# 9. Technology Assessment

## 9.1 Summary

The Space Exploration Vision set forth by President Bush cannot be realized without a significant investment in a wide range of technologies. Thus, key objectives of the Exploration Systems Architecture Study (ESAS) are to identify key technologies required to enable and significantly enhance the reference exploration systems and to prioritize near-term and far-term technology investments. The product of this technology assessment is a revised Exploration Systems Mission Directorate (ESMD) technology investment plan that is traceable to the ESAS architecture and was developed by a rigorous and objective analytical process. The investment recommendations include budget, schedule, and center/program allocations to develop the technologies required for the exploration architecture.

This section summarizes the results of this assessment, including the key technologies required to support the new architecture. The three major tasks of the technology assessment were: (1) to identify what technologies are truly needed and when they need to be available to support the development projects; (2) to develop and implement a rigorous and objective technology prioritization/planning process; and (3) to develop ESMD Research and Technology (R&T) investment recommendations about which existing projects should continue and which new projects should be established.

The following are the major Ground Rules and Assumptions (GR&As) used for the assessment:

- All technology developments shall be directly traceable to architecture requirements.
- Mission reference dates for R&T planning shall be:
  - 2011 Crew Exploration Vehicle (CEV) human flight to the International Space Station (ISS);
  - 2018 goal of human mission to the Moon including landing, but no later than 2020; and
  - 2022 goal of permanent human presence on Moon.
- Technologies shall be developed to Technology Readiness Level Six (TRL–6) or better by Preliminary Design Review (PDR), the reference dates for which shall be:
  - 2007 PDR for CEV and Crew Launch Vehicle (CLV);
  - 2012 PDR for initial lunar mission elements; and
  - 2017 PDR for lunar permanent human presence mission elements.
- The Prometheus Nuclear Systems Technology (PNST) shall receive a funding profile for this study of $100M in FY06 and $50M in FY07–11 followed by significant increases.
- Ten percent (10%) of each program budget shall be reserved for program management.
- The budget shall not include funds for earmarks.
- Legislated requirements (e.g., Small Business Innovative Research (SBIR)) shall be preserved.
- Relevant ISS flight research payloads shall be preserved.
- Funding wedges shall be included for future lunar and Mars R&T requirements.

The ESAS technology assessment determined that technology development projects are needed in 12 major areas:

- Structures and Materials,
- Protection,
- Propulsion,
- Power,
- Thermal Controls,
- Avionics and Software,
- Environmental Control and Life Support (ECLS),
- Crew Support and Accommodations,
- Mechanisms,
- In-Situ Resource Utilization (ISRU),
- Analysis and Integration, and
- Operations.

The final result of the technology assessment is a recommended reduction in the overall funding of ESMD R&T of approximately 50 percent. **Figures 9-1** and **9-2** show the before- and after-budget profiles.

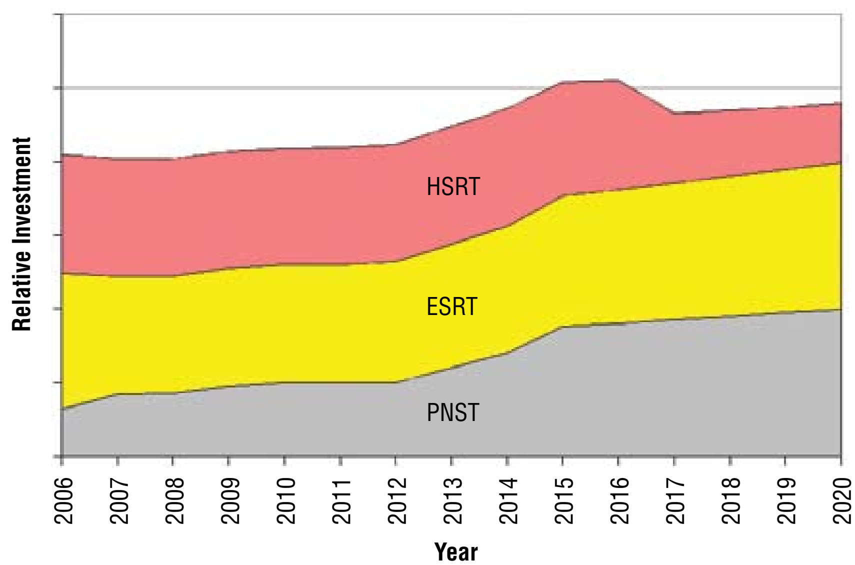


*Figure 9-1. FY06–FY19 Original Funding Profile*

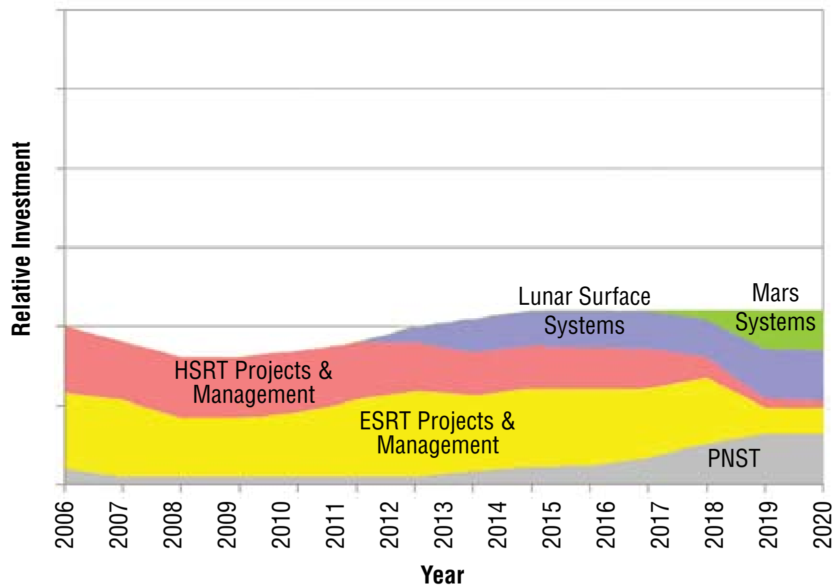


*Figure 9-2. FY06–FY19 ESAS Recommended Funding Profile*

The funding profile includes 10 percent management funds and approximately 30 percent of liens due to prior agency agreements (e.g., Multi-User System and Support (MUSS), the Combustion Integrated Rack (CIR), and the Fluids Integrated Rack (FIR)) and legislated requirements (e.g., SBIR, Small Business Technology Transfer (STTR)).

Seven key recommendations arose from the technology assessment:

- ESMD should share costs with SOMD for MUSS, CIR, and FIR.
- ESMD should transfer the Alpha Magnetic Spectrometer (AMS) to the Science Mission Directorate (SMD) to compete for funding with other science experiments.
- ESMD should quickly notify existing Exploration Systems Research and Technology (ESRT) projects not selected by ESAS that they will be not receive funding beyond FY05.
- ESMD should move Systems Analysis and Tool Development activities (and budget) to a directorate level organization—no longer in ESRT.
- Key ESAS personnel should work with ESMD to facilitate implementation. (Many technologies require immediate commencement on an accelerated schedule.)
- ESMD should develop a process for close coordination between architecture refinement studies and technology development projects. Technology projects should be reviewed with the flight element development programs on a frequent basis to ensure alignment and assess progress.
- ESMD should develop a process for transitioning matured technologies to flight element development programs.

## 9.2 Technology Assessment Process

The above recommendations were developed through a rigorous and objective process consisting of the following: (1) the identification of architecture functional needs; (2) the collection, synthesis, integration, and mapping of technology data; and (3) an objective decision analysis resulting in a detailed technology development investment plan. The investment recommendations include budget, schedule, and center/program allocations to develop the technologies required for the exploration architecture, as well as the identification of other investment opportunities to maximize performance and flexibility while minimizing cost and risk. More details of this process are provided in **Appendix 9A**, **Process**.

The ESAS technology assessment involved an implementation team and an Agency-wide Expert Assessment Panel (EAP). The team was responsible for assessing functional needs based on the ESAS architecture, assembling technology data sheets for technology project(s) that could meet these needs, and providing an initial prioritization of each technology project's contribution to meeting a functional need. This involved key personnel working full time on ESAS as well as contractor support and consultation with technology specialists across NASA, as needed.

The EAP was a carefully balanced panel of senior technology and systems experts from eight NASA centers. They examined the functional needs and technology data sheets for missing or incorrect entries, constructed new technology development strategies, and performed technology development prioritization assessment using the ESAS Figures of Merit (FOMs) for each need at the architecture level. They provided internal checks and balances to ensure even-handed treatment of sensitive issues.

All results were then entered into spreadsheet tools for use by the ESAS team in analyzing technology investment portfolio options. During the final step of the process, the ESAS team also worked with ESMD and the Administrator's office to try to minimize Center workforce imbalance.

## 9.3 Architecture R&T Needs

This assessment was performed in parallel with the architecture development, requiring the whole ESAS team to coordinate closely to ensure that the technology assessment captured the latest architecture functional needs. The functional needs were traced element by element, for each mission, in an extensive Excel file. These needs were the basis for the creation of the technology development plans used in the assessment. Thus, all technology development recommendations were directly traceable to the architecture. This analysis indicated that R&T development projects are needed in the following areas:

- Structures and Materials,
- Protection,
- Propulsion,
- Power,
- Thermal Controls,
- Avionics and Software,
- ECLS,
- Crew Support and Accommodations,
- Mechanisms,
- ISRU,
- Analysis and Integration, and
- Operations.

These areas are described below. Each area's section contains the description of its functional needs, the gaps between state-of-the-art and the needs, and the recommended developments. There is a more detailed write-up for each recommended technology development project listed in **Appendix 9B**, **Technology Development Activity Summaries**.

### 9.3.1 Structures and Materials

The ESAS architecture could potentially meet mission needs using aluminum alloys and state-of-the-art materials. However, reduction in structural mass translates directly to additional up-and-down mass capability that would facilitate logistics and increase science return for current and future mission phases. Reductions in structural mass could also offset growth in other systems. Lightweight structures that provide structural load-bearing support, radiation protection, and possibly other combinations of protection such as thermal or Micrometeoroid/Orbital Debris (MMOD) are also desirable from an architecture robustness perspective.

Simultaneous proof-of-concept demonstrations for integrated lightweight structures and research into advanced materials and structures for future missions to the Moon and Mars must be conducted. A series of building-block demonstrations of key components, elements, and subsystems should be conducted with appropriate validation testing. In order to support lunar surface systems, near-term activities should culminate in a large-scale integrated structures demonstration in relevant environments by 2012 (TRL–6). Critical investments include:

- Novel, multifunctional design concepts, including modularity;
- Integrated system performance (including deployment) in relevant environments of core structural modules;
- Durable flexible materials, including Nextel, aliphatic polymers and polyurethane, tailoring for redundant load paths and self-healing;
- Organic materials, including polymer matrix composites;
- Advanced aluminum alloys, titanium alloys, super alloys, refractory alloys, and metal matrix composites;
- Hybrid organic/metallic composites;
- Integrated thermal management;
- Lightweight radiation protection, including use of advanced materials (boron composites);
- Advanced sensors for structural and environmental monitoring, including embedded fiber optic and acoustic sensors, and other integrated, autonomous sensing technologies; and
- Structures that can adapt to dynamic environmental conditions and mission changes. This includes self-healing materials, redundant structural architectures, and active, embedded sensing and control.

### 9.3.2 Protection

Protection is a category of capabilities that provide protection of an element and its contents from environments, both natural and self-induced. These capabilities include thermal protection, radiation protection, and lunar dust/environment mitigation. Protection is a key area with respect to mission success and safety and warrants considerable investment. The ESAS architecture requires that the CEV Crew Module (CM) be capable of performing entry into the Earth's atmosphere at Earth-orbital, lunar-return, and Mars-return velocities. A Thermal Protection System (TPS) requires materials specifically designed to manage aerothermal heating (heat flux, dynamic pressure) experienced during hypersonic entry, for both nominal and abort scenarios. A single architecture may require both reusable and single-use materials. Only ablators can meet maximum requirements; they are designed to sacrifice mass under extreme heating efficiently and reliably. Reusable materials that preserve the Outer Mold Line (OML) can meet requirements for lower heating locations. The Apollo ablative TPS (AVCOAT–5061) no longer exists. Qualification of new or replacement materials will require extensive analysis and testing.

It is well known that the primary sources of radiation exposure in space are Galactic Cosmic Rays (GCRs) and Solar Particle Events (SPEs). However, due to a number of independent variables associated with these sources of radiation, there is considerable uncertainty about the total shielding required for long-duration missions. Research is needed to confidently predict the shielding capabilities of various materials and spacecraft components along with corresponding research to understand crew exposure limits. Most hydrocarbon-based composites have value as radiation shielding; thus, many materials (e.g., ones developed for lightweight structures) may also be useful for radiation protection.

Apollo lunar Extra-Vehicular Activity (EVA) experience has shown lunar dust to be problematic with respect to seals and mechanical systems. Significant research into dust tolerant airlock systems needs to be performed. Durable and robust materials and systems for airlock structure and seals that include dust mitigation capabilities must be developed. Enhanced durability and dust exclusion technologies for application to EVA surface suit outer protection and pressure seals for both suit and airlock systems are also needed. These technologies must have long-term durability, be damage-tolerant, provide dust-exclusion capabilities, and be nonflammable/oxygen-compatible.

### 9.3.3 Propulsion

The ESAS architecture requires a variety of propulsion technologies to be evolved or developed in support of ISS and lunar missions. In order to maximize safety during ground processing, launch, and space operations, nontoxic propellants were chosen when possible. Larger, nontoxic monopropellant thrusters need to be developed and human rated for the Launch Vehicle (LV) upper stages, the CM, and, perhaps, the Lunar Surface Access Module (LSAM) ascent stage. Specific propulsion research in support of nontoxic propellants includes developing and demonstrating technologies to enable change in LV upper stage Reaction Control Systems (RCSs) from hydrazine to a nontoxic alternate to enable safe/efficient launch operations, infrastructure reduction, performance improvement, logistics reduction, and potential commonality between main and auxiliary propellants. Critical technologies to enable Tridyne-based attitude control propulsion are required, along with 50- to 100-lbf thrusters to support the CEV CM and other applications.

Missions to the ISS prior to return to the Moon can be accommodated assuming current Space Shuttle Main Engine (SSME) production rates and utilization of SSMEs from existing inventory for the CLV upper stage. The Cargo Launch Vehicle (CaLV) requires two J–2 engines on each upper stage. Research is needed to get the SSME and J–2s to the point to where they can be produced economically for the lunar missions. The SSME is an extremely efficient and capable engine but is expensive and takes years to produce using current production methods. The NASA/U.S. Air Force (USAF) Integrated Powerhead Demonstrator (IPD) is a research activity that has demonstrated production methods that can significantly reduce production bottlenecks and reduce engine part count by up to an order of magnitude, while reducing costs. Applying these methods to the SSME will enable cost and production goals to be met for the lunar missions. A subset of these methods can also be applied to making the J–2s more affordable to produce in support of the lunar missions.

The architecture requires a high Specific Impulse (Isp) propulsion system for the Service Module (SM) and lunar ascent that yields high reliability without significant propellant boil-off issues. A propulsion system developed to perform both functions can also reduce costs. A human-rated 5- to 20-klbf pressure-/pump-fed Liquid Oxygen (LOX)/Methane (CH4) in-space engine and propulsion system is required for the SM and the LSAM ascent stage.

The architecture requires the fueled CEV/SM to remain at the ISS for up to 6 months with the ability to leave the ISS within minutes of notification. Thermal conditioning to enable long-term storage of cryogens will be required, along with the ability to have propellant acquisition after dormant periods in zero gravity. Development and demonstration of critical technologies for cryogenic storage for CEV and outpost surface elements (i.e., LSAM, regenerative fuel cells, ISRU reactant storage) are needed—key fluids are LOX, CH4, and Liquid Hydrogen (LH2). Primary research needs include:

- Tank systems, including: Liquid Acquisition Devices (LADs), passive thermal and pressure control, prototype pressure vessel demonstration, low-gravity mass gauging, active thermal control, and Cryogenic Fluid Management (CFM) integrated system demonstration;
- Main engine systems, including: ignition and combustion characterization, long-life ignition system, and bi-propellant valves;
- RCS engine systems, including: RCS thrusters, Electro-Mechanical Actuators (EMAs) inlet valve for RCS, and RCS chamber materials; and

- RCS feed systems, including: Helium (He) pressurization tank, He control system, prototype cryogenic propellant isolation valve, RCS feed system design and LOX test, CH4 feed system test, CH4 specifications and hazards, and integrated RCS demonstration.

The LSAM requires a high-performance, lightweight descent propulsion system that is highly throttleable for the descent module. A LOX/LH2 system maintains adequate margin while also providing a path for utilization of in-situ-produced propellants and eventual LSAM reusability. The LSAM descent stage requires a moderate thrust (5- to 20-klbf) pump-fed, deep-throttling engine. A pump-fed, hydrogen-fueled engine was chosen because of its high Isp and mass savings as compared to a pressure-fed system. This allows the LSAM to perform the circularization burn upon arrival at the Moon, while also maximizing the LSAM cargo delivery capability. The same engines need the capability to restart for the lunar descent with the ability to throttle down to 10 percent of total thrust. As a lunar outpost is established, there is potential to use lunar oxygen and perhaps hydrogen to refuel and reuse the landers. This would require the engines to be capable of many restarts. These new engine capabilities need to be developed, and the RL–10 can be used as the basis for the development.

The ESAS architecture does not address the Mars phase in detail, but it is recognized that traditional chemical propulsion cannot lead to sustainable Mars exploration with humans. Nuclear Thermal Propulsion (NTP) is a technology that addresses the propulsion gap for the human Mars era. NTP's high acceleration and high Isp together enable fast transit times with reasonable initial mass in Low Earth Orbit (LEO). Primary areas of work to be performed in support of future Mars mission include:

- Retire risks and develop high-temperature fuels and materials for NTR operation.
- Identify ground test plans and required facility development. Options include containment with effluent treatment to scrub rocket exhaust of fission products, or use of tunnels at the Nevada Test Site (NTS) to trap exhaust.
- Perform systems analysis to define requirements and engine/system trades (cycle, thrust, Thrust-to-Weight (T/W), Isp).
- Examine feasibility issues including engine clustering, shielding, testing strategy, engine cycle, and use of existing engine components.

### 9.3.4 Power

Significant gaps exist in power capabilities that are on the critical path to enabling human exploration beyond Earth orbit. The ESAS architecture desires nontoxic fluids to reduce ground processing facility requirements and to increase safety for the crew. Hydrazine (toxic) is currently used to drive the Solid Rocket Booster (SRB) and SSME Auxiliary Power Units (APUs). Research into nontoxic power generation for ESAS LVs is required. ESAS architecture elements, including the CEV, LSAM, and surface systems, require long-life/high-capacity/high-density energy storage on the order of 5 to 10 kW. Lithium ion batteries are required to be human rated at load profiles that are currently higher than state-of-the-art. Fuel cell systems provide power largely independent of environment (solar incidence), which allows greater mission flexibility and will typically provide larger power levels for less total mass for short-duration missions. The ESAS architecture requires advanced fuel cells to meet LSAM and surface system design margins. Radioisotope power sources are a technology option to meet LSAM and surface system mission requirements in support of long-duration surface missions. An outpost will require power of at least 25 kWe, with more required for

ISRU. A technology option for providing outpost power is surface solar arrays, but this option requires some research for array deployment on the 1/6th-g lunar surface. Fission power is a technology option, especially if there are periods of darkness at the outpost location. Power Management and Distribution (PMAD) for a lunar surface power infrastructure will be a new and challenging capability due to the temperature environment and distributed outpost environment.

### 9.3.5 Thermal Controls

Heat transfer fluids must be selected early for the CEV Active Thermal Control Subsystem (ATCS) and for all other subsequent vehicles because hardware designs are fluid-dependent. Thermal control fluids are desired that not only have good thermophysical properties, but also are safe for use inside the cabin of a vehicle and in radiators. Fluids must be nontoxic, nonflammable, compatible with the Environmental Control and Life Support System (ECLSS), and have freezing temperatures that allow for use in radiators.

The ESAS architecture features lunar surface destinations that have thermal environments much different than deep space. The impact of dust and surface operations and vehicle integration must be incorporated into the thermal system design. Advanced technology development for heat rejection for short-duration missions to the surface of the Moon include:

- Lightweight radiators made from advanced materials. (Significant mass savings are possible—lightweight radiators are predicted to save over 300 kg for lunar missions.)
- Radiators integral to vehicle structure. (Structural radiators may provide as much as a 40 percent mass savings over body-mounted radiators.)
- Coatings and materials for improved performance and dust resistance.
- Evaporative heat sinks for specific mission elements (e.g., lunar descent/ascent or post landing). These have not undergone development since the 1970s; advances include reduced mass, improved controllability, expanded operating range, and increased life.

Advanced technology development for heat rejection is required for long-duration missions to the surface of the Moon, across the harsh conditions of the lunar day and night. Studies on the effects of lunar dust on radiator performance should be performed. Heat pumps are required to elevate the temperature of radiators. Due to the high-temperature environment, lunar missions near the equator during the day cannot use vertically oriented radiators to reject heat into the environment and would require large horizontal radiators. A heat pump enables the use of vertical radiators and greatly reduces radiator size for horizontally mounted radiators. Two-phase ATCSs have been shown to require less power and mass for applications with high-heat loads and long-transport distances. This is because two-phase heat transfer not only uses the sensible energy of the working fluid, but also the latent energy. This provides higher heat transfer coefficients and enables lower mass flow rates. Two-phase systems are desirable for an outpost or base with high internal heat loads.

### 9.3.6 Avionics and Software

The ESAS architecture requires advanced Integrated Systems Health Management (ISHM) and autonomy beyond that currently utilized in the ISS and Shuttle programs to increase crew safety, increase performance through enhanced autonomy, and reduce operations costs via in-situ diagnostics and mission support. Enhanced ISHM will be required to facilitate lunar outpost activities. The architecture has elements operating from the surface of Earth to the surface of the Moon and back. The radiation environment in space and on the lunar surface can cause electronics to fail in numerous ways. Research is required to make electronics more robust in this environment either with circuit design and/or with shielding. Current crewed system elements have miles of copper wire and data buses that were designed decades ago. It is imperative that research and implementation of advanced crewed spacecraft network solutions be undertaken to increase reliability and robustness and decrease system mass. A substantial amount of new flight software will also need to be developed. A significant amount of the effort associated with this software will be for verification and validation. Enhanced processes and methodologies for developing, validating, and verifying the ESAS element software are needed to enhance safety and reliably and reduce costs.

The ESAS architecture requires the CEV to perform rendezvous and docking with the ISS, the LSAM stack in LEO, and the LSAM in Low Lunar Orbit (LLO) after return from the lunar surface. The CEV performs Automated Rendezvous and Docking (AR&D) when the CEV CM is serving as a pressurized cargo carrier to the ISS. In all other circumstances, the rendezvous and docking is either piloted or facilitated by a human-controlled berthing procedure (unpressurized ISS cargo delivery). Vehicle position, velocity, acceleration, attitude, and attitude rate measurement and estimation are required. The ESAS architecture features a lunar outpost that is gradually built through a series of sortie missions to the outpost location. These sortie missions will be both piloted and automated and will require precision landing and hazard avoidance to ensure outpost deliveries are located properly. The architecture features a near-anytime return capability from the lunar surface to accommodate contingencies. To accommodate these lunar return contingencies, a "skip-entry" guidance system and associated avionics/software need to be developed that can allow the CM to deflect off of the upper atmosphere to phase reentry profiles.

The ESAS architecture requires high data rate communications to support in-space and surface operations. The three primary needs are mission contingency support, science interaction, and public outreach. Sortie and outpost locations may require additional relay antennas or spacecraft. Possible lunar mission sites include some permanent dark regions in craters near the lunar poles. These targets are of interest for scientific and ISRU potential. Low-temperature electronics are needed to enable the sensors, probes, robots, and, eventually, large regolith machinery that may journey into the crater shadows. The architecture features four crew members available for simultaneous EVA while at the lunar outpost for up to 180 days. This is a significant leap beyond the EVA capability that Apollo had and is an opportunity to perform a significant amount of surface science. Technologies associated with science instruments require additional investment. These include: sample acquisition; in-situ chemical, physical, and biological inspection and analysis; sample handling and processing; and sample return. Current modes of on-orbit operations feature different hardware radios for different applications and frequencies. This requires the crew to have access to several different radios to perform certain functions. A software digital radio designed for ISS and lunar sorties may have significant impacts on productivity and hardware requirements for those and future missions.

### 9.3.7 Environmental Control and Life Support

Technologies for ECLS currently exist for crewed sorties to LEO. This technology is implemented in the ISS and Shuttle systems and sometimes can be large, massive, and unreliable. Research is necessary to reduce mass and volume requirements of the systems while also addressing increased reliability and the lunar surface environment.

The CEV will require atmospheric management technology investments to (1) improve volume efficiency of Lithium Hydroxide (LiOH) by advanced packaging and formulation; (2) reduce mass, volume, thermal, and power requirements of air revitalization system by combining Carbon Dioxide (CO2), moisture, and trace contaminant removal into single vacuum swing system; and (3) identify/develop improved adsorbents and chemisorbents for vacuum swing systems. Additional technology investments for atmospheric management in support of lunar sortie missions include: (1) low-maintenance techniques for removing particulate matter including planetary dust from process air streams, (2) technologies and methods to isolate lander/habitat from external dust contamination, and (3) improvements to multifunctional CO2, humidity, and trace contaminant systems for planetary surface use. In order to support long-duration lunar outpost missions, technologies are needed for the reduction of system consumables. These technologies include regeneration of filters for removal of particulates, alternative low-power/temperature systems for removal and recovery of CO2 using advanced amines and nonamine sorbants, and alternative organic contaminant removal technologies including regenerable adsorbents and thermal and photocatalytic oxidation.

Advanced air and water recovery systems for the CEV and lunar missions are needed to reduce the overall supplies of air and water necessary to sustain humans beyond Earth. These technologies will provide for efficient life-sustaining functions inside spacecraft and planetary surface habitats by decreasing mass, expendables, resupply, energy, volume, heat rejection, and crew time. Some specific needs include: (1) improved pretreatment for urine and stabilization of waste water for longer missions, (2) improved potable water treatment for longer missions, and (3) improved water storage tanks to reduce mass and with considerations for radiation protection. These technologies would improve operability and reliability, and reduce operating buffers and system consumables.

Advanced environmental monitoring and control technologies are required to support crewed lunar missions. Updates to material flammability standards for partial gravity are needed. An integrated suite of reliable environment monitors to detect events and maintain environmental contaminant limits needs to be produced and validated. Information and control systems that provide crew with pertinent environment information that guides actions and design information for mixed human/automated fault recovery are needed, as well as lunar-transit and surface-fire scenarios and training.

### 9.3.8 Crew Support and Accommodations

Crew support and accommodations include EVA systems, accommodations for crew escape, crew health systems, habitability systems, and radiation exposure management. The ESAS architecture requires the CEV to have EVA capability for all crew members in support of contingencies. An in-space suit is required that can be used for EVA with an umbilical from the CEV. The suit also needs to support emergency depressurization on launch and entry. Current shuttle pressure suits cannot support an EVA. A robust and highly reliable crew escape system to minimize loss of crew is required. This includes an integrated solution that goes across the LV, escape tower, CEV, in-space suit, and the crew accommodations in the CEV. Technology investments are required for an in-space EVA suit system and associated infrastructure support for crew survival from emergency vehicle depressurization. These technologies include a pressure garment with integral EVA capabilities, tools/mobility aids (tethers, etc.) necessary to perform in-space contingency EVA tasks from the CEV, survival equipment for abort conditions, vehicle support equipment required to interface the in-space EVA suit with the CEV, and equipment/ground support facilities required to test/verify in-space EVA systems. The in-space suit and its associated support equipment are an integral part of the crew escape system. Technology needed to accommodate crew escape include foolproof and rapid failure detection capability to detect pad fallback/reconnect at first motion during liftoff. Other technology needs include launch and entry pressure suits with thermal protection and cooling, flexible (constant volume) joints, and helmets. Safety equipment requirements include parachutes and water survival equipment such as life rafts, life jackets, and search-and-rescue Global Positioning System (GPS) beacons for operation by deconditioned crew. A lunar surface EVA suit and associated systems are needed. Shuttle EVA suits are designed for zero gravity and cannot tolerate the lunar surface environment. Apollo suits are no longer available and are not designed for the cold polar environments or with any embedded radiation protection.

Technology for crew health care systems currently exists for crewed sorties to LEO. Some of this technology is implemented in the ISS and Shuttle systems and can be large, massive, and unreliable. Research is needed to reduce mass and volume requirements of the systems while also addressing increased reliability and the lunar surface environment. The architecture requires a system of crew health tools to enable crew performance for surface operations for lunar missions that span both short- and long-duration stays. Technology development is needed to: (1) mitigate identified biomedical risks to ensure capability of crew to perform missions, (2) stabilize and treat for minor medical events and evacuation for selected major medical events, (3) integrate exercise and EVA pre-breathe countermeasures, (4) develop exposure limits for mission and tool design, and (5) advance state-of-the-art technology for vacuum exposure and volume/mass limits.

Habitability systems for lunar sortie missions include the galley (stored-food system), solid-waste management (including trash), crew accommodations, and human factors engineering. Technology investments are required to provide acceptable crew accommodations within tightly constrained vehicle mass and volume; enhanced galley operations in partial gravity and reduced pressure; waste stabilization, volume reduction, and storage; updated human systems interfaces; and reduction in potential for human error-induced mission failures. Technologies that increase crew efficiency and reduce fatigue need to be developed along with those that yield an improvement in maintainability and operational flexibility.

Research that enhances radiation exposure management is needed in support of the lunar outpost due to the long mission times outside of Earth's magnetic field. The radiation environment is extremely dynamic (a continuous flux of GCRs punctuated by intense fluxes from SPEs). Long-term dosages of GCRs can lead to long-term crew health issues, and SPEs can cause acute radiation sickness. Crew exposures must be managed in real-time to keep them within limits. This requires technology investments to refine nowcasts (i.e., short-term forecasts) of solar outbursts on the sun, forecasts of "all-clear" periods, and accurate forecasts of dose rates versus times at the Moon. It also requires technology developments to enhance active dosimeters and radiation monitors that accompany the crew and report their data back to Earth in real-time. Software development is also needed for modeling the data and training for real-time exposure management.

### 9.3.9 Mechanisms

Mechanisms perform element operations through moveable, deployable, or articulating devices. They include devices to facilitate landing, docking, and element deployment.

The ESAS architecture currently features a land touchdown for the CEV CM. Technologies for human-rated main chutes and supersonic drogues to enhance landing accuracy need to be developed. Reducing the final impact to acceptable levels requires a touchdown decelerator such as an airbag or retro-rocket in addition to the main parachutes. An integrated system test of the CM recovery systems is required for human rating. This includes deployment of chutes and any type of terminal descent system that would be consistent with a nominal or contingency recovery.

The architecture requires that all crewed elements utilize a common and robust docking mechanism. Shuttle/ISS heritage docking systems (Androgynous Peripheral Attachment System (APAS), Probe and Cone (P/C)) require significant docking impulses that would drive CEV design. Those same systems are not manufactured in the United States. Technology development is required to take current Low-Impact Docking System (LIDS) concepts to the point where they can be incorporated into the CEV and LSAM designs.

The architecture builds its lunar outposts through a series of sortie missions. This leads to a need for a slow build up of smaller components that will require transportation and assembly. Much of this could be done autonomously or via teleoperation. Technology research into surface system deployment methodologies and mechanisms is required. Potential lunar targets also include permanent dark regions in craters near the lunar poles. These targets are of interest for scientific and ISRU potential. Low-temperature mechanisms are needed to enable the sensors, probes, robots, and, eventually, large regolith machinery that may journey into the crater shadows.

### 9.3.10 In-Situ Resource Utilization (ISRU)

The ESAS architecture has two primary goals for lunar exploration. The first is developing and demonstrating the capabilities needed for humans to go to Mars and the second is lunar science. ISRU is a blend of science and the development of exploration capabilities. Specific requirements for ISRU will change based on what future lunar robotic probes may discover on the surface, but the benefits of reduced logistics and extended mission durations associated with ISRU are highly desirable.

All lunar ISRU processing and construction requires excavation and handling of lunar regolith. Demonstration of effectiveness and regolith abrasiveness and wear characteristics is required before full-up use of ISRU in the outpost phase. Excavation and handling demonstrations of interest include: excavation and trenching down to at least 1 m, berm building up to 3 m in height (for engine plume debris and radiation shielding), and area clearing/leveling for landing area preparation and road construction for dust mitigation. Also, low-gravity dust, regolith handling, and transport characterization testing is required.

The regolith on the Moon contains approximately 45 percent oxygen by mass. Most oxygen extraction methods are applicable to multiple sites of interest for future exploration. Oxygen production for life support and ascent/hopper propulsion during the Outpost phase could significantly reduce the cost, risk, and delivered mass of outpost missions, while increasing mission effectiveness. Demonstration of process efficiency and life characteristics is required before full use during the outpost phase. Until hydrogen/water extraction from lunar poles is demonstrated, extraction of solar wind hydrogen/methane volatiles from regolith should be pursued. Demonstrations should be low-mass and low-cost to allow easy packaging. Early oxygen extraction techniques developed for lunar sortie and initial lunar outpost activities will be of the simplest and lowest risk possible, which usually equates to low extraction efficiency. The ability to evaluate higher risk but higher efficiency/payback techniques is of interest, especially if production levels rise and/or duration of operations is extended (e.g., hydrofluoric acid reduction). Support hardware developed for initial oxygen production hardware should be utilized to the maximum extent possible.

The Lunar Prospector has shown that significant quantities of hydrogen exist at the lunar poles, but the form of hydrogen is unknown (i.e., hydrogen, water, ammonia, methane). Hydrogen and water are extremely important for long-term life-support and propulsion needs. It is critical that a demonstration (1) characterize the form and concentration of hydrogen present, (2) characterize the regolith and environment in the shadowed crater, (3) operate for an extended period in an approximately 40–K-temperature environment, and (4) demonstrate a scaleable extraction and separation concept before the outpost phase. Commonality with Mars water extraction techniques is desired.

### 9.3.11 Analysis and Integration

The ESAS architecture has identified operational scenarios and crew flight regimes that have not been modeled since the Apollo era. Significant analytical tool development will be required to support mission design, development, and operations along with identification and implementation of analytical standards to facilitate cross-Agency analysis. Trade studies that assess changes in configuration, operations, or technologies to adjust to fluctuating margins and requirements will be needed continuously as designs and technologies mature. Significant cost savings and schedule robustness can be obtained by increasing analysis throughout the program cycle to (1) support key architecture decisions, (2) determine optimal technology investment portfolios, and (3) assess alternative programmatic and architectural "off-ramps" prior to when a contingency may occur.

Investments in analytical tool methodologies, analysis integration, and quantitative technology assessment are required to support the implementation of the ESAS architecture across NASA during the coming decades. Specifically, investments are required to: (1) identify, modify (or develop) and integrate appropriate analytical capabilities to quantitatively model the exploration architecture, missions, systems and technologies; (2) apply and/or develop integration standards to facilitate consistent and defensible analysis and design; and (3) develop and apply a verification, validation, and accreditation approach, while leveraging existing proven tools to the maximum extent possible.

In addition to, and parallel with the above, investments in the application of the analytical methodologies are required to drive analysis capability requirements and yield information critical to the success of the ESAS architecture. These analytical applications include: (1) technology analysis and portfolio assessment supported by investments in technology information collection and management, portfolio development, assessment and recommendations, and ongoing validation of technology development projects and associated impacts on architecture; (2) architecture modeling and analysis supported by investments in advanced concept development and assessment, technology impact assessment, and FOM assessments; and (3) data integration and report development that enable decision makers to rapidly extract significant information.

### 9.3.12 Operations

The ESAS architecture sets the foundation for exploration systems for the next 30 years. In order to be sustainable and robust, the architecture and its associated elements need to incorporate supportability as a design philosophy from the start. This will be especially important as distances and durations increase.

Technology investments to facilitate forward-commonality and interchangeability of CEV systems hardware with other architecture elements are needed. ISS demonstration of technologies to reduce the outpost logistics footprint will be needed, and continued collaboration with the Department of Defense (DoD) for leveraging common needs for repair and manufacturing is required. Specific technology development/demonstration needs include reprogrammable/reconfigurable systems, ISS demonstration of enhanced repair technologies, ISS demonstration of enhanced maintenance information management capabilities, ISS demonstration of key capabilities for on-demand production of spares, automated work control processes for ground processing/logistics, surface robotic systems for maintenance and repair, enhanced maintenance information management capabilities, techniques for reducing ground processing costs, and robust, damage tolerant, self-repairable systems.

The architecture requires human-system interaction beyond that which is currently utilized in the ISS and Shuttle programs. This is necessary to increase crew safety, increase performance, and reduce operations costs. Technology investments are needed to enhance reliable, real-time data and command interface between humans and systems. This includes research into effective forms of shared control between intelligent systems and humans. Technologies are also required for robotic assistance for humans and the intelligent systems technologies for enabling effective interactions between the robotics and humans. Additional technology investments include: (1) highly reliable dexterous manipulators for hostile environments; (2) multi-modal systems/robots with variable autonomy (autonomous/teleoperable to full human control); and (3) reliable personnel tracking.

Technologies that enable surface operations with respect to transportation of logistics and surface mobility require additional investments. An unpressurized vehicle that can support four crew for a 7-day sortie mission, can be reused, can potentially be operated robotically when uncrewed, can survive 4 years of continuous operation, and is capable of 30-km distance required for the architecture. Technology needs in support of surface mobility include: (1) highly durable, highly reliable, and long-life systems; (2) durable mechanisms and power train; (3) tribology for durable and long life; (4) recharging/refueling capability with extended range; (5) operations in extreme/hostile environment (temperature, dust, radiation); (6) simple maintenance; (7) teleoperations and autonomy; (8) high bandwidth communications; (9) multi-modal teleoperations and autonomy; and (10) robotic operation at enhanced speeds.

## 9.4 Recommendations

As a result of the technology assessment, it is recommended that the overall funding of ESMD for R&T be reduced by approximately 50 percent to provide sufficient funds to accelerate the development of the CEV to reduce the gap in U.S. human spaceflight after Shuttle retirement. This can be achieved by focusing the technology program only on those technologies required to enable the architecture elements as they are needed and because the recommended ESAS architecture does not require a significant level of technology development to accomplish the required missions. Prior to the ESAS, the technology development funding profile for ESMD is as shown in **Figure 9-1** (included previously in this section). The ESAS recommendations for revised, architecture-driven technology development is as shown in **Figure 9-2** (included previously in this section).

**Figures 9-3** through **9-5** show, respectively, the overall recommended R&T budget broken out by program with liens, functional need category, and mission. "Protected" programs include those protected from cuts due to statutory requirements or previous commitments.

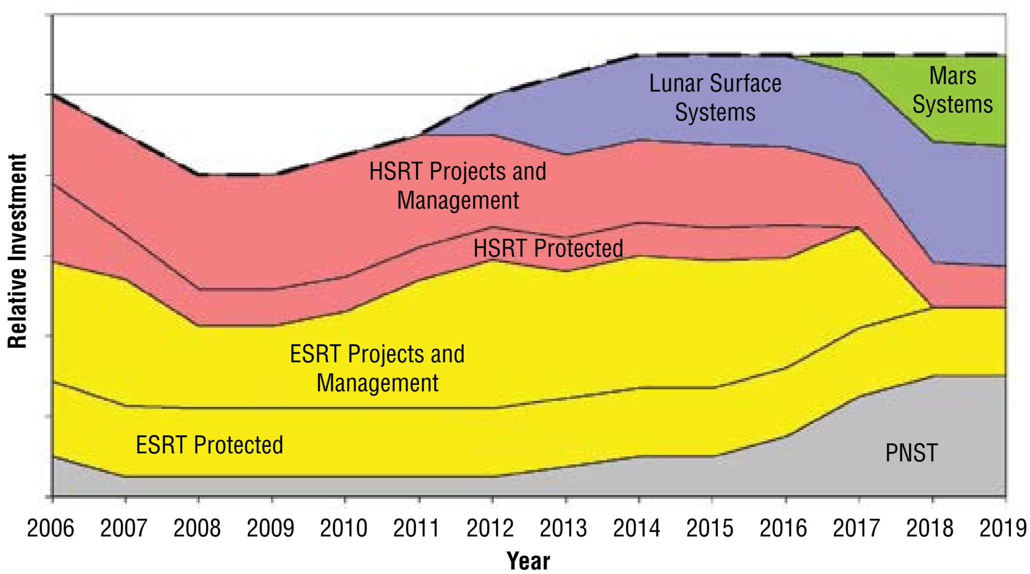


*Figure 9-3. Overall Recommended R&T Budget Broken Out by Program with Liens*

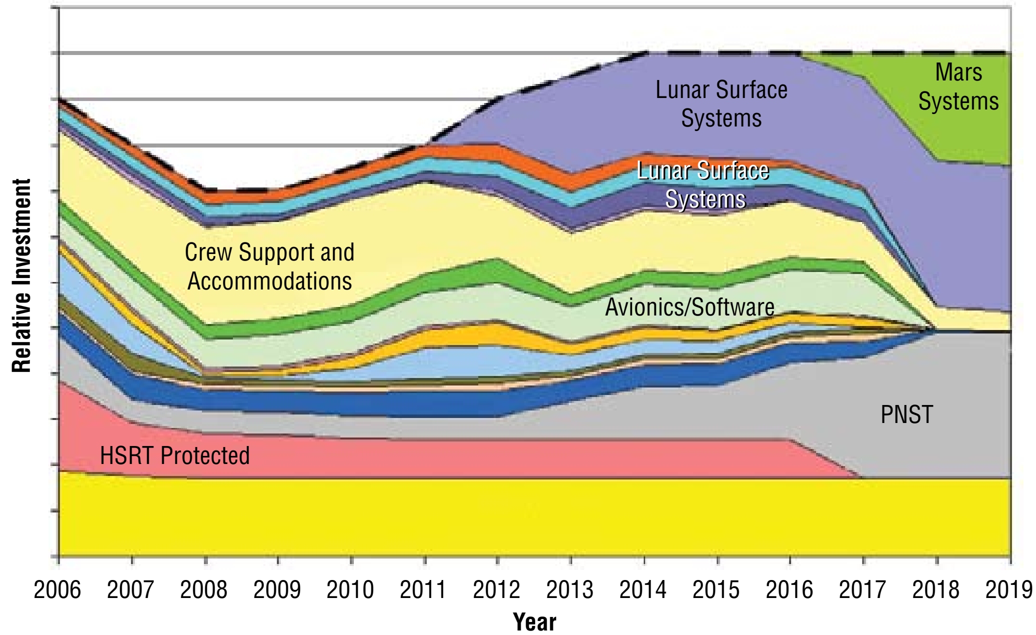


*Figure 9-4. Overall Recommended R&T Budget Broken Out by Functional Need Category*

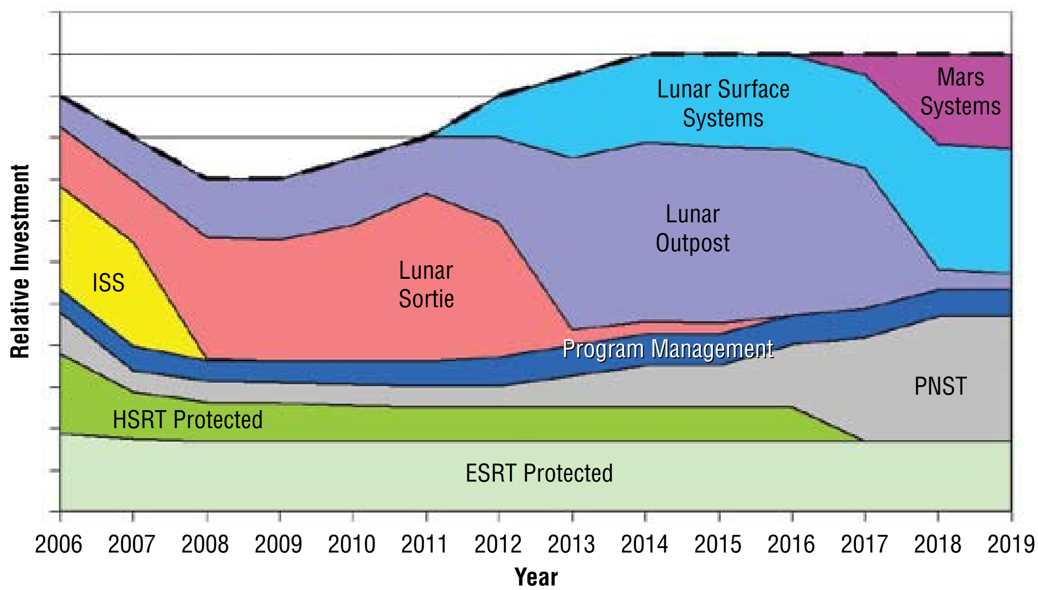


*Figure 9-5. Overall Recommended R&T Budget Broken Out by Mission*

The existing funding profile includes 10 percent management funds and approximately 30 percent of liens due to prior Agency agreements (e.g., MUSS, the CIR, and the FIR) and legislated requirements (e.g., SBIR, STTR).

The final recommended technology funding profile was developed in coordination with the ESAS cost estimators using the results of the technology assessment. The following seven key recommendations arose from the technology assessment:

- ESMD should share costs with the SOMD for MUSS, CIR, and FIR. MUSS, CIR and FIR are all ISS operations activities and, as such, should not be bookkept in ESMD R&T. Funds were identified in the recommended budget; however, cost-sharing plans should be implemented to ensure these facilities are efficiently operated.
- ESMD should transfer the AMS to the SMD to compete for funding with other science experiments. The AMS may be of scientific importance, but does directly contribute to meeting ESMD R&T needs. Therefore, it should be moved to SMD for consideration with other science missions.
- ESMD should quickly notify existing ESRT projects not selected by ESAS that they will receive no funding beyond FY05. If work on the existing ESRT projects not selected for continuation is not stopped in FY05, there will be a potential for significant FY06 funds required to cover the contracts. Accordingly, appropriate notice must be provided as soon as possible to ensure efficient transition.
- ESMD should move Systems Analysis and Tool Development activities (and budget) to a directorate-level organization—no longer in ESRT. These system analysis and tool development functions should not be buried in multiple disparate organizations. While each organization will require its own analytical capabilities, a focal point should be established at the directorate level to ensure consistency in the ground rules, assumptions, and analytical methodologies across ESMD. This will ensure decision makers are provided "apples-to-apples" analysis results. These activities are also required to handle "what-if" studies and strategic analysis actions to provide greater stability in the development programs (i.e., development programs can focus on their work and avoid the disruption of frequent strategic studies and issue analyses).
- Key ESAS personnel should work with ESMD to facilitate implementation. Many technologies require immediate commencement on an accelerated schedule to meet aggressive development deadlines. Key ESAS personnel should also work with ESMD to ensure the analytical basis supporting ESAS recommendations is not lost, but carefully preserved and refined to improve future decisions.
- ESMD should develop a process for close coordination between architecture refinement studies and technology development projects. Technology projects should be reviewed with the flight element development programs on a frequent basis to ensure alignment and assess progress.
- ESMD should develop a process for transitioning matured technologies to flight element development programs. Experience shows that technologies have a difficult time being considered for incorporation into development projects due to uncertainty and perceived risk. The technologies identified in this assessment are essential for the architecture and, therefore, a structured process for transitioning them must be implemented to ensure timely integration into development projects with minimal risk and uncertainty.

The key technology development project recommendations from the study are shown in **Table 9-1**.

*Table 9-1. Technology Project Recommendations*

| Number | ESAS Control Number | Program | Category | New Projects |
|---|---|---|---|---|
| 1 | 1A | ESRT | Structures | Lightweight structures, pressure vessel, and insulation. |
| 2 | 2A | ESRT | Protection | Detachable, human-rated, ablative environmentally compliant TPS. |
| 3 | 2C | HSRT | Protection | Lightweight radiation protection for vehicle. |
| 4 | 2E | HSRT | Protection | Dust and contaminant mitigation. |
| 5 | 3A | ESRT | Propulsion | Human-rated, 5–20 klbf class in-space engine and propulsion system (SM for ISS orbital operations, lunar ascent and TEI, pressure-fed, LOX/CH4, with LADS). Work also covers 50–100 lbs nontoxic (LOX/CH4) RCS thrusters for SM. |
| 6 | 3B | ESRT | Propulsion | Human-rated deep throttleable 5–20 klbf engine (lunar descent, pump-fed LOX/LH2). |
| 7 | 3C | ESRT | Propulsion | Human-rated, pump-fed LOX/CH4 5–20 klbf thrust class engines for upgraded lunar LSAM ascent engine. |
| 8 | 3D | ESRT | Propulsion | Human-rated, stable, nontoxic, monoprop, 50–100 lbf thrust class RCS thrusters (CM and lunar descent). |
| 9 | 3F | ESRT | Propulsion | Manufacturing and production to facilitate expendable, reduced-cost, high production-rate SSMEs. |
| 10 | 3G | ESRT | Propulsion | Long-term, cryogenic, storage and management (for CEV). |
| 11 | 3H | ESRT | Propulsion | Long-term, cryogenic, storage, management, and transfer (for LSAM). |
| 12 | 3K | ESRT | Propulsion | Human-rated, nontoxic 900-lbf Thrust Class RCS thrusters (for CLV and heavy-lift upper stage). |
| 13 | 4B | ESRT | Power | Fuel cells (surface systems). |
| 14 | 4E | ESRT | Power | Space-rated Li-ion batteries. |
| 15 | 4F | ESRT | Power | Surface solar power (high-efficiency arrays and deployment strategy). |
| 16 | 4I | ESRT | Power | Surface power management and distribution (e.g., efficient, low mass, autonomous). |
| 17 | 4J | ESRT | Power | LV power for thrust vector and engine actuation (nontoxic APU). |
| 18 | 5A | HSRT | Thermal Control | Human-rated, nontoxic active thermal control system fluid. |
| 19 | 5B | ESRT | Thermal Control | Surface heat rejection. |
| 20 | 6A | ESRT | Avionics and Software | Radiation hardened/tolerant electronics and processors. |
| 21 | 6D | ESRT | Avionics and Software | Integrated System Health Management (ISHM) (CLV, LAS, EDS, CEV, lunar ascent/descent, habitat/Iso new hydrogen sensor for on-pad operations). |
| 22 | 6E | ESRT | Avionics and Software | Spacecraft autonomy (vehicles & habitat). |
| 23 | 6F | ESRT | Avionics and Software | Automated Rendezvous and Docking (AR&D) (cargo mission). |
| 24 | 6G | ESRT | Avionics and Software | Reliable software/flight control algorithms. |
| 25 | 6H | ESRT | Avionics and Software | Detector and instrument technology. |
| 26 | 6I | ESRT | Avionics and Software | Software/digital defined radio. |

*Table 9-1. Technology Project Recommendations (continued)*

| Number | ESAS Control Number | Program | Category | New Projects |
|---|---|---|---|---|
| 27 | 6J | ESRT | Avionics and Software | Autonomous precision landing and GN&C (Lunar & Mars). |
| 28 | 6K | ESRT | Avionics and Software | Lunar return entry guidance systems (skip entry capability). |
| 29 | 6L | ESRT | Avionics and Software | Low temperature electronics and systems (permanent shadow region ops). |
| 30 | 7A | HSRT | ECLS | Atmospheric management - CMRS (CO2, Contaminants and Moisture Removal System). |
| 31 | 7B | HSRT | ECLS | Advanced environmental monitoring and control. |
| 32 | 7C | HSRT | ECLS | Advanced air and water recovery systems. |
| 33 | 8B | HSRT | Crew Support and Accommodations | EVA Suit (including portable life suppport system). |
| 34 | 8E | HSRT | Crew Support and Accommodations | Crew healthcare systems (medical tools and techniques, countermeasures, exposure limits). |
| 35 | 8F | HSRT | Crew Support and Accommodations | Habitability systems (waste management, hygiene). |
| 36 | 9C | ESRT | Mechanisms | Autonomous/teleoperated assembly and construction (and deployment) for lunar outpost. |
| 37 | 9D | ESRT | Mechanisms | Low temperature mechanisms (lunar permanent shadow region ops). |
| 38 | 9E | ESRT | Mechanisms | Human-rated airbag or alternative Earth landing system for CEV. |
| 39 | 9F | ESRT | Mechanisms | Human-rated chute system with wind accommodation. |
| 40 | 10A | ESRT | ISRU | Demonstration of regolith excavation and material handling for resource processing. |
| 41 | 10B | ESRT | ISRU | Demonstration of oxygen production from regolith. |
| 42 | 10C | ESRT | ISRU | Demonstration of polar volatile collection and separation. |
| 43 | 10D | ESRT | ISRU | Large-scale regolith excavation, manipulation and transport (i.e., including radiation shielding construction). |
| 44 | 10E | ESRT | ISRU | Lunar surface oxygen production for human systems or propellant. |
| 45 | 10F | ESRT | ISRU | Extraction of water/hydrogen from lunar polar craters. |
| 46 | 10H | ESRT | ISRU | In-situ production of electrical power generation (lunar outpost solar array fabrication). |
| 47 | 11A | ESRT | Analysis and Integration | Tool development for architecture/mission/technology analysis/design, modeling and simulation. |
| 48 | 11B | ESRT | Analysis and Integration | Technology investment portfolio assessment and systems engineering and integration. |
| 49 | 12A | ESRT | Operations | Supportability (commonality, interoperability, maintainability, logistics, and in-situ fab.) |
| 50 | 12B | ESRT | Operations | Human-system interaction (including robotics). |
| 51 | 12C | ESRT | Operations | Surface handling, transportation, and operations equipment (Lunar or Mars). |
| 52 | 12E | ESRT | Operations | Surface mobility. |