observing System (AWOS), Automated Surface Observing System (ASOS), and Geostationary Operational Environmental Satellites (GOES). AWOS units provide parameters like barometric pressure, altimeter, wind speed, wind direction, temperature, dew point, visibility, and cloud ceiling. Beginning in 1991, many AWOS units were replaced by more modern ASOS units that also provide parameters like icing, lightning, sea-level pressure, and precipitation accumulation. GOES generate images every 30 minutes using visible, infrared, shortwave infrared, or water vapor instruments. Additionally, meteorologists get information from the Automatic Terminal Information Service, which broadcasts essential information, including weather information. While weather prediction accuracy and response continues to improve, applying emerging technologies could provide additional improvements.

Technical Capability Objectives and Challenges

To support the weather-associated decision-making needs of current mission architectures, Weather Prediction and Mitigation is focused on weather information databases, sensors, sensor platforms, and weather models. A weather information database for aerospace traffic management can provide improvements in the speed and accuracy of operator decision-making based on meteorological conditions, but the primary challenge will be resolving integration issues associated with likely incompatibility of existing data systems.

UAV-based meteorological sensors can improve the speed and accuracy of operator decision-making based on meteorological conditions, but the primary challenges are maturing sensors and developing protocols for UAV-to-UAV communication. A three-dimensional (3D) real-time system to measure electric fields for lightning prediction can improve the speed and accuracy of operator decision-making based on meteorological conditions, but the primary challenges are sensor development, developing lightning prediction models, and resolving complexity issues associated with of taking two-dimensional (2D) to 3D.

A precision lightning-strike locator system can pinpoint strike location to within three feet for determining impacts to ground and flight systems. The primary challenge is scaling up for operational environments. Weather prediction models can improve the speed and accuracy of operator decision-making based on meteorological conditions. The primary challenge will be resolving integration issues associated with likely incompatibility of existing data systems. Small, networked weather stations can improve the speed and accuracy of operator decision-making based on meteorological conditions. The primary challenges are maturing sensors and developing protocols for station-to-station communication.

Benefits of Technology

The primary benefit of Weather Prediction and Mitigation technologies is significant improvement in the speed and accuracy of decision making, thereby reducing ground safety mishaps, process escapes, and close calls and providing safer and more sustainable exploration missions.

Table 25. TA 13.4.3 Technology Candidates - not in priority order

TA	Technology Name	Description
13.4.3.1	Weather Information Database for Aerospace Traffic Management	Weather information database to continually share national airspace data in real time to support aerospace traffic management and safety. The system will include meteorological, space environment, and oceanographic data assimilation and prediction.
13.4.3.2	Weather Information Database for Multiple Users	A common, consistent, and reliable source of information to multiple users for decision support in the Weather Information Database (WIDB), a.k.a., the 4D Weather Data Cube
13.4.3.3	Unmanned Aerial Vehicle-Based Meteorological Sensors	Meteorological sensor systems integrated onto UAV platforms disbursed across a wide area and at different altitudes providing densely tiered levels of data fidelity for real-time updating of weather information database.
13.4.3.4	Three-Dimensional (3D) Real-Time System to Measure Electric Fields for Lightning Prediction	Real-time in-situ measurement of the atmosphere's 3D electric field at various altitudes and model lightning predictions.
13.4.3.5	Precision Lightning Strike Locator System	Acoustic sensors and field mills for precision location of lightning strikes using triangulation.
13.4.3.6	Weather Prediction Models	Improve numerical weather prediction models by using all available information to determine as accurately as possible the state of the atmospheric flow.

TA 13.4.4 Robotics / Telerobotics

For information on Robotics / Telerobotics please refer to the TA 4 Robotics and Autonomous Systems.

TA 13.4.5 Safety Systems

NASA protects its employees from workplace hazards that can cause injury. Facilities are outfitted with hazard-sensing systems like low-oxygen meters, infrared fire detectors, and closed-circuit television monitoring equipment. Employees select standard sizes of personal protective equipment (PPE) from available stock. Hazardous operations are conducted manually using the “buddy system” in which employees work in pairs. However, sensors only perform measurements in their local environment, infrared sensors cannot detect certain types of combustion, and closed-circuit television often has line-of-sight obstructions.

Technical Capability Objectives and Challenges

To support ground the personnel safety needs of current mission architectures, Safety Systems focuses on modeling of hazardous environments, PPE, and monitoring of personnel working in hazardous environments.

Virtual hazardous operations modeling can reduce ground safety mishaps, process escapes, and close calls. The primary challenges are limitations on geographic area scans and human-computer interaction. Virtual range operations modeling can improve speed and accuracy of operator decision-making. The primary challenges are geographic area scan limitations and performance of test demonstrations to validate models.

On-demand, custom-fitted and lighter-weight PPE can reduce ground safety mishaps, process escapes, and close calls. The primary challenge is integrating electronics into 3D-printed articles. Ground safety tools for processing radioactive payloads provide personnel monitoring that use real-time data, have higher sensitivity, and are more rugged. The challenge will be to overcome the developmental costs to achieve full functionality.

A hazardous environment personnel monitoring system, such as one using visible light for data transmission, can result in improved response times to off-nominal conditions by providing test conductors with accurate observations of personnel position location and individual behavior. The primary challenges are integrating technologies for application in an operational environment.

Benefits of Technology

The primary benefit of safety systems technologies is to increase safety of operations personnel by providing reduced instances of safety mishaps, process escapes, and close calls. These safety benefits in turn provide reduced times required for ground processing and reduced mission risk.

Table 26. TA 13.4.5 Technology Candidates - not in priority order

TA	Technology Name	Description
13.4.5.1	Virtual Hazardous Operations Modeling	Virtual modeling, walk-through, and phasing of hazardous operations with focus on safety.
13.4.5.2	Virtual Range Operations Modeling	A "virtual range" to enable range safety analysis and planning for optimal execution of existing and future ground/launch operations.
13.4.5.3	On-Demand, Custom-Fitted and Lighter-Weight Personnel Protective Equipment (PPE)	Custom-fitted and lighter-weight personnel protective equipment (PPE) that use additive manufacturing technologies to enhance PPE and breathing apparatus.
13.4.5.4	Ground Safety Tools for Radioactive Payload Processing	Spectroscopic monitors and protection from radioactive material sourced from payloads.
13.4.5.5	Hazardous Environment Personnel Monitoring System Using Visible Light for Data Transmission	Test conductors with accurate personnel position location and individual behavior observation of ground crew in hazardous environment using visible light for data transmission.

Appendix

Acronyms

2D	Two-Dimensional
3D	Three-Dimensional
ADS-B	Automatic Dependent Surveillance-Broadcast
AFSS	Autonomous Flight Safety System
AI	Artificial Intelligence
ARGOS	Active Response Gravity Offload System
ASE	Autonomous Sciencecraft Experiment
ASOS	Automated Surface Observing System
AWOS	Automated Weather Observing System
BIT	Built-In Test
BSL	BioSafety Level
C4I	Command, Control, Communications, and Computer Intelligence
CASPER	Continuous Activity Scheduling, Planning, Execution, and Replanning
CDF	Confined Detonating Fuse
CoNNeCT	COmmunications, Navigation, and Networking reConfigurable Testbed
COTS	Commercial Off The Shelf
CT	Crawler Transportation
DAQ	Data AcQuisition
DHMR	Dry Heat Microbial Reduction
DTN	Delay Tolerant Networking
EPD	Electronic Personal Dosimeters
FDIR	Fault Detection, Isolation, and Recovery
FLIR	Forward-Looking Infrared Radiometer
FMEA	Failure Mode and Effects Analysis
FMEA/CIL	Failure Mode Effects Analysis / Critical Items List
FOD	Foreign Object Debris
GOES	Geostationary Operational Environmental Satellites
GPS	Global Positioning System
HAZMAT	HAZardous MATerial
HCI	Human-Computer Interaction
ISRU	In-Situ Resource Utilization
IT	Information Technology
IVHM	Integrated Vehicle Health Management
LADEE	Lunar Atmosphere and Dust Environment Explorer
LCC	Launch Control Center
LCC	Launch Commit Criteria
LED	Light Emitting Diodes
LEO	Low-Earth Orbit
LFID	Light Fidelity Data Transmission and Identification

LIDAR	Light Detection and Ranging
LIF	Laser Induced Fluorescence
MLP	Mobile Launch Platform
MPCV	MultiPurpose Crew Vehicle
MSL	Mars Science Laboratory
MTBF	Mean Time Between Failure
MTTR	Mean Time To Repair
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NBP	Normal Boiling Point
NDE	Non-Destructive Evaluation
NEA	Near Earth Asteroid
NPR	NASA Procedural Requirements
NSD	NASA Standard Detonators
NVR	Non-Volatile Residue
OCT	Office of the Chief Technologist
OEM	Original Equipment Manufacturer
OSL	Optically Stimulated Luminescence
PC	Personal Computer
PDA	Personal Digital Assistant
PEM	Proton Exchange Membranes
PIV	Particle Imagery Velocimetry
PLC	Programmable Logic Controller
PPE	Personal Protective Equipment
PSP	Pressure Sensitive Paint
RADAR	RAdio Detection And Ranging
RAM	Random-Access Memory
RED	Reverse-ElectroDialysis
RF	Radio Frequency
RFID	Radio Frequency IDentification
ROFI	Radially Outward Flame Igniters
SLS	Space Launch System
SOA	State Of the Art
T-0	Lift Off
TA	Technology Area
TABS	Technology Area Breakdown Structure
TDRSS	Tracking and Data Relay Satellite Systems
TPS	Thermal Protection Systems
TRL	Technology Readiness Level
TSD	ThermolumineScent Dosimetry
TSP	Temperature Sensitive Paint
UAV	Unmanned Aerial Vehicles
VOIP	Voice Over Internet Protocol
VPN	Virtual Private Network
WIDB	Weather Information DataBase

Abbreviation and Units

Abbreviation	Definition
%	Percent
°	Degrees
BTU/hr-ft	British Thermal Units per Hour Foot
C	Celsius
CH_4	Methane
dB	Decibels
EtO	Ethylene Oxide
FPS	Frames Per Second
gal	Gallon
GB	Gigabytes
Gbps	Gigabits Per Second
GHe	Gaseous Helium
GHz	Gigahertz
K	Kelvin
kbps	Kilobits per second
L	Liters
LH_2	Liquid Hydrogen
LOX	Liquid Oxygen
m	Meters
M	Million
m^2	Square Meters
m^3	Cubic Meters
Mbps	Megabits Per Second
mg	Milligrams
MMH	Monomethyl Hydrazine
NTO	Dinitrogen Tetroxide
PCB	Polychlorinated Biphenyl
psi	Pounds Per Square Inch
Pg	Petagram
s or sec	Seconds
W	Watts

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Technology Candidate Snapshots

13.1 Operational Life Cycle
13.1.1 On-Site Production,Storage, Distribution, and Conservation of Fluids

13.1.1.1 Production of Propellants and Other Fluids from Fresh or Salt Water

TECHNOLOGY

Technology Description: On-site, on-demand production of propellants, other fluids and gases from local environment (fresh or salt water) using emerging technologies that are mobile, modular, and more efficient.

Technology Challenge: Scale up from laboratory demonstration level to industrial level.

Technology State of the Art: Reverse-Electrodialysis (RED) membrane power cell using microbial electrolysis, which requires some electrical input. Chambers of seawater and fresh water with a RED generates energy from the ion difference between the two. The energy is then used in electrolysis to split oxygen and hydrogen from water. Offers potential for unlimited production.

Parameter, Value:	TRL
Percent reduction in cost of propellants and other fluids is 50% in the laboratory.	1

Technology Performance Goal: Reduce overall launch production costs of propellants, other fluids, and gases.

Parameter, Value:	TRL
Achieve laboratory cost savings of 50% but in a relevant environment.	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: On-site, on-demand production of needed propellants, other fluids, and gases.

Capability Description: Meet on-site, on-demand production of needed propellants, other fluids, and gases through a method that uses fresh or salt water.

Capability State of the Art: Air separation plants for oxygen and nitrogen. Natural Gas processing for helium and hydrogen. Methane reformation or industrial waste gas for hydrogen generation. Total cost of propellants and fluids for one Space Shuttle launch was $1.4M. One Space Shuttle launch flew 384,071 tons of liquid hydrogen but needed 450,000-500,000 gallons due to system chill-down, engine bleed, tank pressurization, and venting. Boil-off losses were about 300 gallons per day or 109,500 gallons per year (cost $1 per gallon), and flew 141,750 gallons of liquid oxygen but needed 250,000 gallons due to system chilldown, engine bleed, tank pressurization, and venting. Boil-off losses were about 800-1,000 gallons per day on the pad tank or 292,000 to 365,000 gallons per year (cost $0.67 per gallon).

Parameter, Value:

Cost of propellants and other fluids: $1 per gallon for liquid hydrogen delivered to the launch pad, and $0.67 per gallon for liquid oxygen delivered to the launch pad.

Capability Performance Goal: Apply a reverse-electrodialysis (RED) membrane power cell using microbial electrolysis to produce propellants, other fluids and gases from fresh or salt water.

Parameter, Value:

Cost of propellants and other fluids: $0.50 per gallon for liquid hydrogen delivered to the launch pad, and $0.34 per gallon for liquid oxygen delivered to the launch pad.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.1 Operational Life Cycle
13.1.1 On-Site Production,Storage, Distribution, and Conservation of Fluids

13.1.1.2 Production of Propellants and Other Fluids from Biomass or Landfill

TECHNOLOGY

Technology Description: On-site, on-demand production of propellants, other fluids, and gases from local environment (biomass or landfill) using emerging technologies that are mobile, modular, and more efficient.

Technology Challenge: Technology seen as feasible. Challenge is to compete with natural gas production infrastructure since prices are currently falling.

Technology State of the Art: Several pilot plants have been demonstrated, including some in the Netherlands. The renewable alternative for natural gas is the so-called green natural gas, i.e., gaseous energy carriers produced from biomass comprising both biogas and Synthetic Natural Gas (SNG).

Parameter, Value: Improvement in reduced time to deliver biomass based fuel: 20%

TRL: 4

Technology Performance Goal: Reduce overall launch production costs of propellants, other fluids, and gases.

Parameter, Value: Achieve a cost savings of 50%.

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: On-site, on-demand production of needed propellants, other fluids, and gases.

Capability Description: Produce needed propellants, other fluids, and gases from local resources on-site on an as-needed basis from biomass or landfill.

Capability State of the Art: Air separation plants for oxygen and nitrogen. Natural gas processing for helium. Methane reformation or industrial waste gas for hydrogen generation

Parameter, Value: Cost of propellants and other fluids: $8 per 1,000 cubic feet (natural gas in commercial environment).

Capability Performance Goal: Green natural gas derived from biomass or landfill.

Parameter, Value: Percent reduction in cost of propellants and other fluids: $4 per 1,000 cubic feet (natural gas in commercial environment).

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.1 Operational Life Cycle
13.1.1 On-Site Production,Storage, Distribution, and Conservation of Fluids

13.1.1.3 Low-Loss Storage of Cryogens Through Active Means

TECHNOLOGY

Technology Description: Enable zero loss storage and cryo below their normal boiling point to eliminate storage loss and improve flight mass density for improved rocket performance.

Technology Challenge: Achieving near-zero boil-off will be a challenge. Improvements are technically possible.

Technology State of the Art: There are several laboratory and prototype demonstrations of thermoelectric materials.

Parameter, Value:
Percent improvement in efficiency: 55% (for applications having rare earth elements)

TRL: 3

Technology Performance Goal: Remove heat and return liquid cryogenic propellant to near normal boiling point (NBP) while under transfer pressures through active means.

Parameter, Value:
Percent improvement in efficiency: 50-100%

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Low-loss cryogen storage and storage of cryogens below their normal boiling point.

Capability Description: Enable low-loss storage and storage of cryogens below their normal boiling-point using thermoelectric materials to eliminate storage loss and improve flight mass density for improved rocket performance.

Capability State of the Art: Not currently used in aerospace applications.

Parameter, Value:
Boil-off losses: 0.03% per day (for large vacuum jacketed liquid hydrogen storage tanks).

Capability Performance Goal: Remove heat and return liquid cryogenic propellant to near near normal boiling point while under transfer pressures by using thermoelectric materials.

Parameter, Value:
Percent improvement in efficiency: 50-100%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	4 years

13.1 Operational Life Cycle
13.1.1 On-Site Production,Storage, Distribution, and Conservation of Fluids

13.1.1.4 Higher-Efficiency Storage of Cryogens Through Passive Means

TECHNOLOGY

Technology Description: Reducing parasitic heat leak into storage vessels to reduce energy costs of maintaining them in a cryogenic state.

Technology Challenge: Achieving near-zero boil off will be a challenge. Improvements are technically possible.

Technology State of the Art: Numerous examples of greatly-improved cryogenic system insulation materials include aerogels, sol-gel aerogels, and composite multilayers.

Parameter, Value:

Storage temperature: 118 K (liquid methane), 90 K (liquid oxygen), 20 K (liquid hydrogen) range.

TRL 3

Technology Performance Goal: Remove heat and return liquid cryogenic propellant to near normal boiling point (NBP) while under transfer pressures through passive means.

Parameter, Value:

Achieve current State of the Art but in a relevant environment, i.e., storage temperature: 118 K (liquid methane), 90 K (liquid oxygen), 20 K (liquid hydrogen) range.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Low-loss cryogen storage through passive means.

Capability Description: Reducing parasitic heat leak into storage vessels to reduce energy costs of maintaining cryogenic state.

Capability State of the Art: Perlite radiation barrier in double-wall, vacuum-jacketed storage tanks.

Parameter, Value:

Boil-off losses: 0.03% per day (for large vacuum-jacketed liquid hydrogen storage tanks).

Capability Performance Goal: Achieve near zero boil-off conditions with passive means.

Parameter, Value:

Achieve current storage temperatures with near zero boil-off: 118 K (liquid methane), 90 K (liquid oxygen), 20 K (liquid hydrogen) range.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	4 years

13.1 Operational Life Cycle
13.1.1 On-Site Production,Storage, Distribution, and Conservation of Fluids

13.1.1.5 Higher-Efficiency Transfer of Cryogens Using Active Means

TECHNOLOGY

Technology Description: Autonomously deliver and load normal boiling point or sub-cooled propellant quality at the ground-to-vehicle interface to improve vehicle loading times and flight performance. Includes application of advanced cryocoolers and other active devices embedded throughout system.

Technology Challenge: Achieving near-zero boil off will be a challenge. Improvements are technically possible.

Technology State of the Art: There are several laboratory and prototype demonstrations of thermoelectric materials.

Parameter, Value:

Percent improvement in efficiency: 55%

TRL 3

Technology Performance Goal: Remove heat and return liquid cryogenic propellant to near near normal boil-off while under transfer pressures.

Parameter, Value:

Minimum replenish time: 2 hours;

Percent improvement in boil-off loss efficiency: 50%

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: More efficient management of cryogen transfer using active means.

Capability Description: Deliver normal boiling point or sub-cooled propellant quality at the ground-to-vehicle interface to improve vehicle loading times and flight performance.

Capability State of the Art: Requires long replenish times to return propellant to normal boiling point (NBP) liquid for maximum flight mass.

Parameter, Value:

Minimum replenish time: 1.5 hours (plus 2 hour hold for window);

Percent improvement in boil-off losses: 2.5 BTU/hr-ft

Capability Performance Goal: Remove heat and return liquid cryogenic propellant to near normal boil-off while under transfer pressures using active means.

Parameter, Value:

Minimum replenish time: 2 hours;

Percent improvement in boil-off loss efficiency: 50%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	4 years

13.1 Operational Life Cycle
13.1.1 On-Site Production,Storage, Distribution, and Conservation of Fluids

13.1.1.6 Higher-Efficiency Transfer of Cryogens Using Passive or Vacuum Jacket Means

TECHNOLOGY

Technology Description: Deliver normal boiling point or sub-cooled propellant quality at the ground-to-vehicle interface to improve vehicle loading times and flight performance. Includes application of components having frictionless flow paths and insulative capability embedded within components beyond having this capability in long piping runs.

Technology Challenge: Achieving near-zero boil-off will be a challenge. Improvements are technically possible.

Technology State of the Art: Numerous examples of greatly improved cryogenic system insulation materials.

Parameter, Value:

Thermal conductivity from 0.03 W/m·K in atmospheric pressure down to 0.004 W/m·K in modest vacuum, which correspond to R-values of 14 to 105 (U.S. customary) or 3.0 to 22.2 (metric) for 3.5 inches (89 mm) in thickness.

TRL: 1

Technology Performance Goal: Remove heat and return liquid cryogenic propellant to near normal boil-off while under transfer pressures.

Parameter, Value:

Minimum replenish time: 2 hours;

Percent improvement in boil-off loss efficiency: 50%

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: More efficient management of cryogen transfer using passive/vacuum jackets.

Capability Description: Deliver normal boil-off or sub-cooled propellant quality at the ground-to-vehicle interface to improve vehicle loading times and flight performance using insulative materials for passive/vacuum jackets.

Capability State of the Art: Requires long replenish times to return propellant to normal boiling point (NBP) liquid for maximum flight mass.

Parameter, Value:

Minimum replenish time: 1.5 hours (plus 2 hour hold for window);

Boil-off losses: 2.5 BTU/hr-ft

Capability Performance Goal: Remove heat and return liquid cryogenic propellant to near normal boil-off point under transfer pressures using passive/vacuum jackets.

Parameter, Value:

Minimum replenish time: 2 hours with no hold for window;

Boil-off losses: 1.25 BTU/hr-ft

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	4 years

13.1 Operational Life Cycle
13.1.1 On-Site Production,Storage, Distribution, and Conservation of Fluids

13.1.1.7 Green Propellant Storage and Distribution

TECHNOLOGY

Technology Description: Optimize storage and distribution of green propellants for use on engine test stands and launch complexes. Reduce propellant waste through self-bleeding components.

Technology Challenge: Fluid couplers and fittings that bleed out bubbles internally without loss of propellant do not exist, but are seen as technically feasible.

Technology State of the Art: Fluid couplers and fittings that bleed out bubbles internally without loss of propellant do not exist, but are seen as technically feasible.

Parameter, Value:
Percent loss of propellants: 0%

TRL 3

Technology Performance Goal: Optimize storage and distribution of green propellants for use on engine test stands and launch complexes.

Parameter, Value:
Percent loss of propellants in relevant environment: 0%.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Green propellant storage and distribution with no loss of propellant.

Capability Description: Optimize storage and distribution of green propellants for use on engine test stands and launch complexes with fluid couplers and fittings without loss of propellant.

Capability State of the Art: Traditional ground servicing equipment that requires manual line bleeds to remove bubbles thus causing propellant losses. Example: liquid oxygen/methane for Morpheus test vehicle. Line bleeds to remove bubbles cause propellant losses.

Parameter, Value:
Percent loss of propellants: 10%

Capability Performance Goal: Optimize storage and distribution of green propellants for use on engine test stands and launch complexes by fluid couplers and fittings that self-bleed out bubbles internally without loss of propellant.

Parameter, Value:
Percent loss of propellants: 0%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.1 Operational Life Cycle
13.1.1 On-Site Production,Storage, Distribution, and Conservation of Fluids

13.1.1.8 Toxic Propellant Storage and Distribution

TECHNOLOGY

Technology Description: Optimize storage and distribution of toxic propellants for use on engine test stands and launch complexes. Reduce propellant waste through self-bleeding components.

Technology Challenge: Fluid couplers and fittings that bleed out bubbles internally without loss of propellant do not exist, but are seen as technically feasible.

Technology State of the Art: Fluid couplers and fittings that bleed out bubbles internally without loss of propellant do not exist, but are seen as technically feasible.

Parameter, Value:

Percent loss of propellants: 0%

TRL 3

Technology Performance Goal: Optimize storage and distribution of toxic propellants without manually bleeding the lines.

Parameter, Value:

Percent loss of propellants: 0%

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Toxic propellant storage and distribution with self-bleeding fluid couplers and fittings without loss of propellant.

Capability Description: Optimize storage and distribution of toxic propellants for use on engine test stands and launch complexes.

Capability State of the Art: MMH and N_2O_4 servicing equipment and operations at NASA LC-39 Pads A and B requires manual line bleeding to remove bubbles which cause propellant losses.

Parameter, Value:

Percent loss of propellants: 10%

Capability Performance Goal: Optimize storage and distribution of toxic propellants for use on engine test stands and launch complexes using fluid couplers and fittings that self-bleed out bubbles internally with zero loss of propellant.

Parameter, Value:

Percent loss of propellants: 0%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.1 Operational Life Cycle
13.1.1 On-Site Production,Storage, Distribution, and Conservation of Fluids

13.1.1.9 Helium Waste Stream Recovery, Recondition, and Reuse

TECHNOLOGY

Technology Description: Capture large volumes of helium purge gas waste streams, purify and recover helium, and recycle to high-pressure storage. Production, storage, and transfer of xenon gas may have commonalities with the technological improvements for helium.

Technology Challenge: Scaling up from a laboratory prototype to a system deployed on a launch pad or engine test stand will be a challenge.

Technology State of the Art: Small Business Innovation Research (SBIR) and Small Business Technology Transfer (STTR) projects have demonstrated helium recovery and purification of a hydrogen/helium test gas on a small scale.

Parameter, Value:

Percent helium reused: 40%

TRL 4

Technology Performance Goal: Recover, purify, and reuse of typically used processing helium.

Parameter, Value:

Achieve same reuse percentage as demonstrated in the State of the Art, but in a relevant environment.

Percent helium reused: 40%

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: More efficient management of GHe storage and transportation through helium waste stream recovery, recondition, and reuse.

Capability Description: Capture large volumes of helium waste streams, purify and recover helium, and recycle to high-pressure storage.

Capability State of the Art: None. The closest related technology is closed-loop LHe system used at National Magnetic Labs. Shuttle launches used 1 million cubic feet (10,340 pounds) per launch while only flying 30,000 cubic feet (310 pounds). During the launch of the Space Launch System (SLS) and Multipurpose Crew Vehicle (MPCV) [Block I/Exploration Mission-1], helium consumption will be at a rate of approximately 6 times greater than what was used for Shuttle launches. This approximation does not include the pre-processing of launches.

Parameter, Value:

Percent helium reused: 0%

Capability Performance Goal: Recover, purify, and reuse of typical used processing helium.

Parameter, Value:

Percent helium reused: 40%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	4 years

13.1 Operational Life Cycle
13.1.1 On-Site Production,Storage, Distribution, and Conservation of Fluids

13.1.1.10 Hyperspectral Imaging for Cryogenic Fluids Leak, Fire Detection and Mitigation

TECHNOLOGY

Technology Description: Area surveillance to minimize number of sensors and maximize system coverage for cryogenic fluids and gases. Characterize spectral signature of propellant fires in launch pads and engine test stands through modeling and testing.

Technology Challenge: Field testing of prototype to validate performance.

Technology State of the Art: Several examples of improvements in hyperspectral imaging and prototype demonstrations adequate for use in real-time, accurate surveillance of spills or fires.

Parameter, Value: Percent improvement in time required to identify spills or fires: 50%

TRL: 2

Technology Performance Goal: Real-time, 100% accurate surveillance to identify spills or fires.

Parameter, Value: Achieve SOA percent improvement in time required to identify spills or fires, but in a relevant environment: 50%

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Hyperspectral imaging for cryogenic fluids leak and fire detection/mitigation.

Capability Description: Area surveillance capability to minimize number of sensors and maximize system coverage for cryogenic fluids and gases using spectral imaging characterized to identify spills or fires.

Capability State of the Art: Infrared cameras to image fires not visible to the human eye. Closed-circuit camera surveillance. Mass spectrometers to detect increased background percent of commodities.

Parameter, Value: Time required to identify spills or fires: 1 to 2 minutes.

Capability Performance Goal: Real-time and accurate surveillance through hyperspectral imaging with data processing of characterized spectral signature to identify spills or fires.

Parameter, Value: Percent improvement in time required to identify spills or fires: 30 seconds to 1 minute.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	4 years

13.1 Operational Life Cycle
13.1.1 On-Site Production,Storage, Distribution, and Conservation of Fluids

13.1.1.11 Hyperspectral Imaging for Non-Hazardous Fluids Leak, Fire Detection and Mitigation

TECHNOLOGY

Technology Description: Area surveillance capability to minimize number of sensors and maximize system coverage for green fluids and gases. Characterize spectral signature of propellant fires in launch pads and engine test stands through modeling and testing.

Technology Challenge: Field testing of prototype to validate performance.

Technology State of the Art: Several examples of improvements in hyperspectral imaging and prototype demonstrations adequate for use in real-time, accurate surveillance of spills or fires.

Parameter, Value:	TRL
Percent improvement in time required to identify spills or fires: 50%	2

Technology Performance Goal: Provide real-time, 100 % accurate surveillance through sensors and data processing to identify spills or fires.

Parameter, Value:	TRL
Achieve SOA percent time required to identify spills or fires, but in a relevant environment: 50%	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Hyperspectral imaging for non-hazardous fluids leak and fire detection/mitigation.

Capability Description: Area surveillance capability to minimize number of sensors and maximize system coverage for green fluids and gases using spectral imaging characterized to identify spills or fires.

Capability State of the Art: Infrared cameras to image fires not visible to the human eye. Closed-circuit camera surveillance. Mass spectrometers to detect increased background percent of commodities.

Parameter, Value:

Time required to identify spills or fires: 1 to 2 minutes.

Capability Performance Goal: Real-time and accurate surveillance through hyperspectral imaging with data processing of characterized spectral signature of non-hazardous fluids to identify spills or fires.

Parameter, Value:

Percent improvement in time required to identify spills or fires: 30 seconds to 1 minute.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	4 years

13.1 Operational Life Cycle
13.1.1 On-Site Production,Storage, Distribution, and Conservation of Fluids

13.1.1.12 Hyperspectral Imaging for Toxic Fluids Leak, Fire Detection and Mitigation

TECHNOLOGY

Technology Description: Area surveillance capability to minimize number of sensors and maximize system coverage for hypergolic and toxic fluids and gases. Characterize spectral signature of propellant fires in launch pads and engine test stands through modeling and testing.

Technology Challenge: Field testing of prototype to validate performance.

Technology State of the Art: Several examples of improvements in hyperspectral imaging and prototype demonstrations adequate for use in real-time, accurate surveillance of spills or fires.

Parameter, Value:	TRL
Percent improvement in time required to identify spills or fires: 50%	2

Technology Performance Goal: Provide real-time and 100% accurate surveillance through sensors and data processing to identify spills or fires.

Parameter, Value:	TRL
Achieve SOA percentage of time required to identify spills or fires, but in a relevant environment: 50%	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Hyperspectral imaging for toxic fluids leak and fire detection and mitigation.

Capability Description: Area surveillance capability to minimize number of sensors and maximize system coverage for toxic fluids and gases using spectral imaging characterized to identify spills or fires.

Capability State of the Art: Infrared cameras to image fires not visible to the human eye. Closed-circuit camera surveillance. Mass spectrometers to detect increased background percent of commodities.

Parameter, Value:

Time required to identify spills or fires: 1 to 2 minutes.

Capability Performance Goal: Real-time and accurate surveillance through hyperspectral imaging with data processing of characterized spectral signature of toxic fluids to identify spills or fires.

Parameter, Value:

Percent improvement in time required to identify spills or fires: 30 seconds to 1 minute.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	4 years

13.1 Operational Life Cycle
13.1.2 Automated Alignment, Coupling, Assembly, and Transportation Systems

13.1.2.1 Optical Alignment Systems

TECHNOLOGY

Technology Description: Systems having lasers, cameras, and targets to align payloads to vehicles, engines to test stands, vehicles to pads, and umbilical plates to vehicles for integration of elements.

Technology Challenge: Primary technical challenge will be to ruggedize instruments typically used in air-conditioned spaces for use in outside environments, including launch pads and engine test stands.

Technology State of the Art: Leading candidate technologies that could be developed involve lasers, cameras, and theodolite systems, which are precision instruments for measuring angles in the horizontal and vertical planes.

Parameter, Value:	TRL
Alignment operations time: 8 hours.	4

Technology Performance Goal: Provides for accurate and controlled alignment of hardware for element-to-element integration, such as payloads to vehicles, engines to test stands, vehicles to pads, and umbilical plates to vehicles.

Parameter, Value:	TRL
Alignment operations time in relevant environment: 2 hours.	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Element optical alignment systems.

Capability Description: Accurate and controlled alignment of hardware for element-to-element integration, such as payloads to vehicles, engines to test stands, vehicles to pads, and umbilical plates to vehicles.

Capability State of the Art: SOA includes mechanical alignment pins, concentric boss, and other mechanical fixture systems. Umbilical plates for past and current rockets use a combination mechanical alignment pin, pivot foot, and collet systems. Vehicle stacking and positioning is based on manual observer-based motion and alignment.

Parameter, Value:
Alignment operations time: 8 hours.

Capability Performance Goal: Accurate and controlled optical alignment of hardware for element-to-element integration.

Parameter, Value:
Alignment operations time: 2 hours.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	4 years

13.1 Operational Life Cycle
13.1.2 Automated Alignment, Coupling, Assembly, and Transportation Systems

13.1.2.2 Non-Optical Alignment Systems

TECHNOLOGY

Technology Description: Systems having instrumentation and data processing to non-optically align payloads to vehicles, engines to test stands, vehicles to pads, and umbilical plates to vehicles for integration of elements.

Technology Challenge: Primary technical challenge will be to ruggedize instruments typically used in air-conditioned spaces for use in outside environments, including launch pads and engine test stands.

Technology State of the Art: Leading candidate technologies which could be incorporated include acoustic, inductive (radio frequency), and load or force sensing. There have been laboratory breadboard demonstrations and small-scale operational environment applications.

Parameter, Value: | **TRL**
Alignment operations time: 8 hours. | 3

Technology Performance Goal: Provides for accurate and controlled alignment of hardware for element-to-element integration, such as payloads to vehicles, engines to test stands, vehicles to pads, and umbilical plates to vehicles.

Parameter, Value: | **TRL**
Alignment operations time: 2 hours. | 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Element non-optical alignment systems.

Capability Description: Accurate and controlled alignment of hardware for element-to-element integration, such as payloads to vehicles, engines to test stands, vehicles to pads, and umbilical plates to vehicles.

Capability State of the Art: SOA includes mechanical alignment pins, concentric boss, and other mechanical fixture systems. Umbilical plates for past and current rockets use a combination mechanical alignment pin, pivot foot, and collet systems. Vehicle stacking and positioning is based on manual observer-based motion and alignment.

Parameter, Value:
Alignment operations time: 8 hours.

Capability Performance Goal: Alignment operations time: 8 hours.

Parameter, Value:
Alignment operations time: 2 hours.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	4 years

13.1 Operational Life Cycle
13.1.2 Automated Alignment, Coupling, Assembly, and Transportation Systems

13.1.2.3 Self-Cleaning Couplers

TECHNOLOGY

Technology Description: Ground and flight interfaces of fluid connections self-clean prior to mating in order to reduce the possibility of contamination entering flight hardware.

Technology Challenge: Primary technical challenge will be to integrate passive and active means, as well as ruggedize them for use in outside environments, including launch pads and engine test stands.

Technology State of the Art: Repellent materials and microdevices exist at an individual laboratory scale, but have not been integrated.

Parameter, Value:	TRL
Percent reduction in observed particle counts per 0.1 m^2: 50%	1

Technology Performance Goal: Couplers would have internal materials that do not generate particulates during mating operations and repel particulates.

Parameter, Value:	TRL
In relevant environment, percent reduction in observed particle counts per 0.1 m^2: 50%	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Contamination-resistant, self-cleaning couplers.

Capability Description: Mating of ground and flight interfaces of fluid connections in operational environments introduce levels of contamination into flight hardware. Ground and flight interfaces of fluid connections self-clean prior to mating.

Capability State of the Art: Couplers are disassembled and sent to specialty cleaning shop, or hand cleaned in the field. Protective caps and covers are also utilized to maintain cleanliness.

Parameter, Value:

Particle size, microns/counts per 0.1 m^2:

Class II, GT1000, 0; 700-1000, 40; 175-700; 150

Class III, GT800, 0

Class IV, GT400, 0; 175-400, 5

Capability Performance Goal: Self-cleaning couplers either with passive measures (materials) and/or active measures (purging/heating/mechanical).

Parameter, Value:

Percent reduction in observed particle counts per 0.1 m^2: 50%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	4 years

13.1 Operational Life Cycle
13.1.2 Automated Alignment, Coupling, Assembly, and Transportation Systems

13.1.2.4 Quick Demate/Remate Liftoff (T-0) Couplers

TECHNOLOGY

Technology Description: Couplers that demate/remate prior to T-0.

Technology Challenge: Primary technical challenge will be to integrate and ruggedize for use in outside environments including launch pads.

Technology State of the Art: Quick-response devices using memory-shaped alloys exist at a component level. Nothing exists in a large scale or in a launch environment.

Parameter, Value: Elimination of criticality 1 Failure mode within program failure mode effects analysis critical item list (FMEA/CIL)

TRL: 2

Technology Performance Goal: Reliable demate and remate couplers that demate/remate prior to T-0.

Parameter, Value: Elimination of criticality 1 Failure mode within program FMEA/CIL

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Quick demate and remate T-0 couplers.

Capability Description: Allows for umbilical plates to demate prior to T-0, making launch safer and allows for better protection of ground systems. Quick remate is for abort scenarios.

Capability State of the Art: T-0 umbilical plates demate right at T-0 using mechanical, counter-balanced weights and pyrotechnics into protective enclosures. This is done because remates are currently not possible to support a pad abort scenario. Incomplete remate could cause potential damage to ground and flight systems.

Parameter, Value: Criticality 1 Failure Mode within program FMEA/CIL.

Capability Performance Goal: Umbilical plates to demate prior to T-0; allows quick remate for abort scenarios.

Parameter, Value: Elimination of Criticality 1 Failure Mode within program FMEA/CIL.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.1 Operational Life Cycle
13.1.2 Automated Alignment, Coupling, Assembly, and Transportation Systems

13.1.2.5 Anti-Icing Cryogenic Couplers

TECHNOLOGY

Technology Description: Couplers that self de-ice , i.e., no ice (frozen air constituents) build up on ground-to-flight systems.

Technology Challenge: Primary technical challenge will be to integrate and ruggedize for use in outside environments, including launch pads and engine test stands.

Technology State of the Art: Two universities are developing anti-icing materials.

Parameter, Value:	**TRL**
Elimination of criticality 1 failure mode within program faliure mode effects analysis critical item list (FMEA/CIL).	2

Technology Performance Goal: Cryogenic couplers on ground-to-flight systems that prevent icing (frozen air constituents).

Parameter, Value:	**TRL**
Elimination of criticality 1 failure mode within program FMEA/CIL in relevant environment.	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Anti-icing cryogenic couplers.

Capability Description: Ensures no ice (frozen air constituents) builds up on ground-to-flight system cryogenic couplers. Uses passive (hydrophobic materials) and active (heating) means.

Capability State of the Art: No such systems are used today for this application. Inert nitrogen/helium purge is used in cavity holding mated ground and flight couplers to mitigate icing. Ice breaks away at launch and can damage flight hardware.

Parameter, Value:
Criticality 1 failure mode within program FMEA/CIL.

Capability Performance Goal: Preventing build up of ice to eliminate the risk of ice breaking away at launch and damaging flight hardware.

Parameter, Value:
Elimination of criticality 1 failure mode within program FMEA/CIL.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	4 years

13.1 Operational Life Cycle
13.1.2 Automated Alignment, Coupling, Assembly, and Transportation Systems

13.1.2.6 Self-Locking Liftoff (T-0) Couplers

TECHNOLOGY

Technology Description: Self-locking T-0 couplers on an umbilical plate that provides the overall locking capability of the ground plate to the flight plate.

Technology Challenge: Primary technical challenge will be to integrate and ruggedize for use in outside environments, including launch pads and engine test stands.

Technology State of the Art: Spaceflight systems have current applications of coupler locking devices using Shape Memory Alloys. Applications for fluid couplers are small in size and don't approach the 17 inch disconnect used on the Space Shuttle.

Parameter, Value:	TRL
Percent reduction in weight of flight umbilical plate: 50%	1

Technology Performance Goal: Reduced weight self-locking T-0 couplers.

Parameter, Value:	TRL
Percent reduction in weight of flight umbilical plate: 50%	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Self-locking T-0 couplers.

Capability Description: Allows for weight reduction of flight-side umbilical plate through use of individual couplers on an umbilical plate to provide the overall locking capability of the ground plate to the flight plate, as well as allowing for closer spacing of individual couplers and less complex mechanism.

Capability State of the Art: Redundant solenoid-actuated collets were used on Ares I-X T-0 umbilical.

Parameter, Value:
Weight of flight umbilical plate: 100 pounds

Capability Performance Goal: Reduce weight of flight-side umbilical plate through use of self-locking T-0 couplers on an umbilical plate to provide the overall locking capability of the ground plate to the flight plate, allow for closer spacing of individual couplers with less complex demate mechanism.

Parameter, Value:
Weight of flight umbilical plate: 50 pounds

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.1 Operational Life Cycle
13.1.2 Automated Alignment, Coupling, Assembly, and Transportation Systems

13.1.2.7 Self-Verifying Coupler Interfaces

TECHNOLOGY

Technology Description: Following fluid, electrical ground, and flight coupler mates, leak checks are performed at the source using microdevices.

Technology Challenge: The primary technical challenge will be to integrate and ruggedize interfaces for use in outside environments, including launch pads and engine test stands.

Technology State of the Art: The automobile industry has systems and architectures relevant to electrical connector interface verification systems.

Parameter, Value: | **TRL**

Operations time (electrical or fluid coupler): 8 hours. | 2

Technology Performance Goal: Following flightcoupler mates, leak checks are performed at the source using microdevices that provide go, no-go indications and low-current closed-loop applications across each connector pin-to-pin interface to verify copper path continuity indication.

Parameter, Value: | **TRL**

Operations time (electrical or fluid coupler) reduced to 1 hour. | 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Self-verifying coupler interfaces.

Capability Description: Following fluid, electrical ground, and flight coupler mates, leak checks are performed at the source using microdevices that provide go, no-go indications and low current applications across each connector pin-to-pin interface to self-verify copper paths and go, no-go indication.

Capability State of the Art: No such systems are used today for fluid systems. Electrical connectors are verified through conductivity checks that require control bus drops, circuitry activation, and operator verification of feedback using breakout boxes on downstream connectors, and numerous manual leak checks using bubble solution or helium mass spectrometry devices.

Parameter, Value:

Operations time (electrical coupler): 4 hours; Operations time (fluid coupler): 8 hours.

Capability Performance Goal: Reduced ground operations time to perform interface verification testing.

Parameter, Value:

Operations time (electrical or fluid coupler): 1 hour.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.1 Operational Life Cycle
13.1.2 Automated Alignment, Coupling, Assembly, and Transportation Systems

13.1.2.8 Precision, Automated Vehicle and Equipment Positioning Systems

TECHNOLOGY

Technology Description: Transports and positions vehicles, engines, and payloads where they need to go using embedded sensors, targets, and onboard position determination systems.

Technology Challenge: Primary technical challenge will be to integrate and ruggedize systems for use in outside environments, including launch pads and engine test stands. Need to determine allowable shock and vibration and roadway surface roughness limits.

Technology State of the Art: Military, mining equipment, and automotive applications for automated, guided, vehicle spacing and parking systems using magnetic targets, light detection and ranging (LIDAR), global positioning system (GPS), ultrasonic, etc.

Parameter, Value:
Move operations time: 4 hours.

TRL 9

Technology Performance Goal: Use embedded sensors, targets and onboard position determination systems to reduce operation time and human error.

Parameter, Value:
Move operations time: 1 hour.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Precision, automated vehicle and equipment positioning systems.

Capability Description: Precisely transports and positions vehicles, engines, and payloads in a controlled and precise manner using embedded sensors and targets and onboard position determination systems with reduction in operations time and reduced risk associated with possible human error.

Capability State of the Art: No such systems are used today in the launch environment. All positioning is done manually. There were cases of using alignment tools, such as lasers and targets for Orbiter positioning in the Orbiter Processing Facility.

Parameter, Value:
Move operations time: 4 hours.

Capability Performance Goal: Reduce operations time and reduce risk associated with possible human error.

Parameter, Value:
Move operations time: 1 hour.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.1 Operational Life-Cycle
13.1.2 Automated Alignment, Coupling, Assembly, and Transportation Systems

13.1.2.9 Wireless Power Interfaces for Ground Systems at Pad

TECHNOLOGY

Technology Description: Wireless Power Interfaces for ground systems at pad. Examples include vehicle T-0 interfaces, Mobile Launcher Platform (MLP)-to-pad interfaces, and payload servicing (e.g., battery charging).

Technology Challenge: Improved wireless power transfer efficiency, particularly for systems involving high power and large gaps.

Technology State of the Art: NASA: 250 W+ across up to 6 inches tested;

Academia: 60 W across 6.5 feet;

Industry: 2.5 kW across 2 inches, with parallel connection enabling up to 20 kW.

Parameter, Value:

Power transfer: 2.5 kW;

Efficiency: 60%

TRL 6

Technology Performance Goal: Demonstrate high-power transfer (500 W+) across larger gaps (1 foot or more) for ground systems traditionally connected via physical connectors.

Parameter, Value:

Power transfer: 5 kW;

Efficiency: 90%

TRL 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Development and advancement of wireless power transfer efficiency, and of power-transparent materials for external structures.

CAPABILITY

Needed Capability: More efficient wireless power systems that allow larger transmission distances.

Capability Description: Demonstrate wireless power transfer between: payload (e.g., battery) and ground power; launch vehicle and pad (i.e., T-0 interface); and MLP-to-pad power interfaces. Would provide more robust power interface that is safer (i.e., does not require physical mating/demating), more reliable (no risk of connector damage), and not susceptible to environmental effects (e.g., contamination, corrosion).

Capability State of the Art: High-power wireless systems are used primarily for powering diesel-electric locomotives (U.S.) and for charging electric buses (Europe). Low-power systems are more common for small appliances and electronics. Pad power interfaces involve hardline physical connectors.

Parameter, Value:

Power: 2.5 kW;

Gap/distance: 4.72 in

Capability Performance Goal: Introduction of wireless power for launch pad T-0 interfaces, MLP-to-pad interfaces, and payload prelaunch servicing (e.g., battery charging).

Parameter, Value:

Power: 5kW;

Gap/distance: 10 in

Efficiency: 90%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.1 Life-Cycle Operations
13.1.2 Automatic Alignment, Coupling, Assembly and Transportation Systems

13.1.2.10 Linear Motors as Motive Force for Crawler Transporters

TECHNOLOGY

Technology Description: Provide a low-maintenance, low-emission alternative to diesel-electric motors for the crawler/transporter.

Technology Challenge: Linear motor integration into size and weight of existing crawler transporter.

Technology State of the Art: NASA: Double-sided linear-induction motor prototype, tested to 159 miles per hour (mph).

Other non-NASA linear motors: aircraft carriers' aircraft launcher; maglev transport in service in other countries; "people-mover" public transport; amusement park systems; and urban low-speed maglev systems.

Parameter, Value:
Load: 0.5 tons;
Acceleration: 36.45 ft/s^2

TRL: 6

Technology Performance Goal: Demonstrate low-speed (e.g., 1 mph) translation of a large mass, equivalent to NASA's Crawler Transportation (CT) complement of approximately 14 million pounds.

Parameter, Value:
Load: 7 million tons;
Acceleration: 0.15 ft/s^2

TRL: 8

Technology Development Dependent Upon Basic Research or Other Technology Candidate: Development and advancement of linear motor gap and alignment tolerances, mass capability, and power conversion efficiency.

CAPABILITY

Needed Capability: More efficient linear motors that are also more tolerant of vehicle alignment, distance from stator, and mass.

Capability Description: Demonstrate large mass translation via linear motors at low velocity, incorporated into existing CT infrastructure and vehicle design. Enables fuel conservation, greater reliability, and reduced emissions.

Capability State of the Art: Although the military aircraft launcher has high acceleration capability (approximately 225 mph in 330 ft) for jet aircraft, there are no linear motor systems for translating very large masses.

Parameter, Value:
Load: 0.5 tons;
Acceleration: 36.45 ft/s^2

Capability Performance Goal: Introduction of linear motors for crawler transporters.

Parameter, Value:
Load: 7 million tons;
Acceleration: 0.15 ft/s^2

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.1 Operational Life Cycle
13.1.3 Autonomous Command and Control for Integrated Vehicle and Ground Systems

13.1.3.1 Advanced Planning and Scheduling Systems

TECHNOLOGY

Technology Description: Planning and scheduling systems to optimize the use of resources during operations, from the execution of daily tasks to working within all constraints and requirements to plan longer-range activities such as launch manifests and facility utilization.

Technology Challenge: Accurate information on resource status (availability, quantity). Integration of plans with plan execution via computer software with appropriate feedback to the plan.

Technology State of the Art: Continuous Activity Scheduling, Planning, Execution, and Replanning (CASPER): Autonomous Sciencecraft Experiment (ASE) for photo observation planning and uses space craft command language for plan execution.

NASA's HAL 9000: real-time distributed autonomous planning engine system, nine integrated engines (Mission Manager; power; environmental control and life support systems; communications; guidance, navigation, and control; propulsion; safety; robotics activity) utilizing Timeliner for plan and activity execution.

Nexus planning system prototype: developed at NASA 20 years ago. Explored the challenge of resource modeling to support NASA's request oriented scheduling engine.

Parameter, Value:

Number of Plan Models: 50-75;
Number of Scheduled Activities: 100s;
Difficulty of Model Definition Effort (scale of 1 (low) to 5 (high)): 4;
Resource Based: No;
Activity Based: Yes;
Human-computer interaction (HCI), Graphical: 2D;
Platform: Server class/Desktop
Integrated execution, Partial

TRL
1

Technology Performance Goal: Provide planning and scheduling systems to optimize the use of resources during operations, from the execution of daily tasks to working within all constraints and requirements to plan longer-range activities, such as launch manifests and facility utilization.

Parameter, Value:

In relevant environment:
Number of Plan Models: 1,000s
Number of Scheduled Activities: 1,000s
Difficulty of Model Definition Effort (scale of 1 (low) to 5 (high)): 2

TRL
6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Rapid activity scheduling and plan dissemination.

Capability Description: Provide planning and scheduling systems to optimize the use of resources during operations, from the execution of daily tasks to working within all constraints and requirements to plan longer-range activities such as launch manifests and facility utilization. Must be resource-loaded, integrated and depicted on graphical two-dimensional (2D) and three-dimensional (3D) platform.

Capability State of the Art: For Shuttle: NASA scheduling via commercially-available tools with some customization. Schedules divided into long-term, by test, and daily, around systems and facilities. For International Space Station: use of commercially-available scheduling tool with augmentation by a specialized database. Both applications were not resource-loaded, were not integrated, and were on graphical 2D platform: server class/desktop (typically 2 GHz processor with 6 GB random-access memory (RAM)).

Parameter, Value:

Number of Plan Models: 50-100;
Number of Scheduled Activities: 100s;
Level of difficulty of Model Definition Effort (scale of 1 (low) to 5 (high)): 4

Capability Performance Goal: Provide planning and scheduling system resource-loaded, integrated and depicted on graphical 2D and 3D platform: server cloud/desktop (400 GHz processor with 20 terabytes RAM).

Parameter, Value:

Number of Plan Models: 1,000s;
Number of Scheduled Activities: 1,000s;
Level of difficulty of Model Definition Effort (scale of 1 (low) to 5 (high)): 2

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	4 years

13.1 Operational Life Cycle
13.1.3 Autonomous Command and Control for Integrated Vehicle and Ground Systems

13.1.3.2 Self-Learning Planning Systems

TECHNOLOGY

Technology Description: Activity scheduling primarily determined through system learning (prior good answers, fuzzy logic, and dynamic rule creation).

Technology Challenge: Improvements in system learning and its application (prior good answers, fuzzy logic, and dynamic rule creation). Accurate information on resource status (availability, quantity). Integration of plans with plan execution via computer software with appropriate feedback to the plan.

Technology State of the Art: A commercially-built artificial intelligence (AI) system is capable of answering questions posed in natural language. It is a massive parallel processing computer with a terabyte database and includes highly-focused question-answering capability around hundreds of topics (open domain question answering). The system learns through generalization without specific programming.

Parameter, Value:	TRL
Effort to perform tasks (scale of 1 (low) to 5 (high)): 1	6

Technology Performance Goal: Provide planning and scheduling systems to optimize the use of resources during operations, from the execution of daily tasks to working within all constraints and requirements to plan longer-range activities, such as launch manifests and facility utilization.

Parameter, Value:	TRL
Number of Plan Models: 1,000s; Number of Scheduled Activities: 1,000s; Level of difficulty of Model Definition Effort (scale of 1 (low) to 5 (high)): 1	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Optimum activity schedule generated through machine learning.

Capability Description: Provide planning and scheduling self-learning system to optimize the use of resources during operations, from the execution of daily tasks to working within all constraints and requirements to plan longer-range activities, such as launch manifests and facility utilization. Must be resource-loaded, integrated and depicted on graphical two-dimensional (2D) and three-dimensional (3D) platform.

Capability State of the Art: For Shuttle: NASA scheduling via commercially-available tools with some customization. Schedules divided into long-term, by test, and daily, around systems and facilities. For International Space Station: use of commercially-available scheduling tool with augmentation by a specialized database. Both applications were not resource-loaded, were not integrated and were on graphical 2D platform: server class/desktop (typically 2 GHz processor with 6 GB random access memory (RAM)).

Parameter, Value:

Number of Plan Models: 50-100;

Number of Scheduled Activities: 100s;

Level of difficulty of Model Definition Effort (scale of 1 (low) to 5 (high)): 4

Capability Performance Goal: Provide planning and scheduling self-learning system. Resource-loaded, integrated, and on graphical 2D and 3D platform: server cloud and desktop (400 GHz processor with 20 terabytes RAM).

Parameter, Value:

Number of Plan Models: 1,000s;

Number of Scheduled Activities: 1,000s;

Level of difficulty of Model Definition Effort (scale of 1 (low) to 5 (high)): 1

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.1 Operational Life Cycle
13.1.3 Autonomous Command and Control for Integrated Vehicle and Ground Systems

13.1.3.3 Virtual Training

TECHNOLOGY

Technology Description: Provides immersive training that develops situational awareness and decision making within the assembly and integration, launch preparation, and launch countdown environments.

Technology Challenge: Virtual system, modular components needed. Environment model programming, rapid development techniques. Virtual tactile interfaces.

Technology State of the Art: Virtual reality (VR) is applied to many diverse situations in NASA, the military, commercial industry, and consumer environments. Military uses include vehicle simulators, battlefield simulators, military combat exercises, parachute training, and system repair training. Commercial industry employs virtual training on safety procedures, chemical plant maintenance, and system design evaluations for maintenance.

Parameter, Value:

Level of Rapid Reconfiguration (scale of 1 (difficult) to 5 (easy)): 1;

Level of Support of Situational Awareness/Decision Making (scale of 1 (system specific tasks) to 5 (tactical operations): 3;

Level of Immersion Factor (scale of 1 (conceptual) to 5 (total)): 3

TRL

2

Technology Performance Goal: Seeking a rapidly-reconfigurable system. VR training system supporting operators. Terrestrial factor integration for an airspace and weather facility, launch vehicle interaction, and integration tactical situational awareness.

Parameter, Value:

Level of Rapid Reconfiguration: 5;

Level of Support of Situational Awareness/Decision Making: 5;

Level of Immersion Factor: 5

TRL

6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Rapidly-configurable, interactive virtual environments

Capability Description: Provide immersive training systems to speed situational awareness and decision making and ensure task knowledge and skill proficiency.

Capability State of the Art: International Space Station (ISS) Glass Rack Trainers: visual and touch interactive simulations of science racks for procedure proficiency for ground operators. Access via full-size glass rack and smart pad device. Shuttle, ISS, T-38 Simulators at NASA, pilot, and astronaut training simulators.

Parameter, Value:

Level of Rapid Reconfiguration (scale of 1 (difficult) to 5 (easy)): 1;

Level of Support of Situational Awareness/Decision Making (scale of 1 (system specific tasks) to 5 (tactical operations): 2;

Level of Immersion Factor (scale of 1 (conceptual) to 5 (total)): 2

Capability Performance Goal: Provides exact interaction and visuals for Launch Director for pre-launch and launch countdown. Tele-presence remote robot: hazardous and/or facilitated operations. Holographic monitoring and control for airspace around launch site.

Parameter, Value:

Level of Rapid Reconfiguration: 5;

Level of Support of Situational Awareness/Decision Making: 5;

Level of Immersion Factor: 5

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	4 years

13.1 Operational Life Cycle
13.1.3 Autonomous Command and Control for Integrated Vehicle and Ground Systems

13.1.3.4 Multi-Mission Control Centers

TECHNOLOGY

Technology Description: Provides rapid reconfiguration of the Launch Control Center (LCC) to support different launch vehicles.

Technology Challenge: Common command and control formats. Embedded metadata-based stream decoding. Simple and secure co-hosting of commercial and mission-critical applications. Modular software supporting standard spacecraft and launch vehicle functions with high reuse.

Technology State of the Art: Satellite control rooms joined in the middle by facility service team to facilitate support to multiple customers. Actual operational area is dedicated to one spacecraft. Common bus catalog allows command and telemetry formatting standardization.

Parameter, Value:

Level of Reconfiguration Effort (scale of 1 (easy) to 5 (difficult): 4;

Number of spacecraft/launch vehicles supported simultaneously: 2 to 4;

Number of different spacecraft/launch vehicles system will support: 7 to 10

TRL
9

Technology Performance Goal: Execute rapid deployment for multiple types of spacecraft and multiple spacecraft simultaneously. Commonality of data structures. Commonality of data transmission formats. Data stream intelligent decoding.

Parameter, Value:

Level of Reconfiguration Effort: 4;

Number of spacecraft/launch vehicles supported simultaneously: 2 to 4;

Number of different spacecraft/launch vehicles system will support: 7 to 10

TRL
6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Rapid control room reconfiguration.

Capability Description: Provide distributed, service-oriented architecture technologies for an open architecture LCC to decouple common information services, models, and middleware from applications and improve reuse and interoperability between applications. Easily configurable command and control applications that will work with many vehicles.

Capability State of the Art: Satellite control rooms joined in the middle by facility service team to facilitate support to multiple customers. Actual operational area is dedicated to one spacecraft. Common bus catalog allows command and telemetry formatting standardization.

Parameter, Value:

Level of Reconfiguration Effort (scale of 1 (easy) to 5 (difficult): 4;

Number of spacecraft supported simultaneously: 1;

Number of different spacecraft system will support: 7 to 10

Capability Performance Goal: An LCC that supports multiple types of spacecraft and multiple configurations of the same spacecraft. Commonality of data structures, data transmission formats, or data stream intelligent decoding technology.

Parameter, Value:

Level of Reconfiguration Effort: 1;

Number of spacecraft supported simultaneously: 2 to 4;

Number of different spacecraft system will support: 7 to 10

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	4 years

13.1 Operational Life Cycle
13.1.3 Autonomous Command and Control for Integrated Vehicle and Ground Systems

13.1.3.5 Automated Fault Detection and Isolation Systems

TECHNOLOGY

Technology Description: Provides awareness and determination of faults in a complex system.

Technology Challenge: Embed fault detection, isolation, and recovery system (FDIR) into electronic and avionics assemblies. Processor speed enhancements – 20 GHz verification of rules.

Technology State of the Art: A commercial, real-time embedded diagnostics and reasoner is commercially available. A NASA-developed HAL 9000 Execution Component provides a design and development methodology for intelligent onboard procedures. Autonomous fluid transfer system test-bed. Autonomous intelligent procedures and autonomous plan execution (HAL Execution Component), autonomous mission operations. Another commercial product incorporating intelligent procedures is being used onboard the International Space Station (ISS).

Parameter, Value:

Detection Reliability: .999;

Probability of False Positive: .001;

Probability of Undetected Positive: .001;

Number of parameters monitored: 1,000s;

Number of rules enabled: 100s;

Inference engine limitations.

TRL: 7

Technology Performance Goal: Provide FDIR capability embedded in the system architecture. Detection (D) belongs to situation monitoring, Isolation (I) to situation assessment. Recovery (R) to reaction and planning.

Parameter, Value:

Detection Reliability: .9999;

Probability of False Positive: .0001;

Probability of Undetected Positive: .0001;

Number of parameters monitored; 1,000s;

Number of rules enabled: 1,000s;

Inference engine limitations.

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Fault control and system recovery.

Capability Description: Provide FDIR automated capability embedded in the system architecture.

Capability State of the Art: An existing commercial product is used to perform diagnostics leading to fault isolation. This application is used in test beds and test stands at various centers. NASA's Inductive Monitoring System provides anomaly detection and is based on machine-learning technology to establish knowledge of a system's nominal behavior. A commercial artificial intelligence (AI) expert system has been demonstrated on the ISS for payload monitoring. It is in use at some commercial satellite facilities for control of formation systems. All three systems provide advice to operators, only.

Parameter, Value:

Detection Reliability: .999;

Probability of False Positive: .001;

Probability of Undetected Positive: .001;

Number of parameters monitored: 1,000s;

Number of rules enabled: 100s;

Inference engine limitations.

Capability Performance Goal: FDIR capability embedded in the system architecture will provide operator advice or perform recovery where applicable.

Parameter, Value:

Detection Reliability, .9999

Probability of False Positive, .0001

Probability of Undetected Positive, .0001

Number of parameters Monitored, 1,000s

Number of rules enabled: 1,000s;

Inference engine limitations.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	4 years

13.1 Operational Life Cycle
13.1.3 Autonomous Command and Control for Integrated Vehicle and Ground Systems

13.1.3.6 Real Time Data and Voice Loops to Personal Computer (PC) or Personal Digital Assistant (PDA)

TECHNOLOGY

Technology Description: Provides interactive communication for operators regardless of location.

Technology Challenge: Voice over internet protocol (VOIP) security, VOIP wiretap capability, and voice recognition display real estate.

Technology State of the Art: Data and voice available today via custom and commercial applications.

Parameter, Value:
8 kbps

TRL 8

Technology Performance Goal: Compatible with next four generations of personal data devices. Holographic data display for PDA devices.

Parameter, Value:
8 kbps

TRL 4

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: PC and PDA voice and data.

Capability Description: Control room data and voice available to on-call personnel to support contingency consultation situations and provide situational awareness.

Capability State of the Art: Commercial smartphone applications. VOIP to remote sites.

Parameter, Value:
8 kbps

Capability Performance Goal: Voice recognition and voice command capability.

Parameter, Value:
8 kbps

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	4 years

13.1 Operational Life Cycle
13.1.3 Autonomous Command and Control for Integrated Vehicle and Ground Systems

13.1.3.7 Personal Confirmation Technology

TECHNOLOGY

Technology Description: Provides identity confirmation and location for operators.

Technology Challenge: Reliable voice identification. Reliable but non-obtrusive location technology. Surveillance alerts for critical actions.

Technology State of the Art: Biometrics (eye scan and fingerprinting) in widespread use.

Parameter, Value: Probability of unauthorized access: 0%

TRL: 9

Technology Performance Goal: No unauthorized access.

Parameter, Value: Probability of unauthorized access: 0%

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: System access confirmation.

Capability Description: Allows for easy verification of individuals' identity for system access regardless of location or device, and individuals' location within the work area.

Capability State of the Art: Virtual private network (VPN) technology is prevalent and requires two levels of authentication for log in. Smart card technology use is widespread, but assumes user is the person issued the smart card.

Parameter, Value: Probability of unauthorized access: 0%

Capability Performance Goal: System cannot be compromised.

Parameter, Value: Probability of unauthorized access: 0%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	4 years

13.1 Operational Life Cycle
13.1.3 Autonomous Command and Control for Integrated Vehicle and Ground Systems

13.1.3.8 Concurrent Multi-User Three-Dimensional (3D) Situational Information Environment

TECHNOLOGY

Technology Description: This is the next evolutionary step in reviewing situational data, systems, and operations in a 3D state-driven environment.

Technology Challenge: Multi-user situational data projections with discrete user authorizations.

Technology State of the Art: Large flat computer touch screen display, but does not provide state-driven situational awareness in projected hierarchal manner

Parameter, Value: Time required for team problem solving: minutes to hours.

TRL: 8

Technology Performance Goal: Multi-user, three-dimensional, object oriented projections providing state driven situational data with a topic-specific backdrop, visually rich with subject matter cues and ability to hierarchically break down designs, and operations to subsystem requirements, specifications, or operational performance data that can be manipulated real time through hand gestures and verbal commands.

Parameter, Value: Time required for team problem solving: seconds to minutes.

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Projected, state-driven, situational awareness environment manipulated through three-dimensional physical interaction and hierarchal navigation.

Capability Description: Real-time situational awareness environment to more quickly and safely address launch operation issues.

Capability State of the Art: Limited to large flat video display providing basic system health information.

Parameter, Value: Time required for team problem solving: minutes to hours.

Capability Performance Goal: State-driven data fusion software algorithms providing system design and operation relationship awareness. Projected three-dimensional environment manipulated by hand gestures or voice commands and provide hierarchal navigation through subsystem design, current state, operations, specifications, and requirements.

Parameter, Value: Percent reduction in time required for team problem solving: seconds to minutes.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.1 Operational Life Cycle
13.1.3 Autonomous Command and Control for Integrated Vehicle and Ground Systems

13.1.3.9 Automatic Generation of Ground Operations/Launch Control Software and Test Algorithms

TECHNOLOGY

Technology Description: Human-interactive, automated test procedure and application code reuse in downstream test environments and control centers.

Technology Challenge: Developing strongly-integrated systems for analysis, production, and operations.

Technology State of the Art: Test products reused through manufacturing process and operations environment. Pseudo-code used for flight dynamics analysis software reused in flight code.

Parameter, Value:
Percent of applicable products reused: 100%

TRL 9

Technology Performance Goal: Application code, test scripts, and procedures used in development, assembly, and integration are reused.

Parameter, Value:
Percent of applicable products reused: 100%

TRL 8

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Logic product reuse in progressive testing, assembly and integration, and operational environments.

Capability Description: Human-interactive, automated application code, test scripts, and procedures used in downstream test environments and control centers.

Capability State of the Art: A paper-manual process within NASA.

Parameter, Value:
Percent of applicable products reused: 20%

Capability Performance Goal: Applicable products reused without modification.

Parameter, Value:
Percent of applicable products reused: 100%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	4 years

13.1 Operational Life Cycle
13.1.3 Autonomous Command and Control for Integrated Vehicle and Ground Systems

13.1.3.10 Radio Frequency Identification (RFID) Wireless Instrumentation Systems

TECHNOLOGY

Technology Description: Technology based on RFID-enabled sensing development at the device level and with the interrogator radio frequency (RF) system. An RFID-enabled sensing-based instrumentation system helps to reduce instrumentation design complexity while reducing power requirements through passive sensing.

Technology Challenge: Performance and cross-contamination of RFID sensors under varied environmental conditions needs to be studied and tested. Hydrogen sensors need significant work to make them repeatable and useful.

Technology State of the Art: RFID may be at a relatively high Technology Readiness Level (TRL), but the first field wireless sensor systems are only now being installed, and they still have limitations in the number of sensors and range of operation.

Parameter, Value:

Range: tens of meters (up to 60 meters);

Number of sensors: 10 to 25

TRL 6

Technology Performance Goal: Increase range of operation for sensor systems and increase the number of sensors.

Parameter, Value:

Range: hundreds of meters;

Number of sensors: 50 to 100

TRL 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: RFID sensing applications to enhance sensor accessibility and reliability for launch site operations and processing.

Capability Description: Provide RFID sensing-based applications, to include low-level hydrogen gas sensing for leak detection, liquid level, and humidity sensing, and monitoring strain and pressure measurements.

Capability State of the Art: No deployed RFID sensing system is being used in a NASA operational environment. Use of hand-held bar code readers for inventory management is widespread.

Parameter, Value:

Range: 0 meters;

Number of sensors: 1

Capability Performance Goal: Extended range operation, increase number of sensors; increase reliability and accessibility of sensors.

Parameter, Value:

Range: hundreds of meters;

Number of sensors: 50

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	4 years

13.1 Operational Life Cycle
13.1.3 Autonomous Command and Control for Integrated Vehicle and Ground Systems

13.1.3.11 Standardized Wireless Data Acquisition Systems

TECHNOLOGY

Technology Description: Development of wireless data acquisition systems that can integrate across vendors is a desired technology.

Technology Challenge: Some vendors provide limited wireless integration of their own components with a traditional data acquisition (DAQ) system, but do not integrate outputs of other vendor solutions.

Technology State of the Art: Various wireless acquisition systems exist in industry, but they use proprietary wireless protocols and data formats, which make integration difficult.

Parameter, Value:
Number of channels: 8, 16, or 32 depending on application.

TRL: 4

Technology Performance Goal: Provide a plug-and-play integration capability for multiple wireless data acquisition system deployments into single telemetry stream.

Parameter, Value:
Number of channels: 8, 16, or 32 depending on application.

TRL: 8

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Applications and standard for wireless data acquisition systems.

Capability Description: Provide a communication standard for sharing telemetry that can allow partial wireless solutions to integrate with traditional wired acquisition system solutions.

Capability State of the Art: Various independent wireless acquisition systems deployed in NASA operational environments.

Parameter, Value:
Number of channels: 8, 16, or 32 depending on application.

Capability Performance Goal: Provide a plug-and-play integration capability for multiple wireless data acquisition system deployments into single telemetry stream.

Parameter, Value:
Number of channels: 8, 16, 32 depending on application.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Extending Reach Beyond LEO: DRM 5 Asteroid Redirect – Robotic Spacecraft	Enhancing	2015	2018	2015	1 year

13.1 Operational Life Cycle
13.1.3 Autonomous Command and Control for Integrated Vehicle and Ground Systems

13.1.3.12 Integrated Ground and Flight Vehicle Health Management (IVHM)

TECHNOLOGY

Technology Description: Development in ground and flight hardware and software to provide integrated awareness of ground and vehicle system health and trending conditions.

Technology Challenge: Establishing engineering processes for utilizing elements of IVHM in designs. Enabling the development and use of intelligent devices that can be part of an IVHM knowledge architecture.

Technology State of the Art: IVHM is widely used in the aircraft industry. Modeling of underlying physics of component and use of algorithms to extrapolate life-to-failure thresholds.

Parameter, Value:

Percent reduction in overall operator time to identify, isolate, and correct anomalous conditions: 25%;

Percent reduction in overall costs associated with performance of planned and unplanned maintenance activities: 25%

TRL
9

Technology Performance Goal: IVHM systems to increase visibility into system performance and life-cycle health of flight hardware.

Parameter, Value:

Percent reduction in overall operator time to identify, isolate, and correct anomalous conditions: 25%;

Percent reduction in overall costs associated with performance of planned and unplanned maintenance activities: 25%

TRL
9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Integrated awareness of ground and vehicle system health and trending conditions.

Capability Description: Ground and flight vehicle systems are designed to provide the necessary data such that anomaly detection, diagnostics, and prognostics reduce ground operations time and costs.

Capability State of the Art: Existing systems monitor and respond to critical components that exceed their fault threshold. Ground-based maintenance computers can analyze true vehicle health in real time.

Parameter, Value:

Overall operator time to identify, isolate, and correct anomalous conditions: hours

Overall costs associated with performance of planned and unplanned maintenance activities: $

Capability Performance Goal: Need for rapid recognition and prediction of failures with enough time to take mitigating/corrective action.

Parameter, Value:

Percent reduction in overall operator time to identify, isolate and correct anomalous condition: 25%;

Percent reduction in overall costs associated with performance of planned and unplanned maintenance activities: 25%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	4 years

13.1 Operational Life Cycle
13.1.3 Autonomous Command and Control for Integrated Vehicle and Ground Systems

13.1.3.13 Advanced, Deployable Sensor Networks for Spacecraft, Launch Vehicle, and Pad Monitoring

TECHNOLOGY

Technology Description: Architectures and standards to support the use of sensor networks, data fusion, wireless power and data transfer, integrated health management technologies, and optics for local, remote, portable, and autonomous launch and range operations.

Technology Challenge: Reliability of sensor networks and ability to support safety-critical sensor readings.

Technology State of the Art: Increasing use in industrial process control, automotive, agricultural, and military fields. Some initial use in commercial aircraft.

Parameter, Value:
Sensor deployment time: hours;
Time for reconfiguration of algorithms: minutes.

TRL 3

Technology Performance Goal: Provide ability to rapidly deploy networks of sensors to monitor launch pad and integration environment without the need to deploy or maintain significant wiring infrastructure.

Parameter, Value:
Sensor deployment time: hours;
Time for reconfiguration of algorithms: minutes.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Sensor network architecture and technologies.

Capability Description: Ability to rapidly deploy and configure sensors to monitor new types of conditions, and collaboratively report on their integrated observations.

Capability State of the Art: Initial demonstration of monitoring pad vibro-acoustics via a wireless system has been performed at NASA. Most telemetry from ground support equipment and spacecraft is through traditional sensor networks.

Parameter, Value:
Sensor deployment time: years to months;
Time for reconfiguration of algorithms: months

Capability Performance Goal: Provide ability to rapidly deploy networks of sensors to monitor launch pad and integration environment without the need to deploy or maintain significant wiring infrastructure. Ability to rapidly configure sensors to monitor new types of conditions, and collaboratively report on their integrated observations.

Parameter, Value:
Sensor deployment time: hours;
Time for reconfiguration of algorithms: minutes

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.1 Operational Life Cycle
13.1.3 Autonomous Command and Control for Integrated Vehicle and Ground Systems

13.1.3.14 Rayleigh Scattering

TECHNOLOGY

Technology Description: Provides non-intrusive, seedless gas flow velocity, temperature, and density measurements in ground test facility environment.

Technology Challenge: Low signal-to-noise in low-density environment. Signal contamination from scattered illumination off of facility walls and/or hardware and off of dust entrained in the facility air supply.

Technology State of the Art: Rayleigh scattering has been demonstrated in open jet facilities and high-speed wind tunnels to provide velocity, density, and temperature measurements.

Parameter, Value:

Temperature range: 160 to 500 K;

Velocity range: up to Mach 3.0;

Density range: down to 0.12 kg/m^3

TRL
6

Technology Performance Goal: Rayleigh scattering measurement capabilities (velocity, temperature, and/or density measurements) at relevant environmental conditions.

Parameter, Value:

Percent improvement in accuracy and range of gas flow velocity, temperature, density: 20%

TRL
6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Flow characterization in ground testing.

Capability Description: Characterize flow fields in and around launch system vehicles and/or components in ground tests. Data from ground tests may be used for numerical code validation or design validation.

Capability State of the Art: Traditional wind tunnel smoke traces and array of strings for visual characterization of flow.

Parameter, Value:

Temperature range: 160 to 500 K;

Velocity range: up to Mach 3.0;

Density range: down to 0.12 kg/m^3

Capability Performance Goal: Flow characterization capabilities (velocity, temperature and/or density measurements) at relevant environmental conditions.

Parameter, Value:

Percent improvement in accuracy and range of gas flow velocity, temperature, density: 20%.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.1 Operational Life Cycle
13.1.3 Autonomous Command and Control for Integrated Vehicle and Ground Systems

13.1.3.15 Particle Image Velocimetry (PIV)

TECHNOLOGY

Technology Description: Provides two- or three-component velocity vectors in ground test facility environment.

Technology Challenge: Restricted optical access. Need optical access from at least two orthogonal directions.

Technology State of the Art: Capable of measuring all 2-component or 3-component velocity fields across planar sections of the flow field of interest. Velocity range can be from mm/s up to supersonic.

Parameter, Value:
Test volume size: up to 0.5 m^3

TRL: 6

Technology Performance Goal: Increase field of view coverage by using arrays of cameras. Extend to a tomographic technique for volume velocity measurements.

Parameter, Value:
Percent improvement in volume size: 50%

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Flow characterization in ground testing.

Capability Description: Characterize flow fields in and around launch system vehicles and/or components in ground tests. Data from ground tests may be used for numerical code validation or design validation.

Capability State of the Art: Traditional wind tunnel smoke traces and array of strings for visual characterization of flow.

Parameter, Value:
Test volume size: up to 0.5 m^3

Capability Performance Goal: Able to acquire velocity measurements in low-speed to high-speed flows from ambient temperature up to 2,000 K.

Parameter, Value:
Wider range for 3D velocity vector.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.1 Operational Life Cycle
13.1.3 Autonomous Command and Control for Integrated Vehicle and Ground Systems

13.1.3.16 Advanced Non-Conventional Schlieren Techniques

TECHNOLOGY

Technology Description: Provides two-dimensional (2D) flow visualization of density gradients in ground test facility environment. Provides seedless velocimetry by applying cross-correlation techniques to Schlieren image data in a ground test facility environment.

Technology Challenge: Limited optical access in current facility designs. Harsh environmental constraints, such as high temperatures and supersonic conditions inside the tunnel (affecting interior background-oriented Schlieren designs). Obtaining quantitative density gradients is a very complex problem.

Technology State of the Art: Various Schlieren techniques have been demonstrated in multiple high-speed wind tunnels both small- and large-scale, as well as open jet facilities to provide flow visualization.

Parameter, Value:	TRL
Spatial resolution of flow visualization: 19 microns.	6

Technology Performance Goal: Advanced non-conventional Schlieren techniques. Obtain quantitative density gradients from background-oriented Schlieren image data. Obtain velocity data using cross-correlation methods for post-analysis of Schlieren images.

Parameter, Value:	TRL
Percent improvement in spatial resolution of flow visualization: 20%	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Flow visualization and characterization in ground testing.

Capability Description: Visualize and characterize flow fields in and around launch system vehicles and/or components in ground tests. Data from ground tests may be used for predictive code validations or design validation.

Capability State of the Art: Many of the wind tunnel facilities are currently using conventional Schlieren systems.

Parameter, Value:

Qualitative flow visualization.

Capability Performance Goal: Visualize flow characteristics using different Schlieren techniques most suitable for the specific application.

Parameter, Value:

Percent improvement in spatial resolution: 20%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.1 Operational Life Cycle
13.1.3 Autonomous Command and Control for Integrated Vehicle and Ground Systems

13.1.3.17 Temperature Sensitive Paint

TECHNOLOGY

Technology Description: Paint with temperature sensitive properties that provide surface temperature measurements in ground test facility environment or flight.

Technology Challenge: Less intrusive coatings with good survivability properties, use of sunlight as source for flight and outdoor measurements.

Technology State of the Art: Phosphor thermography and associated coatings have been demonstrated in jet engine environment through space environment conditions where infrared techniques have problems.

Parameter, Value:

Temperature range: -50 to 1,200° C using fluorescence, -50 to 600° C using light absorption.

TRL 6

Technology Performance Goal: Temperature surface measurement capabilities at relevant environmental conditions.

Parameter, Value:

Temperature range: -150° to 1,000° C real-time update of full-field measurements.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Surface property measurements in ground testing.

Capability Description: Characterize temperatures on launch vehicles and/or components in ground or flight tests. Data may be used for predictive code validations, design validation, or safety.

Capability State of the Art: Infrared (IR) thermography.

Parameter, Value:

Temperature range: 250-2,000° C

Capability Performance Goal: Full-field surface temperature characterization on relevant ground and flight test articles using luminescent or absorptive coatings over a wide range of conditions.

Parameter, Value:

Temperature range: -150° to 1,000° C real-time update of full-field measurements.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.1 Operational Life Cycle
13.1.3 Autonomous Command and Control for Integrated Vehicle and Ground Systems

13.1.3.18 Pressure Sensitive Paint

TECHNOLOGY

Technology Description: Paint with pressure sensitive characteristics that provide surface pressure measurements in ground test facility environment.

Technology Challenge: Obtaining images in areas not typically imaged.

Technology State of the Art: Pressure-sensitive paint technology has been demonstrated in aerospace test environments from low to high speed with steady-state and fast-response imaging on stationary and rotating test articles.

Parameter, Value: Pressure range: 0 to 50 psi in partial oxygen environment.

TRL: 6

Technology Performance Goal: Pressure surface measurement capabilities at relevant environmental conditions.

Parameter, Value: Actual pressure at surface rather than calculated estimate (psi).

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Surface property measurements in ground testing.

Capability Description: Characterize surface pressures on launch vehicles and/or components in ground tests. Data may be used for predictive code validations or design validation.

Capability State of the Art: Estimates made through calculations using P, V, T, density.

Parameter, Value: Pressure at surface (psi).

Capability Performance Goal: Full-field surface pressure characterization relevant test articles using oxygen-quenching luminescent coatings.

Parameter, Value: Actual pressure at surface rather than calculated estimate (psi).

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.1 Operational Life Cycle
13.1.3 Autonomous Command and Control for Integrated Vehicle and Ground Systems

13.1.3.19 Advanced Force Measurement System

TECHNOLOGY

Technology Description: Device that provides force measurements in ground test facility environment.

Technology Challenge: Integration of technologies, assurances of non-intrusive applications.

Technology State of the Art: Load cells, torque sensors are common in laboratories and industry.

Parameter, Value: Force measurements, Newtons, or pounds.

TRL: 6

Technology Performance Goal: Provide more accurate, multi-axis and three-dimensional (3D) force measurements in difficult to instrument locations.

Parameter, Value: Percent improvement in force measurements, Newtons, or pounds: 20%

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Force measurements in ground testing.

Capability Description: Device that provides performance data acquired from scale testing of new space vehicle and launch systems in a ground test environment.

Capability State of the Art: Strain gage force and moment measurements balances.

Parameter, Value: Force measurements, Newtons, or pounds.

Capability Performance Goal: Force measurement device that accurately operates in the temperature environments associated with the testing of launch vehicles.

Parameter, Value: Pressure range: 0 to 50 psi in partial oxygen environment. improvement in force measurements, Newtons, or pounds: 20%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.1 Operational Life Cycle
13.1.3 Autonomous Command and Control for Integrated Vehicle and Ground Systems

13.1.3.20 Advanced High-Speed Photography

TECHNOLOGY

Technology Description: Ruggedized equipment for high-speed imaging in ground test facility environment.

Technology Challenge: Ruggedizing and miniaturizing systems for use in NASA ground testing environments.

Technology State of the Art: Several examples of advances in high-speed imaging.

Parameter, Value:
Frame rate: 22,000 frames per second (FPS) at full resolution (1200 x 800).

TRL 6

Technology Performance Goal: High-speed video or imaging that captures visual data of high-speed events during ground tests, such as high-frequency component vibrations.

Parameter, Value:
Frame rate: 22,000 FPS at full resolution (1200 x 800).

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: High-speed video for ground testing.

Capability Description: High-speed video or imaging that captures visual data of high-speed events during ground tests, such as high-frequency component vibrations. Frame rate is improved along with storage capacity.

Capability State of the Art: High-speed cameras.

Parameter, Value:
Frame rate: 7,000 FPS at full resolution (1200 x 800).

Capability Performance Goal: Increased frame rate and storage capability.

Parameter, Value:
Frame rate: 22,000 FPS at full resolution (1200 x 800).

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.1 Operational Life Cycle
13.1.4 Logistics

13.1.4.1 Digital Product Lifecycle Management

TECHNOLOGY

Technology Description: Digital product lifecycle management, reliant on supply chain management and product data management content sourcing. The objective is a system that digitally connects all stakeholders within the extended supply chain processes and products of NASA with informational or bit-based representations of a physical or atom-based object, resulting in the harmonization of people, processes, practices, and technology.

Technology Challenge: The primary challenge is applying to NASA-unique operational environment in regards to integration and commonality.

Technology State of the Art: Engineering: Generates order-specific three-dimensional (3D) models and drawings, multi-directional integration using 3D computer-aided design (CAD) drawing of record with an agile design process using "native" CAD models.

Industrial base manufacturing: data flow, both to and from, CAD and computer-aided manufacturing (CAM) systems to provide for expedient and repeatable generation of computerized numerical control (CNC) programs.

Parameter, Value:	TRL
Percent reduction in logistics costs within Program Lifecycle Cost: 20%	6

Technology Performance Goal: On-demand manufacturing to on-time delivery of product.

Parameter, Value:	TRL
Percent reduction in logistics costs within Program Life Cycle Cost; 20%	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Seamless data and content integration for designing affordability into systems, as well as system commonality and interoperability.

Capability Description: Provide digital product lifecycle management, reliant on supply chain management and product data management content sourcing. The objective is a system that digitally connects all stakeholders within the extended supply chain processes and products of NASA with informational or bit-based representations of a physical or atom-based object, resulting in the harmonization of people, processes, practices, and technology.

Capability State of the Art: Reliance on knowledge base of individual buyers.

Parameter, Value:
Logistics costs within program life cycle cost.

Capability Performance Goal: Digital product lifecycle management, reliant on supply chain management and product data management content sourcing offers potential for 26% reduction in total program cost through 35% reduction in costs for data management; 80% reduction in costs for schedule production; 50% reduction in costs for parts and associated asset management labor; and 18% reduction in recurring costs.

Parameter, Value:
Percent reduction in logistics costs within program lifecycle cost: 20%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.1 Operational Life Cycle
13.1.4 Logistics

13.1.4.2 Supply Chain and Supplier Economic Resilience Modeling

TECHNOLOGY

Technology Description: Next-generation hybrid supply chain management software application that uses programmatic and enterprise hardware demand information, as well as industry financial benchmarks, to efficiently and effectively forecast economic influences on the product and supplier viability throughout the program lifecycle.

Technology Challenge: Applying to NASA-unique operational environment.

Technology State of the Art: A U.S. state government funded a public research university to conduct supply chain analysis on possible effects on state businesses caused by potential defense budget fluctuations. NASA conducted analysis for its exploration program, and a branch of the military employs a supplier risk system.

Parameter, Value:	TRL
Percent reduction in logistics support costs within life cycle costs: 35%	6

Technology Performance Goal: Early identification of supplier and industrial base risk. Allows for collaborative forecast demand planning to help ensure a viable program, multi-program, or multi-agency supply chain.

Parameter, Value:	TRL
Percent reduction in logistics support costs within lifecycle costs: 35%	9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Early determination and objective measuring of risk associated with diminishing manufacturing sources and materials.

Capability Description: Provide a capability for early determination and objective measuring of risks associated with diminishing manufacturing sources and materials, as well as global economic stresses, to allow for concentrated risk mitigation.

Capability State of the Art: Reliance on knowledge base of individual buyers and tactical responses to issues as they arise.

Parameter, Value:
Logistics costs within program lifecycle cost.

Capability Performance Goal: Supply chain and economic resilience modeling offers potential to reduce logistics costs within program lifecycle costs through reduction of recurring and non-recurring costs by improving inventory efficiency.

Parameter, Value:
Percent reduction in logistics support costs within lifecycle costs: 35%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	4 years

13.1 Operational Life Cycle
13.1.4 Logistics

13.1.4.3 Additive Manufacturing as Replacement for Original Equipment Manufacturer (OEM) Spare Parts

TECHNOLOGY

Technology Description: Three-dimensional (3D) printing or additive manufacturing is a process of making a 3D solid object of virtually any shape from a digital model. 3D printing is achieved using an additive process, where successive layers of material are laid down in different shapes.

Technology Challenge: Development, evaluation, and deployment of efficient and flexible additive manufacturing technologies for different types of parts needs.

Technology State of the Art: Emerging applications for composite and metallic materials; still much development needed for other types of materials. Additive manufacturing demonstrated for NASA and commercial rocket engines; NASA electron beam freeform fabrication (EBF3) freeform fabricator laser.

Parameter, Value:	TRL
For specific types of parts, showing potential for percent reduction in logistics warehouse footprint: 50%	2

Technology Performance Goal: Provide 3D printing or additive manufacturing as a process for making a 3D solid object of virtually any shape from a digital model.

Parameter, Value:	TRL
Provide 3D printing or additive manufacturing as a process for making a 3D solid object of virtually any shape from a digital model.	9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: On-demand manufacturing of spare parts to support Earth-based ground operations.

Capability Description: Provide 3D printing or additive manufacturing as a process for making a 3D solid object of virtually any shape from a digital model. Technology creates an adaptive capability for supporting manufacture on-demand while reducing launch costs associated with the logistics footprint.

Capability State of the Art: Stockpiling OEM spare parts in large logistics facility.

Parameter, Value:

Logistics costs within program lifecycle cost resulting from logistics warehouse footprint.

Capability Performance Goal: Provide 3D printing or additive manufacturing as a process for making a three-dimensional solid object of virtually any shape from a digital model.

Parameter, Value:

Percent reduction in logistics warehouse footprint: 50%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	4 years

13.1 Operational Life Cycle
13.1.4 Logistics

13.1.4.4 Light Fidelity Data Transmission and Identification

TECHNOLOGY

Technology Description: Secure wireless communication, continual real-time inventory update and system health using high-intensity, solid-state light emitting diodes (LEDs).

Technology Challenge: Developing transmitting identification tag and component sensors with minimal to no power requirements.

Technology State of the Art: Bench-top demonstrations of this technology have been performed successfully. Offers vast applications within U.S. government and commercial markets. Offers secure wireless data communication and will augment and/or replace existing radio frequency (RF) wireless communication technologies. Visible light communication offers access and multi-user networking is free of disruptive RF signals.

Parameter, Value:

Demonstrated potential for percent reduction in logistics support costs within lifecycle costs: 5%;

Data transmission performance: 10 Gbps

TRL 4

Technology Performance Goal: High-performance computing capability for secure wireless communication, continual real-time inventory update, and system health using high-intensity, solid-state LEDs.

Parameter, Value:

Data transmission performance: 10 Gbps

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Secure and reliable wireless data communication for spare part locations.

Capability Description: High-performance computing capability for secure wireless communication, continual real-time inventory update, and system health using high-intensity, solid-state LEDs.

Capability State of the Art: Databases of parts, counts, and locations within logistics warehouses.

Parameter, Value:

Logistics costs within program lifecycle cost resulting from labor time associated with operating logistics warehouse;

Data transmission performance: not available.

Capability Performance Goal: High-performance computing capability for secure wireless communication, continual real-time inventory update, and system health using high-intensity, solid-state LEDs.

Parameter, Value:

Percent reduction in logistics support costs within lifecycle costs: 5%;

Data transmission performance: 10 Gbps

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	4 years

13.1 Operational Life Cycle
13.1.4 Logistics

13.1.4.5 Counterfeit Part Countermeasures

TECHNOLOGY

Technology Description: Computer chips or nano-scale tags inside genuine parts for systems and other electronics that would identify compromised or counterfeit components and ensure zero incursions into the supply chain.

Technology Challenge: Developing non-intrusive and unique transmitting identification tag and associated vendor deployment costs.

Technology State of the Art: Micro- and nano-scale part identification appears feasible.

Parameter, Value: Potential for zero incursions of counterfeit components into the supply chain is feasible.

TRL: 4

Technology Performance Goal: Provide authentication to positively identify certified parts using computer chips or nano-scale tags inside genuine parts for systems.

Parameter, Value: Zero incursions of counterfeit components into the supply chain.

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Counterfeit part recognition.

Capability Description: Ability to positively identify certified parts using computer chips or nano-scale tags inside genuine parts for systems and other electronics that would identify compromised or counterfeit components and ensure zero incursions into the supply chain.

Capability State of the Art: Tracking vendor component build-up pedigrees.

Parameter, Value: Logistics costs within program lifecycle cost resulting from labor time associated with tracking build-up pedigrees to ensure zero incursions into the supply chain.

Capability Performance Goal: Identify compromised or counterfeit components and ensure zero incursions into the supply chain and eliminate risk of associated catastrophic failure.

Parameter, Value: Zero incursions of counterfeit components into the supply chain.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Extending Reach Beyond LEO: DRM 5 Asteroid Redirect – Robotic Spacecraft	Enhancing	2015	2018	2015	1 year

13.2 Environmental Protection and Green Technologies 13.2.1 Corrosion Prevention, Detection, and Mitigation	**13.2.1.1 Self-Healing, Corrosion-Protective Coatings**

TECHNOLOGY

Technology Description: Self-healing of mechanical damage in corrosion protection coatings.

Technology Challenge: Field application techniques.

Technology State of the Art: There are many efforts reported in the literature using microcapsules for self-healing mechanical damage. NASA's is the only technology that includes the use of elongated microcapsules.	**Technology Performance Goal:** Self-healing of small defects and narrow scratches.
Parameter, Value: Percent reduction in annual maintenance costs: 50%; Life of structure: 20 to 100 years. **TRL** 4	**Parameter, Value:** Percent reduction in annual maintenance costs: 50%; Life of structure: 20 to 100 years. **TRL** 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Self-healing corrosion-protective coatings.

Capability Description: Corrosion-protective coatings with the ability to self-heal or repair mechanical damage, such as abrasion and scratches.

Capability State of the Art: NASA pioneered and patented the technology for smart, environmentally friendly coatings. NASA's corrosion-triggered microcapsules and microparticles are unique in the field. Fielded structures use corrosion-inhibiting coatings.	**Capability Performance Goal:** Self-healing coating that can repair minor mechanical damage, such as scratches and minor scribes.
Parameter, Value: Annual maintenance costs: $; Life of structure: 10 to 50 years	**Parameter, Value:** Percent reduction in annual maintenance costs: 50%; Life of structure: 20 to 100 years.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	4 years

13.2 Environmental Protection and Green Technologies
13.2.1 Corrosion Prevention, Detection, and Mitigation

13.2.1.2 Corrosion or Degradation Resistant Materials

TECHNOLOGY

Technology Description: Materials resistant to corrosion or degradation in launch pad environment, extraterrestrial environments, and human habitats.

Technology Challenge: Ensuring equivalent material properties as current materials.

Technology State of the Art: There are many efforts reported in the literature aimed at developing more corrosion-resistant alloys.

Parameter, Value:

Percent reduction in annual maintenance costs: 50%;

Life of structure: 20 to 100 years.

TRL 3

Technology Performance Goal: Corrosion- and degradation-resistant materials that do not require coatings for protection.

Parameter, Value:

Percent reduction in annual maintenance costs: 50%;

Life of structure: 20 to 100 years.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Corrosion-resistant materials for different environments.

Capability Description: Corrosion- and degradation-resistant materials for different environments, such as the launch environment, extraterrestrial environments, and human habitats.

Capability State of the Art: NASA pioneered and patented the technology for smart, environmentally friendly coatings. NASA's corrosion-triggered microcapsules and microparticles are unique in the field. Fielded structures use corrosion-inhibiting coatings.

Parameter, Value:

Annual maintenance costs: $;

Life of structure: 10 to 50 years.

Capability Performance Goal: Corrosion- and degradation-resistant materials that do not require coatings for protection, resulting in lower maintenance costs and longer life spans.

Parameter, Value:

Percent reduction in annual maintenance costs: 50%;

Life of structure: 20 to 100 years.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.2 Environmental Protection and Green Technologies
13.2.1 Corrosion Prevention, Detection, and Mitigation

13.2.1.3 Self-Healing Launch Structures

TECHNOLOGY

Technology Description: Diagnostic, prognostic fault detection and self-repair in launch pad environment.

Technology Challenge: Ensuring equivalent material properties as current materials.

Technology State of the Art	TRL	Technology Performance Goal	TRL
Technology State of the Art: There are many efforts reported in the literature aimed at developing self-healing structures. Examples include self-healing concrete and self-healing composites.		**Technology Performance Goal:** Reduce need for coatings or repairs.	
Parameter, Value: Percent reduction in annual maintenance costs: 75%; Life of structure: 40 to 200 years.	3	**Parameter, Value:** Percent reduction in annual maintenance costs: 75%; Life of structure: 40 to 200 years.	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Self-repair and fault detection for launch structures.

Capability Description: Structures with diagnostic and prognostic fault detection and self-repair capabilities for high performance. Corrosion-hardened materials that perform without degradation or the need for coatings or repairs.

Capability State of the Art	Capability Performance Goal
Capability State of the Art: Patent filed. Fielded structures use corrosion-inhibiting coatings.	**Capability Performance Goal:** Degradation-resistant structures that self-repair corrosion and heal minor mechanical damage autonomously.
Parameter, Value: Annual maintenance costs: $; Life of structure: 10 to 50 years.	**Parameter, Value:** Percent reduction in annual maintenance costs: 75%; Life of structure: 40 to 200 years.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.2 Environmental Protection and Green Technologies
13.2.1 Corrosion Prevention, Detection, and Mitigation

13.2.1.4 Environmentally Friendly Corrosion Preventative Compounds

TECHNOLOGY

Technology Description: Provides cost effective, temporary corrosion protection in launch environment.

Technology Challenge: Field application techniques are a challenge.

Technology State of the Art: There are no other similar efforts outside of NASA.

Parameter, Value:
Increased life of structure: not available.

TRL
None

Technology Performance Goal: Cost-effective, environmentally friendly, corrosion-preventative compound for temporary corrosion protection when more permanent coatings are not an option.

Parameter, Value:
Increased life of structure: 2x

TRL
6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Temporary corrosion-preventative compounds.

Capability Description: Cost-effective, environmentally friendly, corrosion-preventative compound for temporary corrosion protection in a launch environment.

Capability State of the Art: NASA is currently testing a commercially-available corrosion-preventative compound with the objective of finding environmentally friendly ones that can be used by NASA.

Parameter, Value:
Increased life of structure: 2x

Capability Performance Goal: Cost-effective, environmentally friendly, corrosion-preventative compound for temporary corrosion protection when more permanent coatings are not an option.

Parameter, Value:
Increased life of structure: 2x

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.2 Environmental Protection and Green Technologies
13.2.1 Corrosion Prevention, Detection, and Mitigation

13.2.1.5 Accurate Service Life Prediction Methods for Materials and Coatings

TECHNOLOGY

Technology Description: Methods that predict service life in launch environment.

Technology Challenge: A lengthy test program is required to validate models.

Technology State of the Art: There are many similar efforts reported in the literature, and this has been identified as one of the grand challenges in corrosion research.

Parameter, Value:
Accuracy of prediction: ± 5%

TRL: 2

Technology Performance Goal: An accurate methodology to predict service life of materials and coatings in different environments.

Parameter, Value:
Accuracy of prediction: ± 5%

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Service life prediction methodology for materials and coatings.

Capability Description: An accurate methodology to predict service life of materials and coatings in launch environment.

Capability State of the Art: NASA is currently seeking an accurate method to predict service life of materials and coatings.

Parameter, Value:
Accuracy of prediction: ± 5%

Capability Performance Goal: A method that accurately predicts service life of materials and coatings when compared to historically-available data.

Parameter, Value:
Accuracy of prediction: ± 5%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.2 Environmental Protection and Green Technologies
13.2.1 Corrosion Prevention, Detection, and Mitigation

13.2.1.6 Accurate Service Life Prediction Methods for Legacy Structures

TECHNOLOGY

Technology Description: Algorithm that forecasts structures' remaining service time.

Technology Challenge: A lengthy test program is required to validate models.

Technology State of the Art: There are many similar efforts reported in the literature, and this has been identified as one of the grand challenges in corrosion research.

Parameter, Value:
Accuracy of prediction: ± 5%

TRL: 2

Technology Performance Goal: Forecast of remaining life matches that are obtained with long-term historical data.

Parameter, Value:
Accuracy of prediction: ± 5%

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Service life prediction methodology for legacy structures.

Capability Description: Method that provides an accurate forecast of remaining service time until major repair, replacement, or overhaul becomes necessary, i.e., corrosion prognosis.

Capability State of the Art: NASA is currently seeking a method to predict service life of materials and coatings accurately.

Parameter, Value:
Accuracy of prediction: ± 5%

Capability Performance Goal: A method that accurately predicts service life of materials and coatings when compared to historically available data.

Parameter, Value:
Accuracy of prediction: ± 5%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.2 Environmental Protection and Green Technologies
13.2.1 Corrosion Prevention, Detection, and Mitigation

13.2.1.7 Accelerated Corrosion or Material Degradation Methodology

TECHNOLOGY

Technology Description: Method that provides correlation between laboratory testing and launch environment.

Technology Challenge: A lengthy test program is required to validate models.

Technology State of the Art: There are many similar efforts reported in the literature and this has been identified as one of the grand challenges in corrosion research.

Parameter, Value: 1 week in a laboratory is equivalent to 10 years in the field.

TRL: 2

Technology Performance Goal: A method that accurately predicts remaining service time of materials and coatings when compared to historically-available data.

Parameter, Value: 1 week in a laboratory is equivalent to 10 years in the field.

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Accelerated corrosion and material degradation model.

Capability Description: Model provides an accelerated corrosion testing process under controlled laboratory conditions that would quantitatively correlate to long-term behavior observed in actual service environments.

Capability State of the Art: NASA is currently seeking a method for accelerating corrosion testing.

Parameter, Value: 1 week in a laboratory is equivalent to 10 years in the field.

Capability Performance Goal: A method that accurately predicts remaining service time of materials and coatings when compared to historically-available data.

Parameter, Value: 1 week in a laboratory is equivalent to 10 years in the field.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.2 Environmental Protection and Green Technologies
13.2.2 Environmental Remediation and Site Restoration

13.2.2.1 Environmental Cleanup of Impacted Systems

TECHNOLOGY

Technology Description: Cleanup technologies for impacted environmental systems.

Technology Challenge: Field application techniques are a challenge.

Technology State of the Art: Several examples of testing at cleanup sites.

Parameter, Value:
Percent effective all contaminants: 0-99%

TRL 2

Technology Performance Goal: Effectively cleanup impacted environmental systems by removing heavy metal and other contaminants from water sources, soil, sediment, structures, etc.

Parameter, Value:
Percent effective all contaminants: 99%

TRL 2

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Environmental cleanup of impacted environmental systems (sediments, groundwater, soils).

Capability Description: Effectively remove heavy metals and other contaminants from water sources, soil, sediment, structures, etc.

Capability State of the Art: Polychlorinated biphenyl (PCB) treatment in sediment systems.

Parameter, Value:
Percent effective PCB treatment: 90%

Capability Performance Goal: Develop technologies that effectively remove heavy metals and other contaminants from water sources, soil, sediment, structures, etc.

Parameter, Value:
Percent effective all contaminants: 99%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.2 Environmental Protection and Green Technologies
13.2.2 Environmental Remediation and Site Restoration

13.2.2.2 Environmentally Friendly Alternative Cleaning Techniques

TECHNOLOGY

Technology Description: Environmentally friendly precision cleaning techniques for spacecraft and ground support equipment.

Technology Challenge: Replacing fluorinated solvents is difficult because few other solvents are able to clean fluorinated greases.

Technology State of the Art: Alternative cleaning solvents and technologies have achieved > 90% cleaning efficiencies.

Parameter, Value: Percent effective to achieve non-volatile residue (NVR) level 25A ($1mg/0.1m^2$): 90%

TRL: 5

Technology Performance Goal: Develop alternative technologies that use green solvents and other environmentally friendly cleaning techniques and facilities that are equal to or better than current methods.

Parameter, Value: Percent effective to achieve NVR level 25A ($1mg/0.1m^2$): 100%

TRL: 7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Environmentally friendly precision cleaning.

Capability Description: Alternative green solvents and other enivronmentally friendly techniques for cleaning spacecraft and ground support equipment.

Capability State of the Art: Current precision cleaning practices use fluorinated solvents.

Parameter, Value: Percent effective to achieve NVR level 25A ($1mg/0.1m^2$): 100%

Capability Performance Goal: Green solvents and other environmentally friendly cleaning techniques that are equal or better than current methods.

Parameter, Value: Percent effective to achieve NVR level 25A ($1mg/0.1m^2$); 100%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Extending Reach Beyond LEO: DRM 5 Asteroid Redirect – Robotic Spacecraft	Enabling	2015	2018	2015	1 year

13.2 Environmental Protection and Green Technologies
13.2.2 Environmental Remediation and Site Restoration

13.2.2.3 Automated Deep-Deployment Sediment Analysis Tool

TECHNOLOGY

Technology Description: Capability to adequately sample and analyze for contamination so that effective removal techniques can be employed.

Technology Challenge: Developing an effective set of approaches for all possible contamination sites is a challenge.

Technology State of the Art: Several examples of testing at cleanup sites.

Parameter, Value: Showing potential for time required to characterize contamination: 2 days.

TRL 4

Technology Performance Goal: Adequately sample and analyze for contamination so that effective removal techniques can be employed throught automation.

Parameter, Value: Time required to characterize contamination: 2 days.

TRL 7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Environmental monitoring of contaminated media.

Capability Description: Uses an automated deep-deployment sediment analysis tool to adequately sample and analyze for contamination so that effective removal techniques can be employed.

Capability State of the Art: Automated capability does not exist. Characterizations are performed manually using best practices.

Parameter, Value: Time required to characterize contamination: 2 weeks.

Capability Performance Goal: Adequately samples and analyzes for contamination so that effective removal techniques can be employed in a time efficient manner.

Parameter, Value: Time required to characterize contamination: 2 days.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.2 Environmental Protection and Green Technologies
13.2.3 Preservation of Natural Ecosystems

13.2.3.1 Concrete Aggregates or Binders for Reduced Carbon Emissions

TECHNOLOGY

Technology Description: Cement, concrete, and other composite construction materials that contain synthetic calcium and magnesium carbonate to reduce carbon emissions.

Technology Challenge: Ensuring new cements and concretes have similar curing times and strength properties to current products is a challenge. The key is to reduce production costs.

Technology State of the Art: Cement, concrete, and other composite construction materials that contain synthetic calcium and magnesium carbonate to reduce carbon emissions.

Parameter, Value:

Curing times: 1 to 7 days;

Strength: 200 kg/cm^2;

Cost to produce: $200 per cubic yard;

Carbon quantity: 0.5 ton of CO_2 per 1 ton of cement.

TRL 4

Technology Performance Goal: Cement, concrete, and other composite construction materials that contain synthetic calcium and magnesium carbonate to reduce carbon emissions.

Parameter, Value:

Curing times: 1 to 7 days;

Strength: 200 kg/cm^2;

Cost to produce: $100 per cubic yard;

Carbon quantity: 0.25 ton of CO_2 per 1 ton of cement.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Concrete aggregates/binders that reduced carbon emissions.

Capability Description: Cement, concrete, and other composite construction materials that contain synthetic calcium and magnesium carbonate to reduce carbon emissions.

Capability State of the Art: Almost all cement used today is a commercial product, a convenient and cheap material that reacts with water to bind aggregates like gravel and sand. This cement was patented in 1824, and has become by far the dominant technology, ousting traditional rival construction materials. Cement production is one of the dirtiest industrial processes on the planet. It produces nearly 9% of global carbon emissions. Partial replacement of current common cement products with fly ash or slag reduces CO_2 emissions.

Parameter, Value:

Curing times: 1 to 7 days;

Strength: 200 kg/cm^2;

Cost to produce: $200 per cubic yard;

Carbon quantity: 1 ton of CO_2 per 1 ton of cement.

Capability Performance Goal: Produce cement, concrete, and other composite construction materials that contain synthetic calcium and magnesium carbonate to reduce carbon emission.

Parameter, Value:

Curing times: 1 to 7 days;

Strength: 200 kg/cm^2;

Cost to produce: $100 per cubic yard

Carbon quantity: 0.25 ton of CO_2 per 1 ton of cement.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.2 Environmental Protection and Green Technologies
13.2.3 Preservation of Natural Ecosystems

13.2.3.2 Bio-Char Creation for Soil Improvement and Carbon Sequestration

TECHNOLOGY

Technology Description: Charcoal from plant-removal programs and pyrolysis of organic waste to improve soil quality and sequester carbon.

Technology Challenge: Better understand mechanisms and how to scale up. Improving soil fertility and crop yield is an intricate task.

Technology State of the Art: Improve plant yield to improve water quality, reduce soil emissions of greenhouse gases, reduce nutrient leaching, reduce soil acidity, and reduce irrigation and fertilizer requirements. For biochar to serve a beneficial role in revitalizing nutrient-impoverished soils, there should be a noted increase in the quantity of plant available nutrients and its nutrition retention capacity. However, improving soil fertility and crop yield is an intricate task.

Parameter, Value:
Sustainable use of biocharring could reduce the global net emissions of carbon dioxide, methane, and nitrous oxide by up to 1.8 Pg CO_2-C equivalent (CO_2-C_e) per year which is 12% of current anthropogenic CO_2-C_e emissions.

TRL: 2

Technology Performance Goal: Process that produces bio-char through pyrolysis of organic waste streams and biomass from exotic plant removal programs.

Parameter, Value:
Sustainable use of bio-charring could reduce the global net emissions of carbon dioxide (CO_2), methane, and nitrous oxide by up to 1.8 Pg CO_2-C equivalent (CO_2-C_e) per year which is 12% of current anthropogenic CO_2-C_e emissions.

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Use of organic waste to improve soil quality and carbon sequestration.

Capability Description: Process that produces bio-char through pyrolysis of organic waste streams and biomass from exotic plant removal programs which can both improve soil fertility and sequester carbon when incorporated into soil.

Capability State of the Art: No SOA for this capability exists.

Parameter, Value:
No data is available.

Capability Performance Goal: Process to produce biochar through pyrolysis of organic waste streams and biomass from exotic plant removal programs which can both improve soil fertility and sequester carbon when incorporated into soil.

Parameter, Value:
Sustainable use of bio-charring could reduce the global net emissions of carbon dioxide (CO_2), methane, and nitrous oxide by up to 1.8 Pg CO_2-C equivalent (CO_2-C_e) per year which is 12% of current anthropogenic CO_2-C_e emissions.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.2 Environmental Protection and Green Technologies
13.2.3 Preservation of Natural Ecosystems

13.2.3.3 Multispectral Thermal, Hyperspectral Imaging to Map Evapotranspiration Rates and Detect Disease

TECHNOLOGY

Technology Description: Multispectral thermal, hyperspectral imaging to map evapotranspiration rates to correlate with disease detection and prediction.

Technology Challenge: Integration of technologies for full characterization capabilities.

Technology State of the Art: Several commercially-available multispectral thermal, hyperspectral imaging equipment for specific applications.

Parameter, Value:
Percent accurate characterizations: 99%;
Time required to perform characterizations: 2 days.

TRL 4

Technology Performance Goal: Multispectral thermal, hyperspectral imaging to map evapotranspiration rates and detect disease.

Parameter, Value:
Percent accurate characterizations: 99%;
Time required to perform characterizations: 2 days.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Map evapotranspiration rates and detect disease.

Capability Description: Map evapotranspiration rates and detect disease for coastal communities using multispectral thermal, hyperspectral imaging.

Capability State of the Art: Use separate instruments including on-site visual characterizations such as light detection and ranging (LIDAR), hyperspectral, and thermal.

Parameter, Value:
Percent accurate characterizations: 90%;
Time required to perform characterizations: 2 weeks.

Capability Performance Goal: Reduce time and increase accuracy to map evapotranspiration rates and detect disease.

Parameter, Value:
Percent accurate characterizations: 99%;
Time required to perform characterizations: 2 days.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.2 Environmental Protection and Green Technologies
13.2.4 Alternate Energy Prototypes

13.2.4.1 Energy Storage for Backup Power Using Flywheels

TECHNOLOGY

Technology Description: Large energy storage to serve as back-up power to safety-critical spaceport and test stand operations.

Technology Challenge: Scale-up and reliability will be the challenge.

Technology State of the Art: Flywheel products are a long-lasting, low-maintenance, lightweight, and environmentally sound alternative to flooded and valve regulated lead-acid batteries in uninterruptible power supply systems.

Parameter, Value:
No loss of power to critical systems in event of power grid failure;
Life: 20 to 40 years.

TRL: 6

Technology Performance Goal: Large energy storage to serve as back-up power to safety-critical spaceport and test stand operations with minimal life cycle maintenance costs and hazardous waste stream production.

Parameter, Value:
No loss of power to critical systems in event of power grid failure;
Life: 20 to 40 years.

TRL: 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Energy storage for backup power.

Capability Description: Large energy storage capability to serve as back-up power to safety critical spaceport and test stand operations with minimal lifecycle maintenance costs and hazardous waste stream production.

Capability State of the Art: Banks of lead acid batteries and diesel generators protect launch countdown and engine test stands during critical test timeframes. Proton exchange membrane (PEM) fuel cells as alternative back-up power supplies have been successfully implemented.

Parameter, Value:
No loss of power to critical systems in event of power grid failure;
Life: 10 to 20 years.

Capability Performance Goal: Large energy storage capability to serve as back-up power to safety critical spaceport and test stand operations with minimal life cycle maintenance costs and hazardous waste stream production.

Parameter, Value:
No loss of power to critical systems in event of power grid failure;
Life: 20 to 40 years.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.2 Environmental Protection and Green Technologies
13.2.4 Alternate Energy Prototypes

13.2.4.2 Energy Storage for Backup Power Using Carbon-Based Materials

TECHNOLOGY

Technology Description: Large energy storage using carbon-based materials to serve as back-up power to safety-critical spaceport and test stand operations with minimal lifecycle maintenance costs and hazardous waste stream production.

Technology Challenge: Requires the production of high-quality graphene in sheets large enough to generate suitable electrodes.

Technology State of the Art: A graphene-based battery and ultracapacitor can perform as a robust, lightweight, flexible, thin, and inexpensive energy storage device with energy and power densities superior to those of state of the art lithium-ion batteries.

Parameter, Value:

No loss of power to critical systems in event of power grid failure;

Life: 20 to 40 years.

TRL: 2

Technology Performance Goal: Large energy storage using carbon-based materials to serve as back-up power to safety-critical spaceport and test stand operations.

Parameter, Value:

No loss of power to critical systems in event of power grid failure;

Life: 20 to 40 years.

TRL: 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Energy storage for backup power using carbon-based materials.

Capability Description: Using carbon-based materials, dlevers back-up power to safety-critical spaceport and test stand operations with minimal lifecycle maintenance costs and hazardous waste stream production.

Capability State of the Art: Banks of lead acid batteries and diesel generators to protect launch countdown and engine test stands during critical test timeframes. The use of proton exchange membrane (PEM) fuel cells as alternative back-up power supplies have been successfully implemented.

Parameter, Value:

No loss of power to critical systems in event of power grid failure;

Life: 10 to 20 years.

Capability Performance Goal: Back-up power to safety critical spaceport and test stand operations with minimal life cycle maintenance costs and hazardous waste stream production.

Parameter, Value:

No loss of power to critical systems in event of power grid failure;

Life: 20 to 40 years.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.2 Environmental Protection and Green Technologies
13.2.5 Curatorial Facilities, Planetary Protection, and Clean Rooms

13.2.5.1 Molecular-Based Analysis of Biological Contamination

TECHNOLOGY

Technology Description: Qualitatively assessing or quantitatively measuring the presence or amount of biological contaminant.

Technology Challenge: Moving beyond the standard (culture-based) assay with next-generation, molecular-based analyses for a more comprehensive snapshot of total bioburden (living and dead).

Technology State of the Art: Metagenomics is the study of metagenomes, genetic material recovered directly from environmental samples.

Parameter, Value:

Percent accuracy of results for types and quantities of contaminants: 90-99%;

Time to get test result: 4 to 6 hours.

TRL 4

Technology Performance Goal: Assess biological contaminants present in spaceflight hardware, either prior to launch or after return from space, that is more sensitive and faster than current methods.

Parameter, Value:

Percent accuracy of results for types and quantities of contaminants: 90-99%;

Time to get test result: 4 to 6 hours.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Molecular-based analysis of biological contamination.

Capability Description: Assess qualitatively or quantitatively biological contaminants present in spaceflight hardware either prior to launch or after return from space.

Capability State of the Art: Today, the standard method is a culture-based assay.

Parameter, Value:

Percent accuracy of results for types and quantities of contaminants: 90%;

Time to get test result: 4 to 6 days.

Capability Performance Goal: Assess biological contaminants present in spaceflight hardware either prior to launch or after return from space that is more sensitive and faster than current methods.

Parameter, Value:

Percent accuracy of results for types and quantities of contaminants: 90-99%;

Time to get test result: 4 to 6 hours.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
New Frontiers: Comet Surface Sample Return	Enabling	--	2024	2016	2 years
New Frontiers: Lunar South Pole-Aitken Basin Sample Return	Enabling	--	2024	2016	2 years
New Frontiers: Saturn Probe	Enabling	--	2024	2016	2 years
New Frontiers: Trojan Tour and Rendezvous	Enabling	--	2024	2016	2 years
New Frontiers: Venus In-Situ Explorer	Enabling	--	2024	2016	2 years
Planetary Flagship: Europa	Enabling	--	2022*	2019	4 years
Planetary Flagship: Mars Sample Return	Enabling	--	2026*	2023	4 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

13.2 Environmental Protection and Green Technologies
13.2.5 Curatorial Facilities, Planetary Protection, and Clean Rooms

13.2.5.2 Next Generation Ground and/or In-Flight Sterilization

TECHNOLOGY

Technology Description: Non-destructive penetrating and surface treatments (e.g., hard radiation, gas-phase chemicals, cold plasma, electron-beam irradiation, ion desorption or ablation, and chemical and abrasive cleaning).

Technology Challenge: Developing heat-independent sterilization methods is a challenge.

Technology State of the Art: Emerging methods include: hard radiation, gas-phase chemicals, cold plasma, electron-beam irradiation, ion desorption and ablation, chemical, and abrasive cleaning.

Parameter, Value:	TRL
Percent sterilization effectiveness: 99%	3

Technology Performance Goal: More effective and less complex non-destructive penetrating and surface treatments to sterilize flight hardware either on the ground or in-flight.

Parameter, Value:	TRL
Percent sterilization effectiveness: 99%	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Non-destructive surface treatments for flight sterilization.

Capability Description: Non-destructive penetrating and surface treatments to sterilize flight hardware either on the ground or in-flight.

Capability State of the Art: Today's methods include vapor phase hydrogen peroxide, isopropyl alcohol, ultrasonication, Freon or N_2 purges, and alkaline detergent soap.

Parameter, Value:

Percent sterilization effectiveness: 90%

Capability Performance Goal: More effective and less complex non-destructive penetrating and surface treatments to sterilize flight hardware either on the ground or in-flight.

Parameter, Value:

Percent sterilization effectiveness: 99%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
New Frontiers: Comet Surface Sample Return	Enabling	--	2024	2016	2 years
New Frontiers: Lunar South Pole-Aitken Basin Sample Return	Enabling	--	2024	2016	2 years
New Frontiers: Saturn Probe	Enabling	--	2024	2016	2 years
New Frontiers: Trojan Tour and Rendezvous	Enabling	--	2024	2016	2 years
New Frontiers: Venus In-Situ Explorer	Enabling	--	2024	2016	2 years
Planetary Flagship: Europa	Enabling	--	2022*	2019	4 years
Planetary Flagship: Mars Sample Return	Enabling	--	2026*	2023	4 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

13.2 Environmental Protection and Green Technologies
13.2.5 Curatorial Facilities, Planetary Protection, and Clean Rooms

13.2.5.3 Scaled-Up Ethylene Oxide Chamber for Spacecraft Sterilization

TECHNOLOGY

Technology Description: A scaled-up ethylene oxide (EtO) chamber could accommodate entire spacecraft for post-assembly full sterilization.

Technology Challenge: Mitigation of hazards for ground personnel is a challenge.

Technology State of the Art: Some of the world's largest EtO chambers are located overseas; depends on the size of item or system to be sterilized.

Parameter, Value:

Percent sterilization effectiveness: 99%;

Percent reduction in costs for providing heat-tolerant spacecraft electronic component and other materials: 25%

TRL 9

Technology Performance Goal: More effective and cost-effective capability to sterilize entire spacecraft after assembly and prior to encapsulation and launch that reduces risk and costs associated with baking electronics and other materials.

Parameter, Value:

Percent sterilization effectiveness: 99%;

Percent reduction in costs for providing heat-tolerant spacecraft electronic component and other materials: 25%

TRL 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Sterilize entire spacecraft post-assembly.

Capability Description: Sterilize entire spacecraft after assembly and prior to encapsulation and launch.

Capability State of the Art: Dry heat microbial reduction (DHMR) per NASA Procedural Requirements (NPR) 8010.12D.

Parameter, Value:

Percent sterilization effectiveness: 90%;

Costs for providing heat-tolerant spacecraft electronic component and other materials: $TBD

Capability Performance Goal: More effective and cost-effective capability to sterilize entire spacecraft after assembly and prior to encapsulation and launch that reduces risk and costs associated with baking electronics and other materials.

Parameter, Value:

Percent sterilization effectiveness: 99%;

Percent reduction in costs for providing heat-tolerant spacecraft electronic component and other materials: 25%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
New Frontiers: Comet Surface Sample Return	Enabling	--	2024	2016	2 years
New Frontiers: Lunar South Pole-Aitken Basin Sample Return	Enabling	--	2024	2016	2 years
New Frontiers: Saturn Probe	Enabling	--	2024	2016	2 years
New Frontiers: Trojan Tour and Rendezvous	Enabling	--	2024	2016	2 years
New Frontiers: Venus In-Situ Explorer	Enabling	--	2024	2016	2 years
Planetary Flagship: Europa	Enabling	--	2022*	2019	4 years
Planetary Flagship: Mars Sample Return	Enabling	--	2026*	2023	4 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

13.2 Environmental Protection and Green Technologies
13.2.5 Curatorial Facilities, Planetary Protection, and Clean Rooms

13.2.5.4 Extraterrestrial Sample Return Containment

TECHNOLOGY

Technology Description: Biosafety practices and procedures for handling extraterrestrial sample return.

Technology Challenge: The primary challenges are development and integration of a complete solution for restricted Earth return missions that possess a biosafety level (BSL)-4 type capability at a convenient location, including containers for ultra-safe sample transport. Research is required to understand the environmental conditions necessary to contain, store and preserve extraterrestrial samples during analysis.

Technology State of the Art: BSL-4 currently exists for Earth-based materials.

Parameter, Value:	**TRL**
Percent isolation and containment per BSL-4 requirements for Earth-based materials: 100%	6

Technology Performance Goal: BSL-4 equipment, practices, and procedures for restricted extraterrestrial sample return missions to Earth to include curation.

Parameter, Value:	**TRL**
Percent isolation and containment per BSL-4 requirements for extraterrestrial materials: 100%	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Extraterrestrial sample return containment, handling, and analysis.

Capability Description: BSL-4 containment, processes, and procedures for restricted extraterrestrial sample Earth return missions.

Capability State of the Art: NASA does not currently have this capability. Sample canisters were used during the Apollo era.

Parameter, Value:
Percent isolation and containment per BSL-4 requirements for Earth-based materials: 100%

Capability Performance Goal: BSL-4 analytical tools, containers, manipulators, and processes for handling extraterrestrial samples critically sensitive and potentially destroyed by their surrounding environment.

Parameter, Value:
Percent isolation and containment per BSL-4 requirements for extraterrestrial materials: 100%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
New Frontiers: Comet Surface Sample Return	Enabling	--	2024	2016	2 years
New Frontiers: Lunar South Pole-Aitken Basin Sample Return	Enabling	--	2024	2016	2 years
New Frontiers: Saturn Probe	Enabling	--	2024	2016	2 years
New Frontiers: Trojan Tour and Rendezvous	Enabling	--	2024	2016	2 years
New Frontiers: Venus In-Situ Explorer	Enabling	--	2024	2016	2 years
Planetary Flagship: Mars Sample Return	Enabling	--	2026*	2023	4 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

13.2 Environmental Protection and Green Technologies
13.2.5 Curatorial Facilities, Planetary Protection, and Clean Rooms

13.2.5.5 Robotic Assistants for Spacecraft Assembly

TECHNOLOGY

Technology Description: Robotic assistants for assembly of life detection payloads or spacecraft in an enclosed, clean environment.

Technology Challenge: Ensure materials, themselves, are compatible. Ensure that robots do not risk damage to flight hardware. Ensure that robotic observation capabilities are acceptable to quality control inspectors.

Technology State of the Art: Several examples of robotic manipulation and observation technologies exist. Robotic mobility within the enclosed environment would be a custom solution.

Parameter, Value: Percent reduction in required number of people in clean room environment: 50%

TRL: 4

Technology Performance Goal: Assembly of life detection payloads and spacecraft in an enclosed, clean environment (example: quality control inspection).

Parameter, Value: Percent reduction in required number of people in clean room environment: 50%

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Assembling life detection payloads and spacecraft in an enclosed, clean environment.

Capability Description: Robotic assistants for assembling life detection payloads and spacecraft in an enclosed, clean environment.

Capability State of the Art: All assembly operations today involve tasks performed by humans attired in clean garments in a clean environment.

Parameter, Value: Required number of people in clean room environment: 100

Capability Performance Goal: Assembling life detection payloads and spacecraft in an enclosed, clean environment (example: quality control inspection).

Parameter, Value: Percent reduction in required number of people in clean room environment: 50%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
New Frontiers: Comet Surface Sample Return	Enabling	--	2024	2016	2 years
New Frontiers: Lunar South Pole-Aitken Basin Sample Return	Enabling	--	2024	2016	2 years
New Frontiers: Saturn Probe	Enabling	--	2024	2016	2 years
New Frontiers: Trojan Tour and Rendezvous	Enabling	--	2024	2016	2 years
New Frontiers: Venus In-Situ Explorer	Enabling	--	2024	2016	2 years
Planetary Flagship: Mars Sample Return	Enabling	--	2026*	2023	4 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

13.2 Environmental Protection and Green Technologies
13.2.5 Curatorial Facilities, Planetary Protection, and Clean Rooms

13.2.5.6 Organically Clean Robotics for Processing Extraterrestrial Rocks

TECHNOLOGY

Technology Description: Robotic systems that are organically clean for processing extraterrestrial rocks.

Technology Challenge: Dexterity of robotic system and materials compatibility are challenge.

Technology State of the Art: Highly-dexterous robots of many types exist. The capacity to cleanly process and subdivide rocks of undetermined composition and shape has not been demonstrated.

Parameter, Value:
Percent manual operations for extraterrestrial sample curation: 50%

TRL: 3

Technology Performance Goal: Precision subdivision of rocks by a dexterous, organically-clean robot that can reduce required manual operations while introducing minimal contamination.

Parameter, Value:
Percent manual operations for extraterrestrial sample curation: 50%

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Organically-clean robotics for processing extraterrestrial rocks.

Capability Description: Robotic handling and subdivision of rocks in a laboratory environment, with minimal organic contamination.

Capability State of the Art: Processing of extraterrestrial rock samples brought to Earth by spacecraft is currently conducted by people, with the samples in nitrogen glovebox cabinets. No current requirement exists for organic cleanliness in extraterrestrial sample curation, but assumption is full isolation and containment.

Parameter, Value:
Percent manual operations for extraterrestrial sample curation: 100%

Capability Performance Goal: Precision subdivision of rocks by a dexterous, organically-clean robot that can reduce required manual operations while introducing minimal contamination.

Parameter, Value:
Percent manual operations for extraterrestrial sample curation: 50%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
New Frontiers: Comet Surface Sample Return	Enabling	--	2024	2016	2 years
New Frontiers: Lunar South Pole-Aitken Basin Sample Return	Enabling	--	2024	2016	2 years
New Frontiers: Saturn Probe	Enabling	--	2024	2016	2 years
New Frontiers: Trojan Tour and Rendezvous	Enabling	--	2024	2016	2 years
New Frontiers: Venus In-Situ Explorer	Enabling	--	2024	2016	2 years
Planetary Flagship: Europa	Enabling	--	2022*	2019	4 years
Planetary Flagship: Mars Sample Return	Enabling	--	2026*	2023	4 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

13.2 Environmental Protection and Green Technologies
13.2.5 Curatorial Facilities, Planetary Protection, and Clean Rooms

13.2.5.7 Portable Clean Rooms

TECHNOLOGY

Technology Description: Cleanroom that can be utilized wherever a payload resides (at vendor, integration area, post-flight) in lieu of brick-and-mortar cleanrooms at launch site.

Technology Challenge: Developing clean rooms that are large enough to accommodate payloads and personnel, but small enough to be mobile is a challenge.

Technology State of the Art: Emerging technologies may include mobile facilities that can expand and contract anywhere, purging air prior to accommodating payloads and personnel.

Parameter, Value:
Percent reduction in launch site costs associated with cleanroom capabilities: 50%

TRL: 3

Technology Performance Goal: Cost-effective, mobile clean room that can be used before or after launching payloads vulnerable to contamination.

Parameter, Value:
Percent reduction in launch site costs associated with cleanroom capabilities: 50%

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Mobile clean room that can move with small spacecraft or payload component(s).

Capability Description: Mobile clean room during transport (to and from launch site) to address system vulnerability to foreign particles thus eliminating contamination from sources in the outside environment.

Capability State of the Art: Today's methods include transporting hardware in biobags or positive-pressure vessels to prevent recontamination (preventing personnel access until inside a fixed cleanroom). Mission program must lease required cleanroom space at every location where work on spacecraft will be performed.

Parameter, Value:
Launch site costs associated with cleanroom capabilities: $50K per month.

Capability Performance Goal: Mobile clean room large enough to provide equivalent critical features as brick-and-mortar cleanroom (power, air control, equipment, etc.) and accommodate key personnel, while reducing costs.

Parameter, Value:
Percent reduction in launch site costs associated with cleanroom capabilities: 50%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
New Frontiers: Comet Surface Sample Return	Enabling	--	2024	2016	2 years
New Frontiers: Lunar South Pole-Aitken Basin Sample Return	Enabling	--	2024	2016	2 years
New Frontiers: Saturn Probe	Enabling	--	2024	2016	2 years
New Frontiers: Trojan Tour and Rendezvous	Enabling	--	2024	2016	2 years
New Frontiers: Venus In-Situ Explorer	Enabling	--	2024	2016	2 years
Planetary Flagship: Europa	Enabling	--	2022*	2019	4 years
Planetary Flagship: Mars Sample Return	Enabling	--	2026*	2023	4 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

13.2 Environmental Protection and Green Technologies
13.2.5 Curatorial Facilities, Planetary Protection, and Clean Rooms

13.2.5.8 Portable Gravity Offload System for Ground Checkout

TECHNOLOGY

Technology Description: Portable gravity offloading of space surface system structures for dynamic testing in lunar, Martian, or other microgravity environments.

Technology Challenge: Ensuring there are no coupled loads across test articles is a challenge.

Technology State of the Art: A scalable gravity offload device simulates reduced gravity for the testing of various surface system elements in a relevant environment. The device is capable of simulating reduced gravity over an arbitrary terrain that includes slopes, obstacles, and varying surface concavity. The device consists of a linear movement system, a two degrees-of-freedom manipulator, a passive force application mechanism, and a position tracking mechanism.

Parameter, Value:

Fixed or portable: portable;

Number of test articles: 1;

Maximum load: 250 pounds per article.

TRL 6

Technology Performance Goal: Portable gravity offload system that can be set up at multiple locations, support up to three test articles in dynamic testing in simulated lunar, martian, or other microgravity environments.

Parameter, Value:

Fixed or portable: portable;

Number of test articles: 3;

Maximum load: 500 pounds per article.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Portable gravity offload system for ground checkout.

Capability Description: Portable gravity offload system for ground checkout that can be set up at multiple locations, support up to three test articles in dynamic testing in simulated lunar, martian, or other microgravity environments.

Capability State of the Art: NASA's Active Response Gravity Offload System (ARGOS) simulates reduced gravity environments, such as lunar, martian, or microgravity, using a system similar to an overhead bridge crane. ARGOS uses an inline load cell to continuously offload a portion of a human or robotic payload's weight during all dynamic motions, which can include walking, running, and jumping under lunar or martian gravities, as well as a wide range of microgravity activities.

Parameter, Value:

Fixed or portable: fixed;

Number of test articles: 1;

Maximum load: 750 pounds.

Capability Performance Goal: Portable gravity offload system that can be set up at multiple locations, support up to three test articles in dynamic testing in simulated lunar, martian, or other microgravity environments.

Parameter, Value:

Fixed or portable: portable;

Nmber of test articles: 3;

Maximum load: 500 pounds per article.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	4 years

13.3 Reliability and Maintainability
13.3.1 Launch Infrastructure

13.3.1.1 Supervisory Control System for Cranes

TECHNOLOGY

Technology Description: Protection of high-value spaceflight hardware during crane moves through development of a smaller, less complex and modular system for a parallel crane operation monitoring system compared to a custom commercial-off-the-shelf (COTS) system still having single failure points.

Technology Challenge: Industry does not see a market for this technology to justify capital expense for this development.

Technology State of the Art: Industry standard or even special nuclear material handling requirements do not require the single-failure-proof control system needed for NASA.

Parameter, Value:
System cost: unknown

TRL 1

Technology Performance Goal: Protection of high-value spaceflight hardware during crane moves with a smaller, less complex, and modular system for a parallel crane operation monitoring system.

Parameter, Value:
System cost: $300K

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Supervisory control system for cranes.

Capability Description: Protection of high-value spaceflight hardware during crane moves by developing a smaller, less complex, and modular parallel crane operation monitoring system.

Capability State of the Art: Current COTS crane control systems are proprietary, black box systems. For NASA applications, a supervisory programmable logic controller (PLC) rated for safety applications with custom software is engineered into a COTS control system to provide an acceptable "critical" crane control system. This is expensive and engineered specific for each application.

Parameter, Value:
System cost: $600K

Capability Performance Goal: Protection of high-value spaceflight hardware during crane moves with a smaller, less complex, and modular system for a parallel crane operation monitoring system compared to a custom COTS system still having single failure points.

Parameter, Value:
System cost: $300K

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	4 years

13.3 Reliability and Maintainability
13.3.1 Launch Infrastructure

13.3.1.2 Collision Avoidance System for Cranes

TECHNOLOGY

Technology Description: Collision avoidance system that recognizes obstructions and possesses automated control system stops.

Technology Challenge: Industry does not see a market for this technology to justify capital expense for this development.

Technology State of the Art: Collision avoidance systems are used in areas where remote crane operations are required (such as high radiation areas). These systems are custom engineered.

Parameter, Value:
Probability of damage during crane moves: 1 in 10,000.

TRL 6

Technology Performance Goal: Collision avoidance system where obstructions are recognized and automated control system stops are provided with low level of event probability.

Parameter, Value:
Probability of damage during crane moves: 1 in 10,000.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Collision avoidance system for cranes.

Capability Description: Collision avoidance system that recognizes obstructions and possesses automated control system stops.

Capability State of the Art: In NASA facilities, crane operations are completely manual and rely on operators and observers on radios to control an operation.

Parameter, Value:
Probability of damage during crane moves: 1 in 1,000.

Capability Performance Goal: Collision avoidance system where obstructions are recognized and automated control system stops are provided with low level of event probability.

Parameter, Value:
Probability of damage during crane moves: 1 in 10,000.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	4 years

13.3 Reliability and Maintainability
13.3.1 Launch Infrastructure

13.3.1.3 Crane Control Diagnostic and Prognostic System

TECHNOLOGY

Technology Description: A detailed supervisory monitoring system tailorable to specific applications and incorporate crane component diagnostics and prognostics for improved maintenance planning and reduction in unplanned outages.

Technology Challenge: Crane diagnostics are not needed by all crane users. As yet the industry has only provided limited capability in this area.

Technology State of the Art: Limited diagnostics are provided on crane control systems. Further diagnostics covering crane control field devices like motors, encoders, brakes, etc., are custom engineered.

Parameter, Value:
Cost due to outages: $0K per year

TRL 6

Technology Performance Goal: A detailed supervisory monitoring system tailorable to specific applications and incorporate crane component diagnostics and prognostics resulting in no cost due to outages.

Parameter, Value:
Cost due to outages: $0 K per year

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Crane control diagnostic and prognostic system.

Capability Description: A detailed supervisory monitoring system tailorable to specific applications and incorporate crane component diagnostics and prognostics for improved maintenance planning and reduction of delays during unplanned outages.

Capability State of the Art: There is very limited instrumentation on NASA crane systems that mitigate cost from delays due to failures during crane operations.

Parameter, Value:
Cost due to outages: $10K per year

Capability Performance Goal: A detailed supervisory monitoring system tailorable to specific applications and incorporate crane component diagnostics and prognostics resulting in no cost due to outages.

Parameter, Value:
Cost due to outages: $0K per year.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.3 Reliability and Maintainability
13.3.1 Launch Infrastructure

13.3.1.4 Helmholtz Resonators for Energy Absorption of Rocket Engine Exhaust

TECHNOLOGY

Technology Description: Helmholtz resonators that reduce acoustic energy associated with rocket engine firings.

Technology Challenge: Scaling up smaller industrial applications to launch pad requirements.

Technology State of the Art: Architectural, automotive engines and aircraft engines have applications of passive noise control using Helmholtz resonators.

Parameter, Value:	TRL
Distance requirements for locating launch structures and facilities: not available.	3

Technology Performance Goal: Improvement in quantity-distance requirement for locating launch structures and facilities and reduction in acoustic energy that could reflect upward to the launch vehicle.

Parameter, Value:	TRL
Percent improvement in distance requirements for locating launch structures and facilities: 10%; Percent reduction in acoustic energy: 10%	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Energy absorption of rocket engine exhaust.

Capability Description: Reduces acoustic energy associated with rocket engine firings.

Capability State of the Art: The Space Shuttle launch pad infrastructure included water-filled bags in engine exhaust holes and rain birds on mobile launch platform deck. Saturn V and the Space Shuttle produced approximately 220 dB at source, 197 dB at 1,000 yards, and 135 dB at 1 mile.

Parameter, Value:

Acoustic energy: 135 dB at a distance of 5,000 feet as requirements for locating launch structures and facilities.

Capability Performance Goal: Improvement in quantity-distance requirement for locating launch structures and facilities and reduction in acoustic energy that could reflect upward to the launch vehicle.

Parameter, Value:

Percent improvement in distance requirements for locating launch structures and facilities: 10%;

Percent reduction in acoustic energy: 10%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.3 Reliability and Maintainability
13.3.1 Launch Infrastructure

13.3.1.5 Active Acoustic Source Noise Cancellation System

TECHNOLOGY

Technology Description: Active source noise cancellation system that reduces acoustic energy associated with rocket engine firings.

Technology Challenge: Complex modeling of dynamic launch environment, development of rugged and movable rain bird system, and testing to validate models.

Technology State of the Art: No SOA exists.

Parameter, Value:
Distance requirements for locating launch structures and facilities: not available.

TRL: None

Technology Performance Goal: Improvement in quantity-distance requirement for locating launch structures and facilities and reduction in acoustic energy that could reflect upward to the launch vehicle.

Parameter, Value:
Percent improvement in distance requirements for locating launch structures & facilities: 10%;
Percent reduction in acoustic energy: 10%

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Active acoustic source noise cancellation system.

Capability Description: Reduce acoustic energy associated with rocket engine firings.

Capability State of the Art: The Space Shuttle launch pad infrastructure included water-filled bags in engine exhaust holes and rain birds on mobile launch platform deck. Saturn V and the Space Shuttle produced approximately 220 dB at source, 197 dB at 1,000 yards, and 135 dB at 1 mile.

Parameter, Value:
Acoustic energy: 135 dB at distance of 5,000 feet as requirements for locating launch structures and facilities.

Capability Performance Goal: Improvement in quantity-distance requirement for locating launch structures and facilities and reduction in acoustic energy that could reflect upward to the launch vehicle.

Parameter, Value:
Percent improvement in distance requirements for locating launch structures & facilities: 10%;
Percent reduction in acoustic energy: 10%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.3 Reliability and Maintainability
13.3.1 Launch Infrastructure

13.3.1.6 Hydrogen Pooling Mitigation

TECHNOLOGY

Technology Description: Mitigation of hydrogen gas pooling within structures including engine nozzles for launch vehicles that use hydrogen in order to eliminate risk of explosions during engine ignition that can cause catastrophic results.

Technology Challenge: Complex modeling of engine and vehicle environment and possible improvements. Also, testing to validate models.

Technology State of the Art: Not aware of any activity to mitigate this outside of NASA.

Parameter, Value:

Percent improvement in removal of unburned hydrogen gas in environment prior to engine ignition: not available.

TRL: None

Technology Performance Goal: Alternative means more effective than radially outward flame ignitor (ROFI) to mitigate hydrogen gas pooling within structures, including engine nozzles for launch vehicles that use hydrogen.

Parameter, Value:

Percent improvement in removal of unburned hydrogen gas in environment prior to engine ignition: 10%

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Hydrogen pooling mitigation.

Capability Description: Alternative means from an ROFI system to mitigate hydrogen gas pooling within structures, including engine nozzles for launch vehicles that use hydrogen in order to eliminate risk of explosions during engine ignition.

Capability State of the Art: The Space Shuttle used a ROFI system on each main engine that were ignited just prior to engine ignition. Space Launch Complex-6 for Shuttle planned to use jet engine exhaust. NASA's SLS will use the same model of engine that Shuttle used, but will use 4 of the engines instead of the Shuttle's application of 3 engines.

Parameter, Value:

Percent unburned hydrogen gas in environment prior to engine ignition effectively removed by ROFI: 90%

Capability Performance Goal: Alternative means more effective than ROFI to mitigate hydrogen gas pooling within structures, including engine nozzles for launch vehicles that use hydrogen.

Parameter, Value:

Percent improvement in removal of unburned hydrogen gas in environment prior to engine ignition: 10%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.3 Reliability and Maintainability
13.3.1 Launch Infrastructure

13.3.1.7 Variable Geometry Flame Trenches

TECHNOLOGY

Technology Description: Launch pad or test stand flame trenches that are reconfigurable depending on engine performance and vehicle type that allow for reduced noise and more efficient removal of exhaust products. Trench walls would reconfigure and lock well-prior to launch or engine test operations. This also provides for a multi-use capability at a launch pad or engine test stand.

Technology Challenge: Complex modeling of several launch environments, scaled testing to validate models, ruggedization of materials and systems, and developing a moveable fire brick wall.

Technology State of the Art: No known relevant application of moveable and lockable flame trench walls for a launch environment.

Parameter, Value:
Reduction in acoustic energy: not available.

TRL
None

Technology Performance Goal: Reconfigurable flame trench depending on engine performance and vehicle type that allows for reduced noise and more efficient removal of exhaust products.

Parameter, Value:
Percent reduction in acoustic energy: 25%

TRL
6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Variable-geometry flame trenches.

Capability Description: Launch pad or test stand flame trenches that are reconfigurable depending on engine performance and vehicle type that allow for reduced noise and more efficient removal of exhaust products.

Capability State of the Art: Currently, flame deflectors and flame trenches are fixed. New programs typically use existing facilities that were optimized for legacy programs.

Parameter, Value:
Acoustic energy: 220 dB at source.

Capability Performance Goal: Reconfigurable flame trench depending on engine performance and vehicle type that allows for reduced noise and more efficient removal of exhaust products.

Parameter, Value:
Percent reduction in acoustic energy: 25%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.3 Reliability and Maintainability
13.3.1 Launch Infrastructure

13.3.1.8 Mobile Launch Pad Kit

TECHNOLOGY

Technology Description: A mobile launch pad kit with modular elements supporting a wide variety of different classes of launchers. Elements include: launch platform, flame trench, launch tower, umbilicals, propellant servicing equipment, command and control system, weather station, and range tracking station.

Technology Challenge: Optimizing multi-use functionality of command and control systems is a challenge.

Technology State of the Art: U.S. government mobile launch system for nanosat-launch class vehicle that was designed to place a 25 kilogram payload into low-Earth orbit (LEO).

Parameter, Value:

Capability to be fully mobile: yes;

Capability to support wide variety of launchers: no

TRL: 6

Technology Performance Goal: Mobile launch pad kit with modular elements supporting a wide variety of different classes of launchers.

Parameter, Value:

Capability to be fully mobile: yes; Capability to support wide variety of launchers: yes

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Mobile launch pad kit.

Capability Description: A kit with modular elements supporting a wide variety of different classes of launchers. Elements include: launch platform, flame trench, launch tower, umbilicals, propellant servicing equipment, command and control system, weather station, and range tracking station.

Capability State of the Art: Most launch complexes are custom-designed to support specific launchers. NASA is working toward having a multi-user launch pad, but some elements are fixed in size and location, such as flame trench, mobile launch platform, and crawler or transporter.

Parameter, Value:

Capability to be fully mobile: no;

Capability to support wide variety of launchers: no

Capability Performance Goal: Mobile launch pad kit with modular elements supporting a wide variety of different classes of launchers.

Parameter, Value:

Capability to be fully mobile: yes;

Capability to support wide variety of launchers: yes

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Suborbital: Science, Research & Technology (suborbital program)	Enabling	--	On-going	--	4 years

13.3 Reliability and Maintainability
13.3.1 Launch Infrastructure

13.3.1.9 High-Altitude Balloon Ground Systems

TECHNOLOGY

Technology Description: Ground systems supporting high-altitude balloons include lift gas servicing system for helium or hydrogen and launch tracking system.

Technology Challenge: Ensuring no disruption to a Global Positioning System (GPS) beacon is a challenge.

Technology State of the Art: Transmitting additional snapshots of data within the maximum of 19.2 kbps appears feasible, but not yet performed.

Parameter, Value:

Real-time transmission of onboard data within required maximum of 19.2 kbps: no

TRL 4

Technology Performance Goal: Transmit small amounts of data or snapshots from the onboard instruments or camera in between the every-two-minute GPS tracker beacon.

Parameter, Value:

Real-time transmission of onboard data within required maximum of 19.2 kbps.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: High-altitude balloon ground systems.

Capability Description: Ground systems supporting high-altitude balloons, including lift gas servicing system for helium or hydrogen and launch tracking system that can transmit small amounts of data from onboard instruments in between the GPS tracker beacon.

Capability State of the Art: Ground support includes disposable supplies (the balloon, helium or hydrogen to be used as lift gas, tape, rigging, payload boxes, and zip-ties) and incidentals, such as fuel for the chase vehicle tasked with tracking down and recovering the flight equipment. Two GPS trackers that send beacons every two minutes, with the exact latitude and longitude coordinates through the automatic packet reporting system (APRS) tracking data to a receiver, which will be in a van or truck. Works in the two meter band which covers the 144.000 to 148.000 Mhz.

Parameter, Value:

Data transmission speed: 19.2 kbps.

Capability Performance Goal: Transmit small amounts of data or snapshots from the onboard instruments or camera in between the every-two-minute GPS tracker beacon.

Parameter, Value:

Real-time transmission of onboard data within required maximum of 19.2 kbps.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Suborbital: Science, Research & Technology (suborbital program)	Enabling	--	On-going	--	4 years

13.3 Reliability and Maintainability
13.3.1 Launch Infrastructure

13.3.1.10 Sounding Rocket Ground Systems

TECHNOLOGY

Technology Description: Ground systems supporting sounding rocket missions include: launch pads, launch rails, blockhouse systems, controls, consoles, tracking systems, and telemetry systems.

Technology Challenge: Packaging for available sounding rocket volume is a challenge.

Technology State of the Art: High data rate flight demonstration on CubeSat hydrometric atmospheric mission achieved 150 Mb/sec.

Parameter, Value: Telemetry data rate: 150 Mb/sec

TRL: 6

Technology Performance Goal: Telemetry ground system with increased data rate.

Parameter, Value: Telemetry data rate: 1 Gbps

TRL: 4

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Sounding rocket ground systems.

Capability Description: Provide upgraded ground systems supporting sounding rocket missions, including: launch pads, launch rails, blockhouse systems, controls, consoles, tracking systems, and telemetry systems.

Capability State of the Art: Currently the range provides launch pads, launchers, blockhouse systems, controls, and consoles. Mechanical and electrical/electronic ground support equipment; flight support instrumentation, such as search, tracking, and instrumentation radars; telemetry receiving and data recording stations; television and photographic tracking cameras; special purpose photo-optical equipment; surveillance and recovery operations aircraft; and facilities for payload preparation and check out are also provided as part of the range services. The parameter value existing at these ranges are well below that technology SOA.

Parameter, Value: Telemetry data rate used by ranges: 10 Mbps

Capability Performance Goal: Telemetry ground system with increased data rate.

Parameter, Value: Telemetry data rate: 1 Gbps

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Suborbital: Science, Research & Technology (suborbital program)	Enabling	--	On-going	--	4 years

13.3 Reliability and Maintainability
13.3.1 Launch Infrastructure

13.3.1.11 Common Interfaces for Small Launchers and Payloads

TECHNOLOGY

Technology Description: Standardizing and simplifying fluid, electrical, structural, communication, and data interfaces using an open architecture or industry consensus-driven approach. Common interfaces can incorporate wireless power for on-pad electrical interfaces and payload battery charging.

Technology Challenge: Establishing design consensus with the small launch industry is a challenge.

Technology State of the Art: Commonality for interfaces has been pursued within flight software for some time, but much less progress has been made for physical interfaces. In addition, commonality has been pursued among orbiting spacecraft but not between spacecraft and launchers and their ground infrastructure (example: NASA Universal Propellant Servicing System).

Parameter, Value:	TRL
Ground operations time: 90 days; Number of vehicles able to use same servicing system: 1	3

Technology Performance Goal: Establish interface standards that allow different small launch vehicles and small satellites the ability to perform pre-launch testing and launch activities without custom interface design and development.

Parameter, Value:	TRL
Percent reduction in ground operations time: 50%; Number of vehicles able to use same servicing system: 2	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Common interfaces for small launchers and payloads.

Capability Description: Standardizing and simplifying fluid, electrical, structural, communication, and data interfaces using an open architecture and/or industry consensus driven approach.

Capability State of the Art: Current offering of small launch vehicles under development provide unique interfaces for ground systems. Small satellites such as CubeSats have benefitted more from adoption of industry standards. Generic commonality between the launch vehicles and payloads is new territory.

Parameter, Value:

Ground operations time: 90 days;

Number of vehicles able to use same servicing system: 1

Capability Performance Goal: Establish interface standards that allow different small launch vehicles and small satellites the ability to perform pre-launch testing and launch activities without custom interface design and development.

Parameter, Value:

Percent reduction in ground operations time: 50%;

Number of vehicles able to use same servicing system: 2

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Suborbital: Science, Research & Technology (suborbital program)	Enabling	--	On-going	--	4 years

13.3 Reliability and Maintainability
13.3.1 Launch Infrastructure

13.3.1.12 Runway Surface Movement Detection System

TECHNOLOGY

Technology Description: Detects multiple vehicles on and in vicinity of an active runway.

Technology Challenge: Integrating technologies into NASA operational environment with minimal impact to existing ground surfaces is a challenge.

Technology State of the Art: Induction-loop sensors embedded in surface can detect multiple vehicles. First use was at an overseas international airport.

Parameter, Value: Full assured clear distance between vehicles: yes

TRL 9

Technology Performance Goal: Induction-loop sensors embedded in surface that can detect multiple vehicles.

Parameter, Value:
Full assured clear distance between vehicles: yes

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Runway surface movement detection system.

Capability Description: Detects multiple vehicles on and in vicinity of an active runway.

Capability State of the Art: Limited to visual observation from control tower.

Parameter, Value:
Full assured clear distance between vehicles: no

Capability Performance Goal: Induction-loop sensors embedded in surface that can detect multiple vehicles.

Parameter, Value:
Full assured clear distance between vehicles: yes

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.3 Reliability and Maintainability
13.3.2 Environment-Hardened Materials and Structures

13.3.2.1 Advanced Overrun Runway Materials

TECHNOLOGY

Technology Description: Gradually slow down aircraft that have overrun the runway through use of energy-absorbing materials.

Technology Challenge: Long-term environmental exposure is a challenge.

Technology State of the Art: Foam concrete up to 70 centimeters in depth allows for airplane vehicle wheels to crush the material and absorb energy. Currently only meets needs needs for commercial aviation.

Parameter, Value: Maximum average distance required to stop overrun vehicle: 180 meters.

TRL: 9

Technology Performance Goal: Energy absorbing materials necessary to handle next generation high energy landing profiles

Parameter, Value: Percent improvement in performance to handle high energy landing profiles: 50%

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Advanced overrun runway materials.

Capability Description: Provide an arresting capability to gradually slow down high-energy space planes that have overrun the runway through use of energy-absorbing materials.

Capability State of the Art: NASA runways typically have overrun areas composed of aggregate for commercial aircraft.

Parameter, Value: Maximum average distance required to stop overrun vehicle: 180 meters.

Capability Performance Goal: Energy absorbing materials capable of gradual slow down for future high-energy space plane landing profiles.

Parameter, Value: Percent improvement in length required to slow vehicle: 50%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.3 Reliability and Maintainability
13.3.2 Environment-Hardened Materials and Structures

13.3.2.2 Advanced Flame Trench Surface Materials

TECHNOLOGY

Technology Description: Advanced flame trench materials that provide less degradation over time and less chance to break away and become foreign object debris (FOD) during launch that could strike the vehicle.

Technology Challenge: Developing a material that does not require a time intensive application process while still curing in a uniform manner to reduce incidents of chips breaking off as foreign object debris.

Technology State of the Art: An international launch site uses an all-carbon steel flame deflector and 3 inch diameter steel shingles. Steel shingles set up pressure wave triggers that provide improved thermal performance. However, NASA does not have access to this technology.

Parameter, Value:	TRL
Erosion under max exposure: 0.2 to 0.5 inches.	9

Technology Performance Goal: Material development that reduces operational maintenance and risks of foreign object debris.

Parameter, Value:	TRL
Percent improvement in erosion under max exposure: 50%	9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Advanced flame trench surface materials.

Capability Description: Advanced flame trench materials that reduce degradation over time and minimizes the chance of chips breaking away and become FOD during launch.

Capability State of the Art: Launch pads and engine test stands use fire-resistant concrete in the highest temperature locations (flame deflector and walls) and fire-resistant bricks in lower temperature locations (other surfaces). This fire-resistant concrete on flame deflectors requires repair every three launches.

Parameter, Value:
Erosion under max exposure: 0.2 to 0.5 inches.

Capability Performance Goal: Develop curing and layering processes of advanced ablative or composite, ice-o-phobic, refractory composite materials, would reduce risk, maintenance costs, and risks of FOD.

Parameter, Value:
Percent improvement in erosion under max exposure: 50%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.3 Reliability and Maintainability
13.3.2 Environment-Hardened Materials and Structures

13.3.2.3 Electrostatic Charge Build-up-Resistant Materials and Coatings

TECHNOLOGY

Technology Description: Non-accumulating, discharge, and non-contaminating neutralization materials, coatings that increase the decay rate of charged materials, switchable materials that will become electrically conductive in the presence of rising electric fields, and electrostatically dissipative when charge starts to develop.

Technology Challenge: Current materials have proven adequate for operational environments. NASA is likely to continue to leverage technology development conducted in industry and academia on materials and coatings. Newer materials will require demonstration testing.

Technology State of the Art: Inherently dissipative polymers are an emerging technology. They chemically alter materials to make them more electrostatically disapative.

Parameter, Value:

Resistance of conductive materials: 1 to 10^5 ohms;

Resistance of statically dissipative materials: 10^5 to 10^{12} ohms;

Resistance of insulative materials: 10^{12} ohms and higher;

Suitable for use in multiple operational environments: yes.

TRL 3

Technology Performance Goal: Non-accumulating, discharge, and non-contaminating neutralization materials, coatings that increase the decay rate of charged materials, switchable materials that will become electrically conductive in the presence of rising electric fields, and electrostatically dissipative when charge starts to develop.

Parameter, Value:

Resistance of conductive materials: 1 to 10^5 ohms;

Resistance of statically dissipative materials: 10^5 to 10^{12} ohms;

Resistance of insulative materials: 10^{12} ohms and higher;

Suitable for use in multiple operational environments: yes.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Electrostatic charge build-up-resistant materials and coatings.

Capability Description: Non-accumulating, discharge, and non-contaminating neutralization materials, coatings that increase the decay rate of charged materials, switchable materials that will become electrically conductive in the presence of rising electric fields, and electrostatically dissipative when charge starts to develop.

Capability State of the Art: Electrically grounding flight hardware during ground processing is essential to protect electronics equipment and not cause a spark in an explosive environment, such as a hydrogen-rich environment. The three methods are to use statically dissipative materials and coatings, as well as use atmospheric dionizer systems. The issue is compatibility. Environments with hypergolic propellants require use of aclar and hydrogen-rich environments require use of Kapton, which are not statically disappative. Also, coatings are temporary and require reapplications. In launch pad environments, high humidity affects properties of materials and wind causes surface charging. Water wipedowns are an effective measure to dissipate charges.

Parameter, Value:

Resistance of conductive materials: 1 to 10^5 ohms;

Resistance of statically dissipative materials: 10^5 to 10^{12} ohms;

Resistance of insulative materials: 10^{12} ohms and higher;

Suitable for use in multiple operational environments: yes.

Capability Performance Goal: Non-accumulating, discharge, and non-contaminating neutralization materials, coatings that increase the decay rate of charged materials, switchable materials that will become electrically conductive in the presence of rising electric fields, and electrostatically dissipative when charge starts to develop.

Parameter, Value:

Resistance of conductive materials: 1 to 10^5 ohms;

Resistance of statically dissipative materials: 10^5 to 10^{12} ohms;

Resistance of insulative materials: 10^{12} ohms and higher;

Suitable for use in multiple operational environments: yes.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.3 Reliability and Maintainability
13.3.3 On-Site Inspection and Anomaly Detection and Identification

13.3.3.1 Integrated, Multi-Parameter, Ground-Powered Sensors for Non-Destructive Evaluation and Continuous Monitoring

TECHNOLOGY

Technology Description: Monitors the health and performance of actuators, instrumentation, devices, structure, connectors and wiring, and pressure vessels using smart sensors embedded directly in the materials that are powered wirelessly from ground systems.

Technology Challenge: Ability to embed sensor without impairing integrity of material and/or structure.

Technology State of the Art: Fiber-optic sensors have been embedded in composite materials to detect stress and fractures and are being evaluated for feasibility, though there is no evidence of widespread industry use of embedded sensors.

Parameter, Value:
Percent reduction in test time: 50%

TRL 3

Technology Performance Goal: Monitor the health and performance of actuators, instrumentation, devices, structure, connectors and wiring, and pressure vessels using smart sensors embedded directly in the materials that are powered wirelessly from ground systems.

Parameter, Value:
Percent reduction in test time: 50%

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Non-invasive, multi-parameter embedded sensors.

Capability Description: Wirelessly powered monitoring of the health and performance of actuators, instrumentation, devices, structures, connectors and wiring, and pressure vessels using smart sensors embedded directly in the materials.

Capability State of the Art: Evaluation of structural, mechanical, and electrical integrity is normally done using external test equipment (e.g., ultrasound probes) or via testing (pressurization, electrical conductivity, etc.). Sensors are normally external to the system being evaluated.

Parameter, Value:
Time to perform test including set up: 16 hours.

Capability Performance Goal: Monitor the health and performance of actuators, instrumentation, devices, structure, connectors and wiring, and pressure vessels using smart sensors embedded directly in the materials that are powered wirelessly from ground systems.

Parameter, Value:
Percent reduction in time to perform test: 50%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.3 Reliability and Maintainability
13.3.3 On-Site Inspection and Anomaly Detection and Identification

13.3.3.2 Small Robotic Inspectors

TECHNOLOGY

Technology Description: Small, articulated robotics able to operate in highly-confined spaces and provide in-situ inspection in areas where human inspection is difficult and costly.

Technology Challenge: The ability to recognize and avoid areas where robotic contact could damage components is a challenge.

Technology State of the Art: Robots are used to inspect confined spaces like the interior of pipelines and wings, and for searching through rubble in disaster areas. The need to navigate while avoiding damaging the infrastructure seems to be unique.

Parameter, Value:
Time to identify problems: minutes.

TRL
4

Technology Performance Goal: Continuous inspection and fast, autonomous identification of anomalies, such as leaks and deformations.

Parameter, Value:
Time to identify problems: minutes.

TRL
6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: In-situ inspection and repair in confined spaces.

Capability Description: Autonomously navigate through highly-confined spaces and autonomously identify anomalies via a variety of sensors.

Capability State of the Art: No robotic support. Ability to inspect is limited by human safety and accessibility issues. Diagnosis of issues can be difficult and often requires movement back to the Vehicle Assembly Building or even destacking of the segments.

Parameter, Value:
Time to identify problems: hours to weeks.

Capability Performance Goal: Continuous inspection and fast, autonomous identification of anomalies, such as leaks and deformations.

Parameter, Value:
Time to identify problems: minutes.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	4 years

13.3 Reliability and Maintainability
13.3.4 Fault Isolation and Diagnostics

13.3.4.1 Embedded Fault Detection, Isolation, and Diagnosis

TECHNOLOGY

Technology Description: Launch vehicles and ground systems monitor and assess their own health to identify and repair off-nominal conditions and/or detect timing that might lead to crew abort or flight termination.

Technology Challenge: Challenges include verifying model-based systems and scaling model-based techniques.

Technology State of the Art: Model-based autonomy is the creation of long-lived autonomous systems that are able to explore, command, diagnose, and repair themselves using fast, common sense reasoning.

Parameter, Value:

Time to detect off-nominal behavior: hours;

Time to identify faults: hours;

Time to diagnose faults: hours.

TRL 4

Technology Performance Goal: Continuous monitoring of all critical areas for off-nominal behavior plus continuous verification of correct behavior; near real-time detection, identification, and diagnosis of faulty components.

Parameter, Value:

Time to detect off-nominal behavior: seconds;

Time to identify faults: minutes;

Time to diagnose faults: tens of minutes.

TRL 4

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Ability to represent, understand, and assess complex system behavior against expected behavior.

Capability Description: Represent, understand, and assess complex system behavior against expected behavior.

Capability State of the Art: Most fault-detection approaches employ simple monitor-response mechanisms that look for symptoms of faults that have already occurred, and do not have any knowledge of the current state of the system. This approach is a challenge to manage, verify and validate, and operate. The Mars Science Laboratory employed over 1,000 monitors to detect and respond to faults.

Parameter, Value:

Time to detect off-nominal behavior: hours;

Time to identify faults: hours;

Time to diagnose faults: hours.

Capability Performance Goal: Ability for systems to assess their health (e.g., detect faults, failures, and assess ability to continue to safely operate) by comparing current and local state information to context-aware models that define the expected system behaviors and states. Models also provide a rich source for diagnosing the probable cause of the fault or failure, and also assessing the impact of available remediation and recovery activities.

Parameter, Value:

Time to detect off-nominal behavior: seconds;

Time to identify faults: minutes;

Time to diagnose faults: tens of minutes.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.3 Reliability and Maintainability
13.3.4 Fault Isolation and Diagnostics

13.3.4.2 Smart Materials For Leak Detection

TECHNOLOGY

Technology Description: Smart materials such as color-changing materials to detect and isolate a leak source.

Technology Challenge: Challenges include long-term durability of materials in an operational environment, repeatability, and accuracy.

Technology State of the Art: There are several examples of color-changing materials wrapped around fluid lines for liquid hydrogen and monomethyl hydrazine.

Parameter, Value:

Time to identify and isolate leak source: minutes.

TRL 1

Technology Performance Goal: Identify and isolate leaks in fluid systems.

Parameter, Value:

Time to identify and isolate leak source: minutes.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Identify and isolate fluid system leaks.

Capability Description: Identify and isolate leaks in fluid systems, such as liquid hydrogen, monomethyl hydrazine, nitrogen tetroxide, hydraulic, coolants, methane, kerosene, and liquid oxygen.

Capability State of the Art: Traditional reliance on identification of leaks visually, through internal sensor data (P, T, volume), or using external leak detection systems such as mass spectrometers.

Parameter, Value:

Time to identify and isolate leak source: hours.

Capability Performance Goal: Identify and isolate leaks in fluid systems.

Parameter, Value:

Time to identify and isolate leak source: minutes.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	4 years

13.3 Reliability and Maintainability
13.3.4 Fault Isolation and Diagnostics

13.3.4.3 Smart Materials for Damage Detection

TECHNOLOGY

Technology Description: Smart materials such as color-changing materials to detect and isolate structural impacts and damage.

Technology Challenge: Challenges include long-term durability of materials in a NASA operational environment, repeatability, and accuracy.

Technology State of the Art: Composite impactor paint, paint with embedded carbon nanotubes that change their conductivity when bent, and embedded acoustic sensors with data processing for impact force and triangulation.

Parameter, Value:
Time to identify and isolate structural damage: minutes.

TRL 3

Technology Performance Goal: Identify and isolate structural impacts and damage.

Parameter, Value:
Time to identify and isolate structural damage: minutes.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Identify and isolate structural impacts and damage.

Capability Description: Identifies and isolate structural impacts and damage such as hail strikes, foreign object debris (FOD) strikes, and occurrences during operational mishaps.

Capability State of the Art: Traditional reliance on structural inspection systems such as those using eddy current, dye penetrants, and x-rays.

Parameter, Value:
Time to identify and isolate structural damage: hours.

Capability Performance Goal: Identify and isolate structural impacts and damage.

Parameter, Value:
Time to identify and isolate structural damage: minutes.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.3 Reliability and Maintainability
13.3.4 Fault Isolation and Diagnostics

13.3.4.4 Non-Traditional Sensors for Fault Isolation

TECHNOLOGY

Technology Description: Apply non-traditional sensors to detect and isolate faults. Examples include Radar, Light Detection and Ranging (LIDAR), forward looking infra-red (FLIR), and ultrasound to detect and isolate a failure in a three-dimensional (3D) space such as "hearing" a leak source or a component malfunction and triangulating the location.

Technology Challenge: Challenges include long-term durability of materials in a NASA operational environment, repeatability, and accuracy.

Technology State of the Art: A commercial system for detecting and locating leaks in buried pipes using ground-penetrating radar, induction, acoustic, and vacuum excavation exists. NASA developed a hand-held ultrasonic leak detection system to "hear" high-frequency leak sources and isolate them.

Parameter, Value:	TRL
Percent reduction in time to identify and isolate failures: 50%	3

Technology Performance Goal: Detect and isolate component failures.

Parameter, Value:	TRL
Percent reduction in time to identify and isolate failures: 50%	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Detect and isolate component failures.

Capability Description: Detect and isolate component failures using sensors and instrumentation systems.

Capability State of the Art: Traditional reliance on identifying leaks or component failures through internal sensor data (pressure, temperature, volume, position indicators) or using external leak detection systems, such as mass spectrometers.

Parameter, Value:
Time to identify and isolate failures: 8 hours.

Capability Performance Goal: Detect and isolate component failures.

Parameter, Value:
Percent reduction in time to identify and isolate failures: 50%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	4 years

13.3 Reliability and Maintainability
13.3.5 Prognostics

13.3.5.1 Molecular Agents for Predictive Health of Fluid System

TECHNOLOGY

Technology Description: Targeted, optically active contrast agents provide markers of fluid system deterioration allowing optical images to be acquired in real time with high spatial resolution to image-specific molecular targets.

Technology Challenge: Challenges include long-term durability of materials in a NASA operational environment, repeatability, and accuracy.

Technology State of the Art: Optical molecular imaging is emerging as a technique to help meet this need. Targeted, optically-active contrast agents can specifically provide markers of fluid system deterioration. Optical images can be acquired in real time with high spatial resolution to image-specific molecular targets.

Parameter, Value:

Time to identify and isolate leak source: minutes.

TRL 1

Technology Performance Goal: Monitor fluid system degradation with time to plan for maintenance activities.

Parameter, Value:

Time to identify and isolate leak source: minutes.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Monitor fluid system degradation.

Capability Description: Introduce molecular agents in fluid systems to detect deterioration and health of system.

Capability State of the Art: Traditional reliance on identification of leaks visually through internal sensor data (P, T, volume) or using external leak detection systems, such as mass spectrometers.

Parameter, Value:

Time to identify and isolate leak source: hours.

Capability Performance Goal: Monitor fluid system degradation with time to plan for maintenance activities.

Parameter, Value:

Time to identify and isolate leak source: minutes.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.3 Reliability and Maintainability
13.3.5 Prognostics

13.3.5.2 Built-In Test (BIT) Enhanced Life Forecasting

TECHNOLOGY

Technology Description: Assesses life expectancy of electronic boxes and systems at the card and subsystems level using active probing to estimate remaining life.

Technology Challenge: Challenges include miniaturizing capability to bring on chip, reliability, and repeatability of results.

Technology State of the Art: Built in "canaries" that determine whether a precursor to failure has been tripped.

Parameter, Value:
Provides estimates for life remaining: yes

TRL: 3

Technology Performance Goal: Predict when electronic boxes and systems at the card and subsystems level will degrade from a pass to a failure.

Parameter, Value:
Provides estimates for life remaining: yes

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: BIT for electronic boxes and systems.

Capability Description: Forecast life expectancy at the card and subsystem level.

Capability State of the Art: BIT provided at the box level to assess functioning of component or lack thereof.

Parameter, Value:
Provides estimates for life remaining: no

Capability Performance Goal: Predict when electronic boxes and systems at the card and subsystems level will degrade from a pass to a failure.

Parameter, Value:
Provides estimates for life remaining: yes

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.3 Reliability and Maintainability
13.3.5 Prognostics

13.3.5.3 Models and Approaches for Remaining Useful Life Prognostics

TECHNOLOGY

Technology Description: Estimate the time to failure (or useful remaining life) for new and degraded components.

Technology Challenge: Validation can be tedious if run to failure is required.

Technology State of the Art: Modeling underlying physics of component and using algorithms to extrapolate life to failure threshold given anticipated load profile. Apply machine learning algorithms over fleet-level data to detect precursors of adverse events.

Parameter, Value:
Percent true positives: 99%;
Percent true negatives: 99%

TRL 3

Technology Performance Goal: Predict failure with enough confidence and time to take mitigating action.

Parameter, Value:
Percent true positives: 99%;
Percent true negatives: 99%

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Models and approaches to measure, and estimate or predict time to failure for ground components.

Capability Description: Monitor systems to allow metadata on components to be entered and used in forecasting adverse events and maintenance, and to correlate observed behavior of NASA components and similar commercial military or commercial components.

Capability State of the Art: Monitoring whether critical component parameters exceed fault threshold. Relies on personal knowledge base for assessments.

Parameter, Value:
Percent true positives: 90%;
Percent true negatives: 90%

Capability Performance Goal: Predict failure with enough confidence and time to take mitigating action

Parameter, Value:
Percent true positives: 99%;
Percent true negatives: 99%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.3 Reliability and Maintainability
13.3.6 Repair, Mitigation, and Recovery Technologies

13.3.6.1 Self-Repairing Seals for Fluid Systems

TECHNOLOGY

Technology Description: Polymer or other-based seals for use in fluid systems that detect leaks and self-seal.

Technology Challenge: Challenges include materials compatibility, reliability, and scale-up performance for high-pressure systems.

Technology State of the Art: Several commercial, academic, and international entities have developed self-repair polymer materials for use in automobile tires and fuel tanks.

Parameter, Value:	TRL
Time to identify, isolate, and repair leak source: minutes.	3

Technology Performance Goal: Detect leaks and self-seal.

Parameter, Value:	TRL
Time to identify, isolate, and repair leak source: minutes.	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Self-repairing seals for fluid systems.

Capability Description: Polymer or other-based seals for use in fluid systems that detect leaks and self-seal.

Capability State of the Art: Traditional reliance on identification of leaks visually through internal sensor data (pressure, time, volume) or using external leak detection systems, such as mass spectrometers and then perform repairs manually.

Parameter, Value:

Time to identify, isolate, and repair leak source: hours.

Capability Performance Goal: Polymer or other-based seals detect leaks and self-seal.

Parameter, Value:

Time to identify, isolate, and repair leak source: minutes.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	4 years

13.3 Reliability and Maintainability
13.3.6 Repair, Mitigation, and Recovery Technologies

13.3.6.2 Self-Repairing Wiring Insulation

TECHNOLOGY

Technology Description: Polymer or other-based wiring insulation materials that detect damage and self-repairs.

Technology Challenge: Challenges include materials compatibility and reliability.

Technology State of the Art: NASA has developed self-repair wiring materials with successful lab demonstrations.

Parameter, Value:	TRL
Time to identify, isolate, and repair leak source: minutes.	4

Technology Performance Goal: Detect damage and self-repairs.

Parameter, Value:	TRL
Time to identify, isolate, and repair leak source: minutes.	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Self-repairing wiring insulation.

Capability Description: Polymer or other-based wiring insulation materials that detect damage and self-repairs.

Capability State of the Art: Traditional reliance on identification of damage visually; through sensor data (volts, current). Failures can and have been catastrophic.

Parameter, Value:
Time to identify, isolate, and repair leak source: hours.

Capability Performance Goal: Detect damage and self-repairs.

Parameter, Value:
Time to identify, isolate, and repair leak source: minutes.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	4 years

13.3 Reliability and Maintainability
13.3.6 Repair, Mitigation, and Recovery Technologies

13.3.6.3 Small Robots for Repairs and Mitigation Actions

TECHNOLOGY

Technology Description: Perform repairs and remediation tasks such as spill clean-ups, leak repairs, opening access panels, connecting fluid or electrical lines, or foreign object debris (FOD) removal in sometimes highly hazardous or inaccessible environments (such as launch pads, engine test stand, processing facilities with hydrazine spills, etc.).

Technology Challenge: Robot resiliency to a variety of hazardous environments while maintaining suitable dexterity and minimizing size is a challenge. Ability to perform operations autonomously while working with hazardous products (certification of the safety of the software) is another challenge.

Technology State of the Art: Special-purpose robotics used in oil pipelines to identify and repair leaks. Several commercial robots are able to navigate tight spaces. Another government agency demonstrated similar capabilities (turning door knobs, etc.) but not at the level of safety/sophistication NASA would need.

Parameter, Value:

Repair and remediation time: minutes to hours.

TRL: 4

Technology Performance Goal: Sense and image environment, navigate around the ground support infrastructure, and perform sophisticated mechanical functions (e.g., opening access panels, connecting refueling lines).

Parameter, Value:

Repair and remediation time: minutes to hours.

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Dexterous hazardous material robot for repairs and mitigation actions.

Capability Description: Dexterous robots able to sense and image their environment, navigate around the ground support infrastructure, and perform sophisticated mechanical functions (e.g., opening access panels, connecting refueling lines).

Capability State of the Art: Primarily manual processes done by people who are sometimes attired in HAZMAT suits. No significant robotics or automation.

Parameter, Value:

Repair and remediation time: hours to days.

Capability Performance Goal: Dexterous robots able to sense and image their environment, navigate around the ground support infrastructure, and perform sophisticated mechanical functions (e.g., opening access panels, connecting refueling lines).

Parameter, Value:

Repair and remediation time: minutes to hours.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	4 years

13.3 Reliability and Maintainability
13.3.6 Repair, Mitigation, and Recovery Technologies

13.3.6.4 Field Repair Through Predictive and Reconfigurable Components

TECHNOLOGY

Technology Description: Real-time mitigation of failures based on local estimates of remaining capability and ability to pre-emptively replace or reconfigure components.

Technology Challenge: Constraining a set of implementable design solutions to a practical size is a challenge.

Technology State of the Art: Self-healing materials; modular design. Only conceptual. Example papers from academia.

Parameter, Value:
Repair and remediation time: minutes to hours.

TRL: None

Technology Performance Goal: Pre-emptively replace or reconfigure components based on models predicting remaining component lifetime or capability; self-track and report usage cycles; and, accurately predict remaining lifetime based on correlated performance of similar components and industry analogs as fielded in similar environments.

Parameter, Value:
Repair and remediation time: minutes to hours.

TRL: 2

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Field repair through predictive and reconfigurable components.

Capability Description: Pre-emptively replace or reconfigure components based on local estimates of remaining capability and ability to pre-emptively replace or reconfigure components.

Capability State of the Art: Manual repair processes using replacement parts.

Parameter, Value:
Repair and remediation time: hours to days.

Capability Performance Goal: On-the-fly modification of system components.

Parameter, Value:
Repair and remediation time: minutes to hours.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.3 Reliability and Maintainability
13.3.7 Communications Networking, Timing, and Telemetry

13.3.7.1 State Aware Monitor and Control

TECHNOLOGY

Technology Description: State aware monitor and control of ground infrastructure and flight assets by exchanging high-level states and constraints and goals on those states.

Technology Challenge: Ability to reliably handle real-time critical information is a challenge.

Technology State of the Art: Increasing use in utilities and processing plants, but focused primarily on low-level programmable logic controller (PLC) based systems.

Parameter, Value:
Operator time: minutes to hours.

TRL 6

Technology Performance Goal: Reduce overall operator time in a relevant environment.

Parameter, Value:
Percent reduction in operator time: 75%

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: State-based command and control architectures and systems.

Capability Description: Convert low-level sensor readings into estimates of system state; convert a series of goals and constraints on system into an actionable set of commands; and, evaluate the estimated state of a system with respect to its actual or true state.

Capability State of the Art: Mostly manual with some automated comparison of predicted spacecraft and launch vehicle behavior using telemetry. Human analysis required to understand what the spacecraft and launch vehicle is expected to do and whether or not a deviation represents an expected (but safe) outcome, or a concern that needs to be addressed.

Parameter, Value:
Operator time: minutes to hours.

Capability Performance Goal: Reduce overall operator time in an relevant environment.

Parameter, Value:
Percent reduction in operator time: 75%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.3 Reliability and Maintainability
13.3.7 Communications Networking, Timing, and Telemetry

13.3.7.2 On-Demand, Adaptive Communications

TECHNOLOGY

Technology Description: Establish reconfigurable communications any time, any place, and connectivity for anything. Provide ability to quickly reconfigure ground communications equipment to adapt to a variety of different launch vehicle frequencies, modulations, and coding.

Technology Challenge: Ability to support a wide range of frequencies efficiently. Need to deal with spurious events and unexpected reconfiguration (especially when dealing with human-rated communications links or range abort decisions).

Technology State of the Art: Content-defined networks are used by large content providers to dynamically change bandwidth and routing based on the type and priority of the information being exchanged. The Communications, Navigation, and Networking Reconfigurable Testbed (CoNNeCT) experiment is being conducted on the International Space Station.

Parameter, Value: | **TRL**
Time for frequency/protocol changes: seconds. | 3

Technology Performance Goal: Improve flexibility to rapidly adapt frequency/protocol to variable frequencies, modulations, and coding from flight and ground telecommunications.

Parameter, Value: | **TRL**
Time for frequency/protocol changes: minutes to days. | 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Software-defined ground station.

Capability Description: Establish reconfigurable communications at any time, in any place, and connectivity for anything. Ability to quickly define communications parameters and have ground station automatically reconfigure and adapt to support. Ability for ground station to automatically detect and choose the best available communications configuration for optimal data return.

Capability State of the Art: Software-defined radios are used on several spacecraft and allow frequencies, protocols, and data-rates to be dynamically changed. Ground-based software-defined radios are planned, but not yet fielded. Communications do not currently automatically adapt to changes.

Parameter, Value:
Time for frequency and protocol changes: weeks to months.

Capability Performance Goal: Improve flexibility to rapidly adapt frequency and protocol changes.

Parameter, Value:
Time for frequency and protocol changes: minutes to days.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.3 Reliability and Maintainability
13.3.7 Communications Networking, Timing, and Telemetry

13.3.7.3 Advanced Networking Protocols for Delay-Tolerant Networking

TECHNOLOGY

Technology Description: Networking protocols that allow launch systems to function during periods of network disconnection or disruption without losing critical information.

Technology Challenge: Determining the amount of information to exchange, the frequency that in-range devices query each other for updates, and which devices are chosen among others for information exchange is a challenge.

Technology State of the Art: Mobile networking companies are using delay tolerant networking (DTN) to enhance communication reliability and data integrity.

Parameter, Value:

Average acceptable latency: 30 seconds or less;

Node reliability: 0.999;

Node Mean Time To Repair (MTTR): 60 to 90 seconds.

TRL 4

Technology Performance Goal: Depositing the bundle at its ultimate destination with enough power to remain usefully active over long periods.

Parameter, Value:

Average acceptable latency: 30 seconds or less;

Node reliability: 0.999;

Node MTTR: 60 to 90 seconds.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Advanced networking protocols for disruption-tolerant networks.

Capability Description: Protocols that support reliable delivery of information over unreliable networks. Advanced routing mechanisms that predict next-best route based on time criticality and likely connectivity of network nodes.

Capability State of the Art: DTN protocols are in operation on the International Space Station and in a variety of ground test labs. Not used in NASA ground or launch at this time. NASA installed and tested the essential elements of DTN on the Deep Impact Network Experiment in 2008. Around 300 images were transmitted from the DTN nodes to the spacecraft where they were automatically forwarded from the spacecraft back to the nodes. This experiment demonstrated DTN's readiness for operational use in space missions.

Parameter, Value:

Average acceptable latency: 500 milliseconds;

Node reliability: not available;

Node MTTR: not available.

Capability Performance Goal: Tolerance of delays and disconnections of minutes (to facility umbilical/system reconnects, etc.).

Parameter, Value:

Average acceptable latency: 30 seconds or less;

Node reliability: 0.999;

Node MTTR: 60 to 90 seconds.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	4 years

13.3 Reliability and Maintainability
13.3.7 Communications Networking, Timing, and Telemetry

13.3.7.4 Highly Secure and Access-Controlled Flexible Data Networking

TECHNOLOGY

Technology Description: Securely and dynamically route information based on content rather than pushed to specific addresses.

Technology Challenge: Ability to handle real-time critical information (e.g., commands to fueling valves) and ensure delivery is a challenge.

Technology State of the Art: Dynamically change bandwidth and routing based on the type and priority of the information being exchanged.

Parameter, Value:
Network reconfiguration time: seconds.

TRL 3

Technology Performance Goal: Dynamically change bandwidth and routing based on the type and priority of the information being exchanged.

Parameter, Value:
Network reconfiguration time: seconds.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Enhanced secure content delivery networks supporting real-time critical operations.

Capability Description: Securely and dynamically route information within a highly secure and access-controlled flexible data networking based on content rather than pushed to specific addresses.

Capability State of the Art: Isolated networks are currently used to provide confidentiality between launch pads and control centers. Manually configured network security policies are used for non-isolated networks.

Parameter, Value:
Network reconfiguration time: minutes.

Capability Performance Goal: Assure the authenticity, integrity, and confidentiality of data transmitted through the network; efficiently move data between source(s) and destination(s) without predefining either the content or the destination; and, interoperate with existing commercial and institutional networks.

Parameter, Value:
Network reconfiguration time: seconds.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.3 Reliability and Maintainability
13.3.7 Communications Networking, Timing, and Telemetry

13.3.7.5 Free Space Optics for Ground Communications

TECHNOLOGY

Technology Description: Alternative to radio frequency communication with high-speed and tap-proof optical communication systems.

Technology Challenge: Overall durability and reliability due to increased hours of operation in real world and space environment.

Technology State of the Art: Laser communications between the Moon and Earth has been demonstrated by the Lunar Atmosphere and Dust Environment Explorer (LADEE) mission.

Parameter, Value:
Downlink data rate: 20 MBps;
Uplink data rate: 620 MBps

TRL 6

Technology Performance Goal: Duplex optical communications from a spacecraft in lunar orbit to an Earth-based receiver.

Parameter, Value:
Downlink data rate: 20 MBps;
Uplink data rate: 620 MBps

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: High-data-rate optical communications.

Capability Description: Optical communications as an alternative to radio frequency communication with high-speed and tap-proof optical communication systems.

Capability State of the Art: LADEE and the International Space Station optical payload for lasercomm science (OPAL) communications packages have demonstrated use of optical downlink. Typical communications systems for launch are through fiber optics with RF as backup.

Parameter, Value:
Downlink data rate: 20 MBps;
Uplink data rate: 620 MBps

Capability Performance Goal: Data rates required to support full pad 4K (Ultra HD) video and multi-spectral sensing.

Parameter, Value:
Downlink data rate: 10 GBps;
Uplink data rate: 10 GBps

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.3 Reliability and Maintainability
13.3.7 Communications Networking, Timing, and Telemetry

13.3.7.6 Model-Based Configuration of Ground Control Systems

TECHNOLOGY

Technology Description: Rapidly and reliably configure ground support equipment and launch control systems to meet the particular needs of the vehicle being integrated or launched.

Technology Challenge: Need an agreed-upon model of significant ground systems characteristics and configurations.

Technology State of the Art: Software deployments and tailored system builds are typically used in industry. However, their scope is generally limited to selecting from a set of pre-defined configurations or to vendor-specific tools and configuration languages.

Parameter, Value: Time to reconfigure ground data systems: hours to minutes.

TRL: 3

Technology Performance Goal: Automated reconfiguration of systems to meet spacecraft and launch vehicle specific characteristics.

Parameter, Value: Time to reconfigure ground data systems: hours to minutes.

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Autonomous software configuration for ground control systems.

Capability Description: Allows ground control system to be automatically adapted to vehicle, spacecraft, and instrument-specific needs, ensuring that ground control systems adapt to a variety of systems that need to be controlled.

Capability State of the Art: Automated configuration of command and telemetry systems by ingesting definitions in extensible markup language. Configuration is limited to the command and telemetry systems, and does not impact displays or provide context-aware alarming. All other reconfigurations of ground equipment and control systems are manual.

Parameter, Value: Time to reconfigure ground data systems: weeks to months.

Capability Performance Goal: Automated reconfiguration of systems to meet spacecraft and launch vehicle-specific characteristics.

Parameter, Value: Time to reconfigure ground data systems: hours to minutes.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.3 Reliability and Maintainability
13.3.7 Communications Networking, Timing, and Telemetry

13.3.7.7 Mobile Network and Information Services

TECHNOLOGY

Technology Description: Mobile and modular non-persistent network and information services for the purpose of providing remote visibility, voice, video, data, and networking for multiple users such as analog test sites and nano-launchers.

Technology Challenge: Optimizing capabilities to fully satisfy multi-user needs is a challenge.

Technology State of the Art: U.S. government's mobile launch system for nanosat class launch vehicle was designed to place a 25 kilogram payload into low earth orbit (LEO).

Parameter, Value:
Mobile capability: yes;
Fully satisfy multi-user requirements: no

TRL 3

Technology Performance Goal: Mobile and modular non-persistent network and information services satisfying multi-user requirements.

Parameter, Value:
Mobile capability: yes;
Fully satisfy multi-user requirements: yes

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Mobile network and information services.

Capability Description: Mobile and modular non-persistent network and information services for the purpose of providing remote visibility, voice, video, data, and networking for multiple users, such as analog test sites and nano-launchers.

Capability State of the Art: NASA has established a level of mobile capabilities for voice, video, data and networking and have deployed to analog sites.

Parameter, Value:
Mobile capability: yes;
Fully satisfy multi-user requirements: no

Capability Performance Goal: Mobile and modular non-persistent network and information services satisfying multi-user requirements such as remote visibility, voice, video, data, and networking

Parameter, Value:
Mobile capability: yes;
Fully satisfy multi-user requirements: yes

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Suborbital: Science, Research & Technology (suborbital program)	Enabling	--	On-going	--	4 years

13.3 Reliability and Maintainability
13.3.8 Decision-Making Tools

13.3.8.1 Intelligent Procedures for Launch Operations Sequencing and System Troubleshooting

TECHNOLOGY

Technology Description: Intelligent procedures to advise launch control team during launch operations including propellant loading, constraints management, mission management team polling, late-in-the-launch countdown time-critical actions such as access arm retraction and cryogenic systems hold-times, and launch commit criteria (LCC).

Technology Challenge: Reliability of results is a challenge.

Technology State of the Art: Several examples of intelligent advisory systems for investments, farming, and manufacturing.

Parameter, Value:
Identify, evaluate, and respond time: minutes to seconds

TRL: 6

Technology Performance Goal: Identify, evaluate and respond to launch operations and system troubleshooting.

Parameter, Value:
Identify, evaluate, and respond time: minutes to seconds.

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Intelligent procedures for launch operations sequencing and system troubleshooting.

Capability Description: Troubleshoots launch operations sequencing and system problems with intelligent procedures to advise launch control team during launch operations, including propellant loading, constraints management, mission management team polling, late-in-the-launch countdown time-critical actions like access arm retraction and cryogenic systems hold-times, and LCC.

Capability State of the Art: Launch team and management team manually initiate and verify final launch operations step by step. Constraints are identified and evaluated manually. Launch commit criteria are evaluated manually. Hold times are initiated and managed manually. For the Space Shuttle, in the final minutes the Ground Launch Sequencer was used for automation of commands and responses and the final 28 seconds was controlled onboard by the Redundant Set Launch Sequencer. The launch team had limited rule-based decision-making tools.

Parameter, Value:
Identify, evaluate, and respond time: hours to minutes.

Capability Performance Goal: Identify, evaluate and respond to launch operations and system troubleshooting with intelligent procedures.

Parameter, Value:
Identify, evaluate, and respond time: minutes to seconds.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	4 years

13.3 Reliability and Maintainability
13.3.8 Decision-Making Tools

13.3.8.2 Advanced Ground Crew Work Instructions and Procedures Display

TECHNOLOGY

Technology Description: Augmented reality glasses allowing ground crew procedures and instructions to be visually and aurally overlayed onto the actual work as it is being performed. Procedures monitor user actions and provide directions, or certify that the process has been performed correctly.

Technology Challenge: The ability to correlate and assess images of actions with successful completion of steps (particularly from multiple viewpoints) is a challenge.

Technology State of the Art: Research has been conducted by corporations into using this type of technology, but there are currently no active deployments or use in large-scale production.

Parameter, Value: Percent reduction in time to perform tasks: 50%

TRL: 3

Technology Performance Goal: Reduce time to perform tasks.

Parameter, Value: Percent reduction in time to perform tasks: 50%

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Context and situation aware procedures and directions integrated with augmented reality glasses.

Capability Description: Register and overlay complex engineering schematics over the actual system in the user's visual field of view on the augmented reality glasses thus providing the ability to monitor user activities and compare with procedures to determine whether the procedure is complete, or whether additional directions need to be provided.

Capability State of the Art: Procedures and instructions are currently provided in either paper or electronic form. No mechanism exists to overlay on top of the user work environment, nor provide context-sensitive tips. 3D models and simulations are used to understand geometry of systems (e.g., modeling of rocket processing through Vehicle Assembly Building). Work on electronic procedures is not yet synthesized into an integrated situation-aware product.

Parameter, Value: Time to perform tasks: 4 to 40 hours.

Capability Performance Goal: Register and overlay complex engineering schematics on augmented reality glasses to reduce time to perform tasks.

Parameter, Value: Percent reduction in time to perform tasks: 50%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	4 years

13.4 Mission Success
13.4.1 Range Tracking, Surveillance, and Flight Safety Technologies

13.4.1.1 Space-Based Range

TECHNOLOGY

Technology Description: Tracks launch vehicles using space-based surveillance assets.

Technology Challenge: Non-recurring costs to develop and launch the space-based assets is a barrier. Will still require some ground assets for launch debris tracking.

Technology State of the Art: The U.S. government has space-based assets for tracking missile launches and multiple independent re-entry vehicles, including radar and infrared systems. In 2005, NASA conducted the space-based telemetry and range safety (STARS) project to demonstrate the capability of space-based platforms to provide telemetry, low-rate and ultra high reliability metric tracking and flight termination data support. Demonstrated with NASA's tracking and data relay satellite system (TDRSS) satellite.

Parameter, Value: Recurring costs: $0 per year.

TRL: 6

Technology Performance Goal: Cost reduction through the tracking of launch vehicles using space-based surveillance assets.

Parameter, Value: Recurring costs: $0 per year.

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Space-based surveillance assets for performing range functions.

Capability Description: Launch vehicles using space-based surveillance assets that allow for elimination of ground-based assets and their associated operations and maintenance costs.

Capability State of the Art: Use of ground-based down-range assets such as C-band radar, GPS metric tracking telemetry, and optical observation equipment.

Parameter, Value: Recurring costs: not available.

Capability Performance Goal: Eliminate the recurring operations and maintenance costs of ground-based assets.

Parameter, Value: Recurring costs: $0 per year.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.4 Mission Success
13.4.1 Range Tracking, Surveillance, and Flight Safety Technologies

13.4.1.2 “Smart” Sonobuoys for Range Operations

TECHNOLOGY

Technology Description: “Smart” sonobuoys that measure sea states, detect various watercraft, both above and below water and signal processing to determine vessel type, position, speed, and bearing, and transmitting the information to range safety officers via satellite relay.

Technology Challenge: Integrating technologies and field demonstrations to verify performance.

Technology State of the Art: Current technology only can provide directional vector information.

Parameter, Value:	TRL
Line of Site Identification accuracy: 99.9% Identification time: 5 to 30 minutes;	4

Technology Performance Goal: Identificaton of vessel traffic type and predictive patterns for range safety.

Parameter, Value:	TRL
Remote and Automated Identification accuracy: 99.9% Identification time: 20%	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Remote and automated capability to detect and clear air and sea areas for range safety control.

Capability Description: Detect various watercraft and aircraft to determine vessel type, position, speed, and bearing, and transmit the information to range safety officers.

Capability State of the Art: Observers with binoculars in patrolling aircraft reporting their observations on range safety communications network

Parameter, Value:

Identification time: 5 to 30 minutes;

Line of Site Identification accuracy: 99%

Capability Performance Goal: Remote and automatd range capability with improved vessel signatures.

Parameter, Value:

Percent improvement in identification time: 4-24;

Remote and Automated Identification accuracy: 99.9%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.4 Mission Success
13.4.1 Range Tracking, Surveillance, and Flight Safety Technologies

13.4.1.3 Onboard Tracking for Range Operations

TECHNOLOGY

Technology Description: Tracking systems with global positioning system (GPS)-metric tracking, Automatic Dependent Surveillance-Broadcast (ADS-B) technology, autonomous flight safety system (AFSS), and other concepts.

Technology Challenge: Integrating technologies and field demonstrations to verify performance is a challenge.

Technology State of the Art: In 2005, NASA conducted the space-based telemetry and range safety (STARS) project to demonstrate the capability of space-based platforms to provide telemetry, low-rate and ultra high reliability metric tracking and flight termination data support. Demonstrated with tracking and data relay satellite system (TDRSS) satellite.

Parameter, Value:
Tracking reliability: 100%;
Down time: 0 weeks per year.

TRL: 6

Technology Performance Goal: Positively track launch vehicles with high reliabitliy and no operational downtime.

Parameter, Value:
Tracking reliability: 100%;
Down time: 0 weeks per year.

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Onboard tracking for range operations.

Capability Description: Positively track launch vehicles through onboard tracking systems with GPS-metric tracking, ADS-B technology, AFSS, and other concepts.

Capability State of the Art: Reliance on C-band radar for tracking. There are periods of radars being down for repairs or maintenance.

Parameter, Value:
Tracking reliability; 100%;
Down time: 2 weeks per year.

Capability Performance Goal: Positively track launch vehicles, eliminating range down time due to radars being down for repairs or maintenance.

Parameter, Value:
Tracking reliability: 100%;
Down time: 0 weeks per year.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.4 Mission Success
13.4.1 Range Tracking, Surveillance, and Flight Safety Technologies

13.4.1.4 Advanced Telemetry Systems for Range Operations

TECHNOLOGY

Technology Description: Highly-reliable transmission capability during launch and re-entry using software-programmable radios, high-frequency transmissions, transmissions through plasma, and exhaust plumes.

Technology Challenge: Requires flight demonstrations to verify performance.

Technology State of the Art: Plasma aerodynamic systems to dramatically improve engine performance; neural network systems, including avionics; fault detection and isolation; robotics; command, control, communications, and computer intelligence (C4I); signal processing; and air traffic control waveguide limiters are developed for use in waveguide systems for use between the circulator and the antenna.

Parameter, Value:
Loss of telemetry on ascent or reentry: periodic.

TRL 3

Technology Performance Goal: Highly-reliable transmission capability during launch and reentry.

Parameter, Value:
Loss of telemetry on ascent or reentry: none.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Advanced telemetry systems for range operations.

Capability Description: Highly-reliable transmission capability during launch without signal loss including transmissions through plasma and exhaust plumes.

Capability State of the Art: Data transmission interruptions when exhaust plume interferes with signal strength and interference due to plasma.

Parameter, Value:
Loss of telemetry on ascent or reentry: periodic.

Capability Performance Goal: Highly reliable transmission capability during launch and reentry.

Parameter, Value:
Loss of telemetry on ascent or reentry: none.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.4 Mission Success
13.4.1 Range Tracking, Surveillance, and Flight Safety Technologies

13.4.1.5 Advanced Antenna Systems for Range Operations

TECHNOLOGY

Technology Description: Highly-reliable antenna technologies to increase data rates and bandwidth for sending and receiving imagery, and integrated flight antennas for range operations.

Technology Challenge: Challenges include scaling up and ruggedizing.

Technology State of the Art: Phased array configuration is particularly advantageous for electrically-large, high-gain, two-dimensional, traveling-wave, conformal arrays with electronic beam steering in two planes and endfire capabilities; the type most suited for seeker applications in missiles and remotely piloted vehicles.

Parameter, Value: Percent improvement in transmission performance: 25%

TRL: 3

Technology Performance Goal: Improve transmission performance.

Parameter, Value: Percent improvement in transmission performance: 25%

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Advanced antenna systems for range operations.

Capability Description: Send and receive imagery and integrate flight antennas for range operations using increased data rates and bandwidth.

Capability State of the Art: The antenna elements are connected in a one-to-one correspondence in both number and form to a lattice of identical, multiport, isotropic, wave-coupling networks physically located under the antenna element array as a backplane of the antenna element layer.

Parameter, Value: Transmission performance: not available.

Capability Performance Goal: Improve transmission performance.

Parameter, Value: Percent improvement in transmission performance: 25%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.4 Mission Success
13.4.1 Range Tracking, Surveillance, and Flight Safety Technologies

13.4.1.6 Steerable Beam Antennas for Range Operations

TECHNOLOGY

Technology Description: Steerable beam antennas responsive to vehicle position and attitude and conformal to the vehicle skin.

Technology Challenge: Challenges include scaling up and ruggedizing.

Technology State of the Art: Steerable beam antennas have been demonstrated with moveable vehicles and roadside antenna platforms.

Parameter, Value:	TRL
Percent improvement in transmission performance: 25%	4

Technology Performance Goal: Improves transmission performance and also improve the data throughput by a factor of 2.

Parameter, Value:	TRL
Percent improvement in transmission performance: 50%	6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Advanced antenna systems for range operations.

Capability Description: Send and receive imagery and integrate flight antennas for range operations using increased data rates and bandwidth.

Capability State of the Art: The antenna elements are connected in a one-to-one correspondence in both number and form to a lattice of identical, multiport, isotropic, wave-coupling networks physically located under the antenna element array as a backplane of the antenna element layer.

Parameter, Value:

Transmission performance: unknown.

Capability Performance Goal: Improve transmission performance using highly reliable antennas with increased data rates and bandwidth.

Parameter, Value:

Percent improvement in transmission performance: 50%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.4 Mission Success
13.4.1 Range Tracking, Surveillance, and Flight Safety Technologies

13.4.1.7 Autonomous Flight Termination System

TECHNOLOGY

Technology Description: Autonomous flight safety system (AFSS) to track a vehicle's position onboard and autonomously terminate if it deviates from the controlled corridor.

Technology Challenge: Multiple field demonstrations are required to validate performance.

Technology State of the Art: Several U.S. government aerial vehicle applications including NASA demonstrated AFSS in 2010.

Parameter, Value:

Percent reduction in operations and maintenance costs for ground systems: 25%;

Time required to identify deviation and send destruct command: 150 milliseconds.

TRL: 6

Technology Performance Goal: Reduce operations and maintenance costs while meeting a sequence command time response.

Parameter, Value:

Percent reduction in operations and maintenance costs for ground systems: 25%;

Time required to identify deviation and send destruct command: 150 milliseconds.

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Vehicle position tracking for flight termination systems.

Capability Description: Track a vehicle's position and terminate if it deviates from the controlled corridor.

Capability State of the Art: Traditional range safety officer monitoring vehicle position on radar display with overlaid controlled corridor and a manually initiated destruct command button. Launch director also has destruct command button. Fully redundant ground systems to maintain.

Parameter, Value:

Operations and maintenance costs for ground systems: not available.

Time required to identify deviation and send destruct command: 10 seconds.

Capability Performance Goal: Identify vehicle deviations from the controlled corridor and terminate, reducing operations and maintenance costs.

Parameter, Value:

Percent reduction in operations and maintenance costs for ground systems: 25%;

Time required to identify deviation and send destruct command: 150 milliseconds.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.4 Mission Success
13.4.1 Range Tracking, Surveillance, and Flight Safety Technologies

13.4.1.8 Solid-State Laser-Initiated Ordnance for Flight Termination System

TECHNOLOGY

Technology Description: Innovative lasers that allow flight termination ordnance initiation systems to be more reliable, cost less, and have less complexity.

Technology Challenge: Multiple field demonstrations are required to validate performance.

Technology State of the Art: In 1995, NASA demonstrated a laser-initiated ordnance sounding rocket demonstration on a 2-stage sounding rocket.

Parameter, Value:
Rating of reliability (scale of low, medium, high): High;
Rating of cost (scale of low, medium, high): High;
Rating of complexity (scale of low, medium, high): Medium.

TRL 6

Technology Performance Goal: Improvements in reliability, cost, and complexity.

Parameter, Value:
Rating of reliability: High;
Rating of cost: High;
Rating of complexity: Medium

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Ordnance initiation for flight termination system.

Capability Description: Initiate ordnance for flight termination.

Capability State of the Art: The Space Shuttle solid rocket booster range safety system consisted of two antenna couplers, command receivers and decoders, a dual distributor, a safe-and-arm device with two NASA standard detonators (NSD), two confined detonating fuse manifolds (CDF), seven CDF assemblies and one linear-shaped charge. The NSD is the relevant component for this discussion.

Parameter, Value:
Rating of reliability (scale of low, medium, high): Medium;
Rating of cost (scale of low, medium, high): High;
Rating of complexity (scale of low, medium, high): High.

Capability Performance Goal: Improved ability to initiate ordnance for flight termination.

Parameter, Value:
Rating of reliability: High;
Rating of cost: High;
Rating of complexity: Medium.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.4 Mission Success
13.4.1 Range Tracking, Surveillance, and Flight Safety Technologies

13.4.1.9 Anti-Jamming and Anti-Spoofing Communications for Range Operations

TECHNOLOGY

Technology Description: Security measures affecting communications, information technology, networks, data storage, intrusion detection, and jamming.

Technology Challenge: Scaling up to real-world conditions is a challenge.

Technology State of the Art: Anti-jamming broadcast communication using uncoordinated spread spectrum techniques.

Parameter, Value:
Percent effective: 100%

TRL: 3

Technology Performance Goal: Proven, highly effective communications security measures.

Parameter, Value:
Percent effective: 100%

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Anti-jamming and anti-spoofing communications for range operations.

Capability Description: Security measures affecting communications, information technology, networks, data storage, intrusion detection, and jamming with full-spread spectrum coverage.

Capability State of the Art: No SOA exists for this capability.

Parameter, Value:
Percent effective: not available

Capability Performance Goal: Proven, highly-effective communications security measures.

Parameter, Value:
Percent effective: 100%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	4 years

13.4 Mission Success
13.4.1 Range Tracking, Surveillance, and Flight Safety Technologies

13.4.1.10 Aerospace Traffic Control System

TECHNOLOGY

Technology Description: Provide aerospace traffic control system capable of monitoring, deconflicting, debris tracking, weather overlays, local and global scheduling, and rapid reconfiguration for concurrent launches, reentries, and flights of diverse flight platforms (manned/unmanned aircraft/launch vehicles/buoyant systems).

Technology Challenge: Scaling up to real-world conditions; developing national and international standards; and integrating with regional, national, and international systems are challenges. The basic system is required by 2020 to maintain range capabilities for mission support due to planned decommissioning of obsolete technologies, and introduction of new technologies.

Technology State of the Art: Other government agencies using Global Positioning System (GPS) and very high frequency (VHF) omnidirection radio range (VOR) systems with mode C transponders; NASA and U.S. government range C-band radar. Several examples of launch and reentry models developed (example: 2002 NASA NextGen range within advanced range technologies working group). Current legacy systems are not certified, do not have weather overlays, and have limited control approach and landing capabilities.

Parameter, Value:

Percent coverage of flight profile: 100%;
Number of flights at a time: 1;
Safe spacing between vehicles: yes;
Weather overlays: no;
Control approach and landing: no;
Government certified: no;
Air traffic control intra-facility data sharing: no;
Debris tracking overlays: no

TRL: 3

Technology Performance Goal: Monitor, deconflict, debris track, local and global schedule, and rapidly reconfigure for concurrent launches, reentries, and flights of diverse flight platforms.

Parameter, Value:

Percent coverage of flight profile: 100%;
Number of flights at a time: multiple;
Safe spacing between vehicles: yes;
Weather overlays: yes;
Control approach and landing: yes;
Government certified: yes;
Air traffic control intra-facility data sharing: yes;
Debris tracking overlays: yes

TRL: 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Aerospace traffic control system.

Capability Description: Aerospace traffic control system capable of monitoring, deconflicting, debris tracking, weather overlays, local and global scheduling, and rapid reconfiguration for concurrent launches, reentries, and flights of diverse flight platforms (manned/unmanned aircraft/launch vehicles/buoyant systems).

Capability State of the Art: Tracking of aircraft; launch vehicles and reentries conducted on a one-by-one basis in coordination with other government agencies.

Parameter, Value:

Percent coverage of flight profile: 100%;
Number of flights at a time: 1;
Safe spacing between vehicles: yes

Capability Performance Goal: Aerospace traffic control for diverse vehicles, to ensure complete coverage of flight profiles, increase number of flights managed, and ensure safe spacing between vehicles.

Parameter, Value:

Percent coverage of flight profile: 100%;
Number of flights at a time: multiple;
Safe spacing between vehicles: yes

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.4 Mission Success
13.4.2 Landing and Recovery Systems and Components

13.4.2.1 Unmanned Aerial Vehicles for Payload Recovery

TECHNOLOGY

Technology Description: Recovering payloads from re-entry, suborbital rockets, or balloons by providing coverage of the entire recovery area then autonomously focusing to smaller areas based upon shared tracking and remote sensing data targeting the landing site.

Technology Challenge: Challenges include maturing sensors and developing protocols for unmanned aerial vehicle to unmanned aerial vehicle communications focused on the landing site.

Technology State of the Art: Unmanned aerial vehicles (UAVs) have been used extensively and very successfully for military purposes. NASA owns UAVs and has used them effectively in science missions, such as hurricane research. Extensive development efforts are now underway to adapt these systems to a wide array of commercial applications.

Parameter, Value:	TRL
Time required to recover payload: 0.25 to 0.5 hours.	2

Technology Performance Goal: Timely recover payloads.

Parameter, Value:	TRL
Time required to recover payload: 0.25 to 0.5 hours.	7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Reentry, suborbital rocket, and balloon payload recovery system.

Capability Description: Timely recover payloads from reentry, suborbital rockets, or balloons by providing coverage of the entire recovery area then autonomously focusing to smaller areas based upon shared tracking and remote sensing data targeting the landing site.

Capability State of the Art: For payload recovery from suborbital rockets, and balloons, operators monitor telemetered coordinates in land or sea chase vehicles and visually monitor landing using binoculars. Reentry payload recovery can involve radar tracking as well as visual monitoring.

Parameter, Value:
Time required to recover payload: 1 to 2 hours.

Capability Performance Goal: Improved timely system to recover payloads from reentry, suborbital rockets, or balloons.

Parameter, Value:
Time required to recover payload: 0.25 to 0.5 hours.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
New Frontiers: Comet Surface Sample Return	Enabling	--	2024	2016	2 years
New Frontiers: Lunar South Pole-Aitken Basin Sample Return	Enabling	--	2024	2016	2 years
New Frontiers: Saturn Probe	Enabling	--	2024	2016	2 years
New Frontiers: Trojan Tour and Rendezvous	Enabling	--	2024	2016	2 years
New Frontiers: Venus In-Situ Explorer	Enabling	--	2024	2016	2 years
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	4 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

13.4 Mission Success
13.4.2 Landing and Recovery Systems and Components

13.4.2.2 Unmanned Aerial Vehicle Aerial Recovery

TECHNOLOGY

Technology Description: Utilize global positioning system (GPS) data communicated from a payload to the unmanned aerial vehicle (UAV) recovery aircraft to develop enhanced aerial recovery techniques for payloads from balloons, sounding rockets, first-stage rockets, and small orbital vehicles.

Technology Challenge: Challenges include the integration of technologies for precision UAV capture, highly reliable grapple hook system, and the requirement for a flight demonstration program.

Technology State of the Art: Other government agencies and commercial industry have demonstrated the precision flying ability of UAVs and aerial recovery of paylaods up to 1,200 pounds.

Parameter, Value: Success rate: 98%

TRL 3

Technology Performance Goal: To near 100% accuracy, intercept the location of the payloads under parachute.

Parameter, Value: Success rate: 99%

TRL 7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: UAV aerial recovery.

Capability Description: Recover reentry, first-stage rocket, suborbital rocket, or balloon payloads under parachute or parafoil while in-flight prior to landing on land or water. Capture vehicle decelerates element being recovered after grappling.

Capability State of the Art: No current capability exists.

Parameter, Value: Success rate: unknown

Capability Performance Goal: Recover reentry, first-stage rocket, suborbital rocket, or balloon payloads under parachute or parafoil while in-flight prior to landing on land or water. Class A – 300-750 pounds, Class B – 3,000-4,500 pounds, Class C – up to 25,000 pounds.

Parameter, Value: Success rate: 99%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
New Frontiers: Comet Surface Sample Return	Enabling	--	2024	2016	2 years
New Frontiers: Lunar South Pole-Aitken Basin Sample Return	Enabling	--	2024	2016	2 years
New Frontiers: Saturn Probe	Enabling	--	2024	2016	2 years
New Frontiers: Trojan Tour and Rendezvous	Enabling	--	2024	2016	2 years
New Frontiers: Venus In-Situ Explorer	Enabling	--	2024	2016	2 years
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	4 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

13.4 Mission Success
13.4.2 Landing and Recovery Systems and Components

13.4.2.3 Arc Jet Test Capabilities for Thermal Protection Material and Systems Development and Flight Qualification for Mission Assurance during Atmospheric Entry

TECHNOLOGY

Technology Description: Arc jet testing provides a reasonable approximation of the heat flux, pressure, shear and the gas enthalpy experienced by a vehicle during hyper-velocity atmospheric entry into Mars, Venus, Titan and outer planets including Saturn.

Technology Challenge: Arc jet data for modeling hyper-velocity atmospheric entry into Mars, Venus, Titan and outer planets including Saturn doesn't exist.

Technology State of the Art: Test gas limited to Earth's atmosphere. Testing limited to convective heating. Testing at a fixed or a discontinuous step function, ability to test at a variable flight profile. Test article size is limited; small sizes (~4") stagnation coupons and ~6" wedge coupons at relatively low heating (~1000 W/cm^2). Non-intrusive measurements; surface temperature by two-color pyrometer and laser induced fluorescence (LIF) for free stream characterization. Technology Readiness Level (TRL) 9 level reflects current technologies SOA and TRL of those technologies specified in the technology performance goal.

Parameter, Value:

Moderate heat-flux;

Moderate pressure;

Moderate enthalpy on 4" stagnation and 6" wedge and 10" panel test articles;

Convective heating only;

A single test condition with limited profile capability;

Air and N_2;

Limited non-intrusive measurement techniques;

Provides surface temperature of test article at 1,650° C/3,000° F.

TRL
9

Technology Performance Goal: Arc jet testing gas mixtures at higher enthalpy;

Generate heat-flux and pressures based on anticipated entry environment for human and robotic science missions; combined convective and radiative heat flux testing;

Develop test environments to handle larger integrated components;

Create test conditions to match entry profile for Mars, Venus, Titan and other planets.

Parameter, Value:

Combined (convective and radiative) heat-flux;

High pressure;

Expanded range of enthalpy with larger (2 or 3 times) test article sizes in stagnation, wedge, and panel orientation;

Carbon dioxide, hydrogen/helium with methane;

Variable profile (heatflux, pressure, and enthalpy) test capability;

Non-intrusive measurement such as ablation spectroscopic measurement;

Provide surface temperature of test article at near 6,648° C/12,000° F associated with hardware return speeds approaching 50,000-70,000 fps.

TRL
6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Enhanced arc jet testing capabilities for thermal protection system (TPS) and integrated components and sub-system testing simulating entry and descent environments from other worlds.

Capability Description: Thermal and vacuum chamber capabilities with arc jet providing a reasonable approximation of the surface temperature and pressure and the gas enthalpy found in a high velocity, supersonic flow.

Capability State of the Art: Current capabilities are limited to testing in air and limited size TPS coupons at moderate heatflux (convective only) with limited diagnostic data acquisition capability.

Hardware testing includes: low Earth orbit (LEO) returns are approximately 25,000 fps with surface heating of 1,650° C/3,000° F. Lunar returns are approximately 36,000 fps. The Stardust sample-return capsule was the fastest man-made object ever to reenter Earth's atmosphere at 42,000 fps.

Capability Performance Goal: Test larger articles, convective and radiative heating, and flight-relevant variable (profiled) conditions. Test at different gas mixtures. Thermal/vacuum technologies that, on Earth, replicate a vehicle's experienced environment from atmospheric reentry into Mars, Venus, near Earth object, or other destinations.

This capability is also relevant for both human return missions at higher reentry velocites than the Multi-Purpose Crew Vehicle (MPCV), LEO and lunar, and robotic missions with non-intrusive diagnostic and data for building ablation models.

CAPABILITY - CONTINUED	
Parameter, Value: Current test gases, air and nitrogen, are more suitable for LEO and limited lunar return speeds (11.5 km/s). Convective heating only. Model size 4” – 10” stagnation, wedges, and panels. Non-intrusive measurements limited to pyrometry. Provides surface temperature of test article at 1,650° C/ 3,000° F.	**Parameter, Value:** Test conditions relevant for other planet entry (human and sample return) return conditions, testing in carbon dioxide for Mars entry in support of human and large payload robotic missions, testing in carbon dioxide is relevant for Venus and hydrogen/helium and other gas mixtures relevant for outer planet entries in support of robotic missions. Diagnostics and data acquisition techniques such as ablation spectroscopy. Surface temperature of test article at near 6,648° C/ 12,000° F associated with hardware return speeds approaching 50,000-70,000 fps.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect –Crewed in DRO	Enabling	2022	2022	2015-2021	5-7 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enabling	2027	2027	2021	5-7 years
Planetary Exploration: DRM 8a Crewed Mars Moons	Enabling	2033	--	2027	10 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enabling	2033	--	2027	10 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enabling	2033	--	2027	10 years
New Frontiers: Comet Surface Sample Return	Enabling	--	2024	2016	2 years
New Frontiers: Saturn Probe	Enabling	--	2024	2016	2 years
New Frontiers: Venus In-Situ Explorer	Enabling	--	2024	2016	2 years
Planetary Flagship: Mars Sample Return	Enabling	--	2026*	2023	4 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

13.4 Mission Success
13.4.2 Landing and Recovery Systems and Components

13.4.2.4 Ablation Spectroscopy

TECHNOLOGY

Technology Description: Measure spectroscopic signatures during arc jet, shock tube or ballistic range testing. Laser induced fluorescence, optical emission spectroscopy are used primarily for atomic species characterization. Characterization is expanded to include ablation materials.

Technology Challenge: Spectroscopic capabilities exist but are not presently used in routine practice or are not installed in high-enthalpy facilities. Resources are required for operation and analysis.

Technology State of the Art: A range of spectroscopic capabilities are known but not for ablation materials.

Parameter, Value:

Measurement of atomic density, temperature, and velocity;

Enthalpy estimation.

TRL 6

Technology Performance Goal: Detection instrumentation integrated with the standard spectroscopy which will extend the capability to measure new parameters focused on ablation materials.

Parameter, Value:

Measurement of species compositions and densities in ablative material.

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Spectroscopic characterization in high-enthalpy testing.

Capability Description: Spectroscopic characterization measurement signatures of ablative material during arc jet, shock tube, or ballistic range testing.

Capability State of the Art: Laser-induced fluorescence and optical emission spectroscopy are used in arc jets, primarily for atomic species characterization.

Parameter, Value:

Spectral radiance;

Atom densities;

Temperatures.

Capability Performance Goal: Spectroscopic characterization capabilities to include absorbance, and molecular densities for ablation materials.

Parameter, Value:

Spectral radiance;

Absorbance;

Molecular densities;

Composition.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	5-7 years
Exploring Other Worlds: DRM 6 Asteroid Redirect – Crewed in DRO	Enhancing	2027	2027	2021	5-7 years
Exploring Other Worlds: DRM 7 Crewed to Lunar Surface	Enhancing	2027	2027	2021	5-7 years
Planetary Exploration: DRM 8a Crewed Mars Moons	Enhancing	2033	--	2027	10 years
Planetary Exploration: DRM 9 Crewed Mars Surface Mission (DRA 5.0)	Enhancing	2033	--	2027	10 years
Planetary Exploration: DRM 9a Crewed Mars Surface Mission (Minimal)	Enhancing	2033	--	2027	10 years
New Frontiers: Comet Surface Sample Return	Enhancing	--	2024	2016	2 years
New Frontiers: Saturn Probe	Enhancing	--	2024	2016	2 years
New Frontiers: Venus In-Situ Explorer	Enhancing	--	2024	2016	2 years
Planetary Flagship: Europa	Enhancing	--	2022*	2019	4 years
Planetary Flagship: Mars Sample Return	Enhancing	--	2026*	2023	4 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

13.4 Mission Success
13.4.3 Weather Prediction and Mitigation

13.4.3.1 Weather Information Database for Aerospace Traffic Management

TECHNOLOGY

Technology Description: Weather information database to continually share national airspace data in real time to support aerospace traffic management and safety. The system will include meteorological, space environment, and oceanographic data assimilation and prediction.

Technology Challenge: Incompatibility is likely with existing data systems.

Technology State of the Art: Scalable data warehouse using commercial software. Relational teradata capability and ability to migrate legacy non-relational and operational data.

Parameter, Value:

Percent improvement in operator decision-making speed: 25%;

Percent improvement in operator decision-making accuracy: 25%

TRL: 3

Technology Performance Goal: Improve speed and accuracy of operators in decision-making based on meteorological conditions.

Parameter, Value:

Percent improvement in operator decision-making speed: 25%;

Percent improvement in operator decision-making accuracy: 25%

TRL: 7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Weather information database for aerospace traffic management.

Capability Description: Weather information database to continually share national airspace data in real time to support aerospace traffic management and safety. The system will include meteorological, space environment, and oceanographic data assimilation and prediction.

Capability State of the Art: Automated weather observation sensor suites and automatic terminal information service, which are designed to serve aviation and meteorological observing needs for safe and efficient aviation operations.

Parameter, Value:

Operator decision-making speed: not available;

Operator decision-making accuracy: not available.

Capability Performance Goal: Improve the speed and accuracy of operators in decision-making based on meteorological conditions by sharing an information database.

Parameter, Value:

Percent improvement in operator decision-making speed: 25%;

Percent improvement in operator decision-making accuracy: 25%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.4 Mission Success
13.4.3 Weather Prediction and Mitigation

13.4.3.2 Weather Information Database for Multiple Users

TECHNOLOGY

Technology Description: A common, consistent, and reliable source of information to multiple users for decision support in the Weather Information Database (WIDB), a.k.a., the 4D Weather Data Cube

Technology Challenge: Incompatibility is likely with existing data systems.

Technology State of the Art: Scalable data warehouse using commercial software. Relational teradata capability and ability to migrate legacy non-relational and operational data.

Parameter, Value:

Percent improvement in operator decision-making speed; 25%;

Percent improvement in operator decision-making accuracy: 25%

TRL 3

Technology Performance Goal: Improve the speed and accuracy of operators in decision-making based on meteorological conditions.

Parameter, Value:

Percent improvement in operator decision-making speed: 25%;

Percent improvement in operator decision-making accuracy: 25%

TRL 7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Weather information database for multiple users.

Capability Description: A common, consistent, and reliable source of information to multiple users for decision support in the Weather Information Database (WIDB), a.k.a., the 4D Weather Data Cube.

Capability State of the Art: Automated weather observation sensor suites and automatic terminal information service, which are designed to serve aviation and meteorological observing needs for safe and efficient aviation operations.

Parameter, Value:

Operator decision-making speed: not available;

Operator decision-making accuracy: not available.

Capability Performance Goal: Automated weather observation sensor suites and automatic terminal information service for safe and efficient aviation operations.

Parameter, Value:

Percent improvement in operator decision-making speed: 25%;

Percent improvement in operator decision-making accuracy: 25%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.4 Mission Success
13.4.3 Weather Prediction and Mitigation

13.4.3.3 Unmanned Aerial Vehicle-Based Meteorological Sensors

TECHNOLOGY

Technology Description: Meteorological sensor systems integrated onto unmanned aerial vehicle (UAV) platforms disbursed across a wide area and at different altitudes providing densely tiered levels of data fidelity for real-time updating of weather information database.

Technology Challenge: Challenges include maturing sensors and developing protocols for UAV to UAV communications for the swarm approach.

Technology State of the Art: UAVs have been used extensively and very successfully for military purposes. NASA owns UAVs and has used them effectively in science missions such as hurricane research. Extensive development efforts are now underway to adapt these systems to a wide array of commercial applications.

Parameter, Value:

Percent improvement in operator decision-making speed: 25%;

Percent improvement in operator decision-making accuracy: 25%

TRL 3

Technology Performance Goal: Real-time updating of weather information database.

Parameter, Value:

Percent improvement in operator decision-making speed: 25%;

Percent improvement in operator decision-making accuracy: 25%

TRL 7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: UAV-based meteorological sensors.

Capability Description: Densely-tiered levels of data fidelity for real-time updating of weather information database using sensor systems integrated onto UAV platforms.

Capability State of the Art: Automated weather observation sensor suites and automatic terminal information service, which are designed to serve aviation and meteorological observing needs for safe and efficient aviation operations.

Parameter, Value:

Operator decision-making speed: not available;

Operator decision-making accuracy: not available.

Capability Performance Goal: Densely-tiered levels of data fidelity for real-time updating of weather information database.

Parameter, Value:

Percent improvement in operator decision-making speed: 25%;

Percent improvement in operator decision-making accuracy: 25%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.4 Mission Success
13.4.3 Weather Prediction and Mitigation

13.4.3.4 Three-Dimensional (3D) Real-Time System to Measure Electric Fields for Lightning Prediction

TECHNOLOGY

Technology Description: Real-time in-situ measurement of the atmosphere's 3D electric field at various altitudes and model lightning predictions.

Technology Challenge: Challenges include sensor development, lightning prediction models, and the complexity of taking two-dimensional (2D) to 3D.

Technology State of the Art: NASA advanced ground based field mill network consists of 34 field mills providing data in real time for the launch pad lightning warning system. Each field mill detects the electrostatic field strength. No evidence of development of sensors to be deployed at different altitudes.

Parameter, Value:	TRL
Percent improvement in operator decision-making speed: 25%; Percent improvement in operator decision-making accuracy: 25%	3

Technology Performance Goal: Improve the speed and accuracy of operators in decision-making based on meteorological conditions.

Parameter, Value:	TRL
Percent improvement in operator decision-making speed: 25%; Percent improvement in operator decision-making accuracy: 25%	7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: 3D, real-time system to measure electric fields for lightning prediction.

Capability Description: Measures the atmosphere's electric field for launch support.

Capability State of the Art: Automated weather observation sensor suites and automatic terminal information service, which are designed to serve aviation and meteorological observing needs for safe and efficient aviation operations.

Parameter, Value:

Operator decision-making speed: not available;

Operator decision-making accuracy: not available.

Capability Performance Goal: Improves the speed and accuracy of operators in decision-making based on meteorological atmospheric electric field conditions.

Parameter, Value:

Percent improvement in operator decision-making speed: 25%;

Percent improvement in operator decision-making accuracy: 25%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.4 Mission Success
13.4.3 Weather Prediction and Mitigation

13.4.3.5 Precision Lightning Strike Locator System

TECHNOLOGY

Technology Description: Acoustic sensors and field mills for precision lightning strike location using triangulation.

Technology Challenge: Scaling up existing systems is a challenge.

Technology State of the Art: In 2002, a proof-of-concept sonic lightning locator system was deployed at NASA.

Parameter, Value:
Accuracy of strike location and intensity: 15 feet.

TRL 6

Technology Performance Goal: Accurate location of a lightning strike and the intensity of the associated electric and magnetic fields.

Parameter, Value:
Accuracy of strike location and intensity: 3 feet.

TRL 7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Precision lightning strike locator system.

Capability Description: Accurate location of a lightning strike and the intensity of the associated electric and magnetic fields with acoustic sensors and field mills using triangulation.

Capability State of the Art: Lightning location is based on camera and witness observations. Sometimes, a strike location is found on the ground or on a launch tower. To be safe, many launch vehicle and payload systems are re-verified if a close-proximity lightning strike occurs near the launch pad.

Parameter, Value:
Accuracy of strike location and intensity: 15-100 feet.

Capability Performance Goal: Accurate location of a lightning strike and the intensity of the associated electric and magnetic fields by triangulation of sensors.

Parameter, Value:
Accuracy of strike location and intensity: 3 feet.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.4 Mission Success
13.4.3 Weather Prediction and Mitigation

13.4.3.6 Weather Prediction Models

TECHNOLOGY

Technology Description: Improve numerical weather-prediction models by using all available information to determine as accurately as possible the state of the atmospheric flow.

Technology Challenge: Achieving compatibility between existing and new systems is a challenge.

Technology State of the Art: Another U.S. government agency's forecasting systems will be upgraded to use a supercomputer to run the models (213 teraflops to 2,600 teraflops by 2015.)

Parameter, Value: (TRL 3)

Percent improvement in operator decision-making speed: 25%;

Percent improvement in operator decision-making accuracy: 25%

Technology Performance Goal: Determine as accurately as possible the state of the atmospheric flow.

Parameter, Value: (TRL 7)

Percent improvement in operator decision-making speed: 25%;

Percent improvement in operator decision-making accuracy: 25%

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Weather prediction models.

Capability Description: Improved numerical weather prediction models by using all available information to determine as accurately as possible the state of the atmospheric flow.

Capability State of the Art: Automated weather observation sensor suites and automatic terminal information service, which are designed to serve aviation and meteorological observing needs for safe and efficient aviation operations.

Parameter, Value:

Operator decision-making speed: unknown;

Operator decision-making accuracy: unknown

Capability Performance Goal: Determine as accurately as possible the state of the atmospheric flow.

Parameter, Value:

Percent improvement in operator decision-making speed: 25%;

Percent improvement in operator decision-making accuracy: 25%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.4 Mission Success
13.4.5 Safety Systems

13.4.5.1 Virtual Hazardous Operations Modeling

TECHNOLOGY

Technology Description: Virtual modeling, walk-through, and phasing of hazardous operations with focus on safety.

Technology Challenge: Challenges include geographic area scan limitations and human-computer interaction (HCI).

Technology State of the Art	TRL	Technology Performance Goal	TRL
Technology State of the Art: Several examples of virtual modeling and training are used in military programs.		**Technology Performance Goal:** Minimze safety incidents and mishaps.	
Parameter, Value: Number of safety incidents and mishaps: 0 to 1 per year.	6	**Parameter, Value:** Number of safety incidents and mishaps: 0 to 1 per year.	7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Virtual hazardous operations modeling.

Capability Description: Virtual modeling, walk-through, and phasing of hazardous operations to identify issues, develop procedures with effective safety controls, and illustrate safe techniques and required sequencing. System can be applicable across a range of hazardous operations from routine ground-based hazardous operations to extreme environments.

Capability State of the Art	Capability Performance Goal
Capability State of the Art: Virtual modeling has been used along with mockups of spaceflight hardware for astronauts to plan and practice intricate operations and maneuvers. Hazardous operations planning relies on lessons learned from experienced individuals.	**Capability Performance Goal:** Minimal safety incidents.
Parameter, Value: Number of safety incidents and mishaps: 1 to 2 per year.	**Parameter, Value:** Number of safety incidents and mishaps: 0 to 1 per year.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.4 Mission Success
13.4.5 Safety Systems

13.4.5.2 Virtual Range Operations Modeling

TECHNOLOGY

Technology Description: A "virtual range" to enable range safety analysis and planning for optimal execution of existing and future ground/launch operations.

Technology Challenge: Challenges include geographic area scan limitations and the need for test demonstrations to validate models.

Technology State of the Art: Elements of the virtual range operations model have been developed by various vendors and available as commercial-off-the-shelf (COTS) software, but are not yet fully integrated.

Parameter, Value:
Time for decision making: minutes to seconds.

TRL 6

Technology Performance Goal: Improve the time required for operators to make decisions.

Parameter, Value:
Time for decision making: minutes to seconds.

TRL 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Virtual range operations modeling.

Capability Description: A "virtual range" to enable range safety analysis and planning for optimal execution of existing and future ground and launch operations, both nominal and off-nominal, using different weather conditions, vehicle configurations, etc. Expands existing data set to reflect new launch vehicles and proposed mission sets. Iincorporate weather influences and limitations.

Capability State of the Art: Some modeling and visualization tools of launch vehicles, radar, telemetry and control reach, and effectiveness modeling.

Parameter, Value:
Time for decision making: minutes.

Capability Performance Goal: Reduces time for decision making.

Parameter, Value:
Time for decision making: minutes to seconds.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.4 Mission Success
13.4.5 Safety Systems

13.4.5.3 On-Demand, Custom-Fitted and Lighter-Weight Personnel Protective Equipment (PPE)

TECHNOLOGY

Technology Description: Custom-fitted and lighter-weight personnel protective equipment (PPE) that use additive manufacturing technologies to enhance PPE and breathing apparatus.

Technology Challenge: Integrating electronics into three-dimensional (3D)-printed articles is a challenge.

Technology State of the Art: Custom-fitted PPE is an emerging product. An example is a hard hat with three days for delivery. Custom-fitted PPE hard hat shows improved performance to minimize employee exposure to workplace hazards. Several examples of on-demand 3D printing of products.

Parameter, Value:

Percent reduction in employee exposure to workplace hazards in hours: 10%;

Percent reduction in number of serious workplace injuries or illnesses: 50%

TRL
3

Technology Performance Goal: Enhanced monitoring and alerting for early signs of exposure to chemicals or other hazards.

Parameter, Value:

Percent reduction in employee exposure to workplace hazards in hours: 10%;

Percent reduction in number of serious workplace injuries or illnesses: 50%

TRL
7

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: On-demand, custom-fitted and lighter-weight PPE.

Capability Description: Custom-fitted and lighter-weight PPE that use additive manufacturing technologies to enhance PPE and breathing apparatus, along with improved measurements for fitting and combined with on-demand manufacturing to enhance protective functionality, comfort, and wearability. The system can also provide PPE with enhanced monitoring and alerting for early signs of exposure to chemicals or other hazards.

Capability State of the Art: The Occupational Safety and Health Administration requires that employers protect their employees from workplace hazards that can cause injury. Employees select standard sizes from available stock. The objectives are to minimize employee exposure to workplace hazards with zero serious workplace injuries or illnesses.

Parameter, Value:

Employee exposure to workplace hazards in hours: not available;

Number of serious workplace injuries or illnesses: not available.

Capability Performance Goal: Reduction in employee exposure to workplace hazards as well as reduction in serious workplace injuries or illnesses.

Parameter, Value:

Percent reduction in employee exposure to workplace hazards in hours: 10%;

Percent reduction in number of serious workplace injuries or illnesses: 50%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: Push	Enhancing	--	--	--	4 years

13.4 Mission Success
13.4.5 Safety Systems

13.4.5.4 Ground Safety Tools for Radioactive Payload Processing

TECHNOLOGY

Technology Description: Spectroscopic monitors and protection from radioactive material sourced from payloads.

Technology Challenge: Challenges include development costs to achieve full functionality.

Technology State of the Art: Electronic personal dosimeters (EPDs) have come into general use using semiconductor detection and programmable processor technology. These are worn as badges, but can give an indication of instantaneous dose rate and an audible and visual alarm if a dose rate or a total integrated dose is exceeded.

Parameter, Value:
Sensitivity (EPD): 50 keV-6 MeV;
Subject to electromagnetic interference: yes;
Real-time data: yes.

TRL 6

Technology Performance Goal: Ruggedly constructed dosimeter badges with real-time data, and higher sensitivity.

Parameter, Value:
Sensitivity: 50 keV-6 MeV;
Subject to electromagnetic interference: no;
Real-time data: yes.

TRL 9

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Ground safety tools for radioactive payload processing.

Capability Description: Spectroscopic monitoring and protective measures for personnel directly and indirectly involved with radioactive payload processing.

Capability State of the Art: Personal dosimeter badges using thermoluminescent dosimetry (TSD) or optically stimulated luminescence (OSL). Radiation dose measures are: absorbed dose (D) measured in grays (Gy), Equivalent dose (H) measured in sieverts (Sv), Effective dose (E) measured in sieverts and Kerma (K) measured in grays, along with dose area product (DAP) and dose length product (DLP). 1 Gy = 100 rad and 1 Sv = 100 rem. The worldwide average background dose for a human being is about 3.5 mSv per year.

Parameter, Value:
Sensitivity (TSD): 5 keV-6 MeV;
Sensitivity (OSL): 5 keV-10 MeV;
Subject to electromagnetic interference: no;
Real-time data: no.

Capability Performance Goal: Ruggedly constructed dosimeter badges with real-time data, and higher sensitivity.

Parameter, Value:
Sensitivity: 50 keV-6 MeV;
Subject to electromagnetic interference: no;
Real-time data: yes.

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
New Frontiers: Comet Surface Sample Return	Enabling	--	2024	2016	2 years
New Frontiers: Lunar South Pole-Aitken Basin Sample Return	Enabling	--	2024	2016	2 years
New Frontiers: Saturn Probe	Enabling	--	2024	2016	2 years
New Frontiers: Trojan Tour and Rendezvous	Enabling	--	2024	2016	2 years
New Frontiers: Venus In-Situ Explorer	Enabling	--	2024	2016	2 years
Planetary Flagship: Europa	Enabling	--	2022*	2019	4 years
Planetary Flagship: Mars Sample Return	Enabling	--	2026*	2023	4 years

*Launch date is estimated and not in Agency Mission Planning Model (AMPM)

13.4 Mission Success
13.4.5 Safety Systems

13.4.5.5 Hazardous Environment Personnel Monitoring System Using Visible Light for Data Transmission

TECHNOLOGY

Technology Description: Test conductors with accurate personnel position location and individual behavior observation of ground crew in hazardous environment using visible light for data transmission.

Technology Challenge: Integrating technologies is a challenge.

Technology State of the Art: Industry has demonstrated data transmission using visible light. It is feasible to incorporate camera, speakers, and face recognition capabilities.

Parameter, Value:

Percent reduction in employee exposure to workplace hazards in hours: 10%;

Percent reduction in number of serious workplace injuries or illnesses: 50%

TRL 3

Technology Performance Goal: Reduce workplace hazard exposure.

Parameter, Value:

Percent reduction in employee exposure to workplace hazards in hours: 10%;

Percent reduction in number of serious workplace injuries or illnesses: 50%

TRL 6

Technology Development Dependent Upon Basic Research or Other Technology Candidate: None

CAPABILITY

Needed Capability: Capability to monitor personnel working in hazardous environments.

Capability Description: Track position and monitor behavior of ground crew in hazardous environments using modulating light signals that communicate with lamps and equipment that are embedded within the visible light generated by light emitting diode (LED).

Capability State of the Art: Limited closed-circuit television observation capability and radio communication by ground crew. There are a few examples of ground crew fatalities in the Space Shuttle Program.

Parameter, Value:

Employee exposure to workplace hazards in hours: not available;

Number of serious workplace injuries or illnesses: not available.

Capability Performance Goal: Reduction in employee exposure to workplace hazards as well as reduction in serious workplace injuries or illnesses. lamps.

Parameter, Value:

Percent reduction in employee exposure to workplace hazards in hours: 10%;

Percent reduction in number of serious workplace injuries or illnesses: 50%

Technology Needed for the Following NASA Mission Class and Design Reference Mission	Enabling or Enhancing	Mission Class Date	Launch Date	Technology Need Date	Minimum Time to Mature Technology
Into the Solar System: DRM 5 Asteroid Redirect – Crewed in DRO	Enhancing	2022	2022	2015-2021	4 years