The

NASA-ESA

Comparative Architecture Assessment

1. Executive Summary

The National Aeronautics and Space Administration (NASA) is currently studying lunar outpost architecture concepts, including habitation, mobility and communication systems, to support U.S. lunar exploration and science objectives. Elements of a surface architecture will rely on the Ares I and Ares V launch vehicles, the Orion crew exploration vehicle, and the Altair lunar lander for transport to the Moon. The European Space Agency (ESA) is currently studying scenarios and associated architectures for human space exploration to follow the International Space Station Program. These studies are at their earliest conceptual stage and fall into three general scenario categories, each with their own technical capabilities and related timeframes, and each having the potential to constitute a distinct European contribution to future lunar exploration missions.

In January 2008, NASA and ESA agreed to conduct a comparative architecture assessment to determine if their respective lunar architecture concepts could complement, augment, or enhance the exploration plans of the other. From January through March representatives from NASA and ESA engaged in a series of joint, qualitative assessments of potential ESA capabilities as applied to NASA's architecture concepts. Initial findings from these assessments, with respect to each potential ESA category under study, are as follows:

- **Scenario 1: ESA Provision of Stand-Alone Capabilities**
    - Automated Lunar Cargo Landing System: This capability (approximately 1.5 metric tons of payload to the lunar surface) would significantly extend surface exploration opportunities by enabling enhanced mobility or extended habitation, and creates more opportunities for science. Further quantitative analysis is required to determine how an ESA lander, combined with various mission scenarios could enhance global lunar surface exploration and enable potential joint missions.
    - Communication and Navigation Systems: Beyond a basic capability for communication to be secured by NASA, ESA systems for enhanced communication and navigation could provide significant mission enhancement for all NASA mission scenarios. There are also opportunities for international commercial engagement for the provision of communications services. In both cases, opportunities for detailed collaboration merit further dialogue.

- **Scenario 2: ESA Development of Crew Transportation Architecture Elements**
    - Human Crew Transportation to low-Earth orbit (LEO), including a human-rated Ariane 5 launch vehicle and a crew transportation vehicle: Experience on the ISS demonstrates that redundant transportation is welcome. However, real redundancy with NASA's architecture requires a transportation capability that has at least access to lunar orbit.

- Orbital Infrastructures: A low lunar orbiting station as analyzed within the ESA transportation architecture studies and that can be utilized by NASA has the potential to enhance mission safety and performance, and could enable different mission profiles. To fully understand the benefits of this station would require further dialogue. Other ESA orbital infrastructure concepts (LEO, Lagrange points) do not have synergy with NASA's architecture.

- **Scenario 3: ESA Development of Dedicated Lunar Surface Exploration Elements**
  - Surface Habitation Elements or a Surface Rover: Each of these is a fundamental, enabling component of any surface architecture. These capabilities merit further quantitative analysis to determine how they may enable joint lunar exploration missions or enhance total mission capabilities.

There are differences between what NASA believes to be its key capabilities and the three categories of potential ESA contributions to space exploration. For NASA, the key capabilities identified include the transportation elements of the Constellation Program that NASA is committed to developing; they are part of NASA's mandate to explore, as expressed in both the 2004 U.S. Space Exploration Policy and 2005 NASA Authorization Act. For ESA, future contributions to human space exploration are similar to NASA's key capabilities in that they address areas of high strategic interest to the agency and to Europe as a whole, but final decisions on their development and implementation have yet to be made, and likely will not be made final until 2011. In this respect any particular ESA contribution is more like the surface exploration elements NASA has examined during its LAT exercises, which will not receive funding for development until 2011. An important goal of this phase of the CAA therefore is to provide the reader an early perspective on opportunities for long-term collaboration between NASA and ESA; a perspective which can be valuable in the near-term as programmatic and funding decisions are being made.

NASA is prepared to continue the dialogue following completion of the report, and is committed to support more detailed joint studies to further define concepts starting in 2009.

2. Context: The Global Exploration Strategy (GES)

In accordance with the 2004 U.S. Space Exploration Policy, NASA has begun developing the capabilities necessary to pursue human and robotic exploration missions to the Moon and Mars, as well as other future destinations. This process includes completion of the International Space Station (ISS), safe operation of the Space Shuttle until its retirement in 2010, and development of the Crew Exploration Vehicle leading to a return to the Moon by 2020. An integral part of U.S. space exploration will be the cooperative exploration of the Moon and other destinations in cooperation with international partners. To that end, in 2005 NASA initiated a dialogue with representatives of 13 international space agencies, among them ESA, and science organizations around the world aimed at developing a strategy that would define the role of lunar exploration within the broader context of space exploration.

The initial focus of NASA's dialogue with international participants was to seek global input on two fundamental questions: "Why are we returning to the Moon?" and "What can we accomplish when we get there?" The ensuing international dialogue, referred to as the "Global Exploration Strategy," produced a set of "Themes and Objectives." These themes and objectives were derived from a common desire to develop a broad, global framework that would: 1) articulate a compelling case for globally coordinated space exploration, and 2) set the stage for future international discussions on coordination mechanisms and initial lunar architectures. This process culminated with the release in May 2007 of *The Global Exploration Strategy: The Framework for Coordination.* Consistent with the Themes and Objectives exercise, the "Framework Document" identified five general themes in which space exploration provided benefits to society:

- New Knowledge in Science and Technology - the pursuit of scientific activities that address fundamental questions about the history of Earth, the Solar System, and the universe – and about our place in them;
- A Sustained Presence - Extending Human Frontiers - the extension of human presence to other planets to enable eventual settlement;
- Economic Expansion - the expansion of Earth's economic sphere and the conduct of space activities that benefit life on the home planet;
- A Global Partnership – the provision of challenging, shared, and peaceful activities that unite nations in pursuit of common objectives; and,
- Inspiration and Education – the use of vibrant space exploration programs to engage the public, encourage students and help develop the high-tech workforce required to address the challenges of tomorrow.

A fundamental tenant underlying the GES discussions was the recognition that, while general agreement exists on broad exploration themes, individual space agencies are required to pursue their unique scientific, technological and societal objectives at a scale and pace dictated by national priorities. Thus, successful cooperation can only occur with a thorough discussion of shared interests and capabilities. It is with this spirit that NASA and ESA chose to pursue this Comparative Architecture Assessment (CAA).

3. NASA's Lunar Exploration Architecture

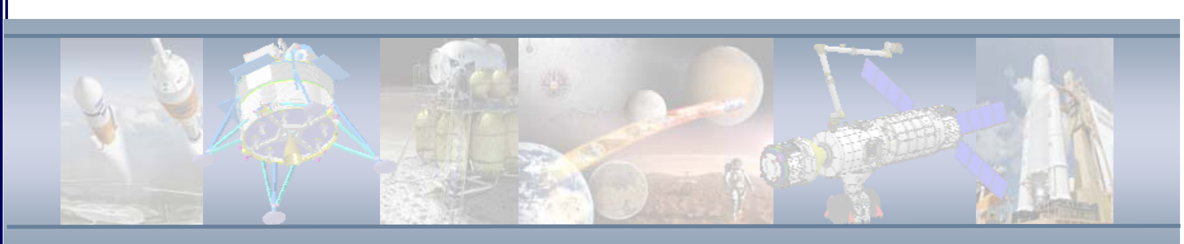
3.1 NASA's Transportation Architecture

As described above, NASA was directed in 2004 to initiate a program that would bring astronauts back to the surface of the Moon no later than 2020. In 2005 NASA completed its Exploration Systems Architecture Study (ESAS), which outlined as its highest priority NASA's intent to safely transport a crew of four astronauts to and from the lunar surface. To meet this objective NASA identified the architecture that will constitute the next generation of human space transportation for the United States. Elements of this transportation architecture include the following:[1]

- Orion crew exploration vehicle.
- Ares I crew launch vehicle and Ares V cargo launch vehicle.
- Altair lunar lander (and ascent return vehicle).

Of these systems, the Orion and Ares I are already under development, and will conduct Preliminary Design Reviews in 2008. The Ares V launch vehicle and Altair lunar lander will begin development after 2010.

In the context of international cooperation in space exploration, this transportation architecture is seen as a strategic capability for the United States. In addition, NASA has committed to developing the initial extra-vehicular activity (EVA) space suits that would accompany astronauts on their first missions to the Moon, as well as ensuring that a minimum level of communication and navigation infrastructure is in place to support astronaut activities on the lunar surface. NASA's transportation architecture, EVA capabilities, and basic communication infrastructure constitutes the core capability that NASA will provide to enable its initial lunar objectives. Lunar surface systems have been studied, but final decisions on the lunar surface exploration architecture, or on specific system designs, are still several years away. For the purpose of this study, the above elements were identified as NASA's "key capabilities" for the purpose of the Comparative Architecture Assessment.



[1] The Orion and Ares I were designed with missions to the Moon in mind, but will be capable of supporting ISS operations as well.

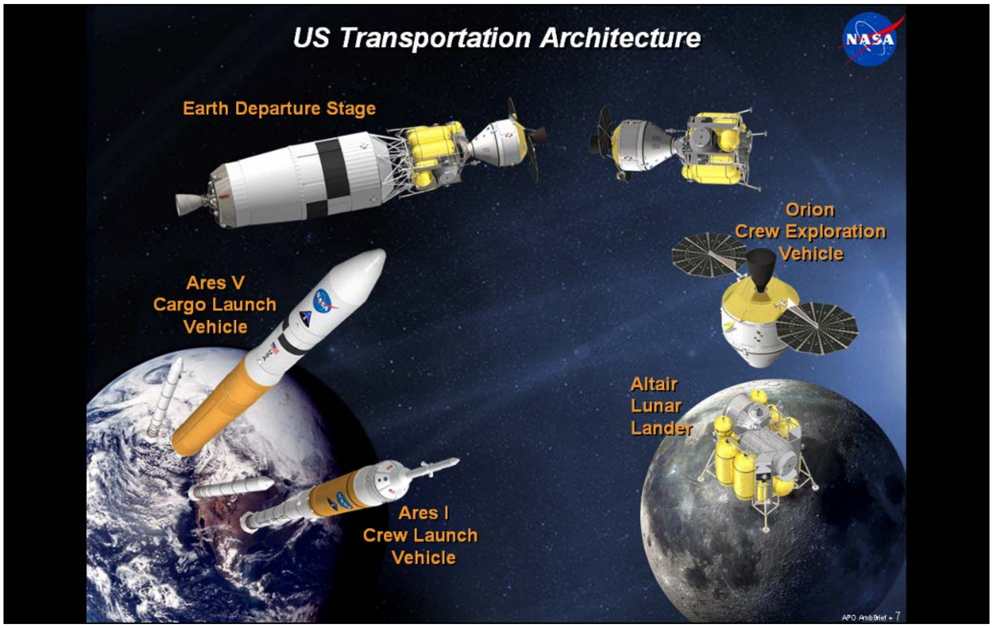


Figure 3.1: The U.S. Space Transportation Architecture

3.2 NASA Studies of a Lunar Surface Architecture

In order to inform requirements development for the Orion, Ares I, Ares V, and Altair, NASA began to study lunar surface architecture options following the conclusion of ESAS. Two lunar architecture studies were conducted. The first, known as Lunar Architecture Team 1 (LAT-1), started in parallel with the international GES discussions. Using the GES process to inform its objectives and with a focus on developing a reference architecture and design reference missions, NASA completed the LAT-1 activity in December 2006. There were two significant outcomes from LAT-1 that are worth addressing in the context of this report. First, in order to enable a sustainable lunar exploration program it was determined that NASA's highest priority should be the development of an outpost near a lunar pole. Second, in order to facilitate international cooperation NASA will proceed with an "open architecture" approach, wherein all elements of a surface exploration architecture would be open to participation and contribution from international and commercial partners.

The follow-on study, known as LAT-2, utilized both the findings of LAT-1 and the Themes and Objectives from the GES process to derive a specific collection of science and exploration objectives to be achieved on the surface (and at a potential outpost in particular). From these specific objectives NASA was able to determine what features of a broad lunar exploration architecture, utilizing NASA's transportation systems, might meet both U.S. and international science and exploration needs at the

Moon. The LAT-2 study was completed in 2007.[2] Key findings from these studies have led NASA to consider the following lunar architecture priorities. Based on these findings, NASA believes it should::

- Begin its exploration program with initial lunar sortie missions capable of sustaining a crew of four on the lunar surface for at least a week;
- Begin the development of an outpost (at a precise location yet to be specified) as soon as is feasible, with habitation capabilities and logistics resupply to enable crew rotations of up to six-months;
- Ensure that its architecture enables sortie missions to any location on the Moon at any time, which permit return to Earth at any time; and,
- Prioritize the earliest feasible development of enhanced mobility to enable long-distance excursions from any outpost or sortie landing site.

Combined with NASA's transportation architecture, NASA's lunar surface architecture concepts constitute the heart of NASA's exploration roadmap, show in Figure 2.2.

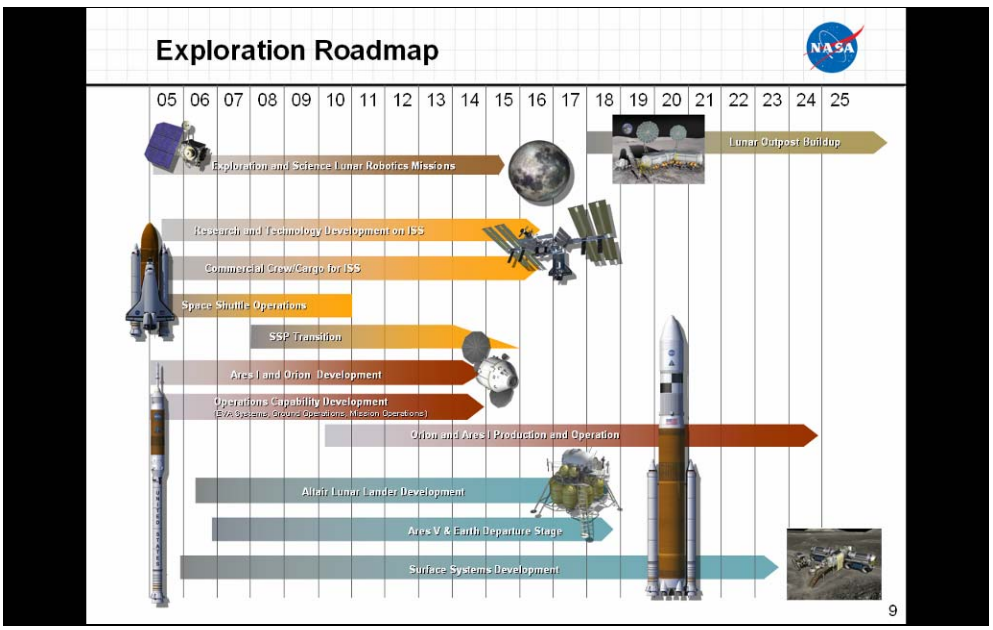


Figure 3.2: NASA's Exploration Roadmap

3.3 NASA's View on International Participation

NASA's initial architecture studies have been very informative in defining possible lunar exploration scenarios and their required functional capabilities. In conducting the LAT-1 and LAT-2 exercises NASA identified preliminary conceptual designs for surface systems – modules for habitation,

[2] NASA is also participating in an effort to mature lunar science priorities within the international lunar science community. There are ideas for planetary science investigations, far-side telescopes, life sciences studies, as well as other ideas that will continue to evolve. In October 2007, NASA announced the intent to establish a Lunar Science Institute for the purpose of leading the agency's lunar research program formulation and execution.

pressurized and unpressurized surface rovers, power modules, and even communication infrastructure. However, beyond the identification of the above general priorities NASA has not yet identified a specific 'baseline' scenario for lunar exploration, nor has it chosen a specific design for any surface exploration element. In keeping with the Themes and Objectives of the GES, NASA intends to seek opportunities to review and adjust its initial exploration concepts as necessary to support a global open-architecture – this is part of NASA's motivation for participating in the CAA. The open-architecture concept extends beyond elements of a lunar surface exploration architecture, and includes precursor missions that reduce risk or demonstrate new technologies, both for lunar surface operations and for Mars-forward applications.

3.4 NASA's Perspectives on the Benefit of Lunar Exploration

NASA's decision to focus on the early development of an outpost, while retaining the capability to conduct a dedicated sortie mission to any point on the lunar surface that might prove to be of interest for scientific reasons, fulfills many concurrent objectives:

- Enabling lunar sustained presence early
- Developing infrastructure while actively engaged in science and exploration
- Ensuring the architecture supports a broad range of exploration objectives
- Supporting the establishment of a Mars analog
- Allowing the earliest partnership opportunities for commerce and International Partners.
- Continuous and focused public engagement.

These objectives are all resonant with the five themes of the GES, as it is NASA's goal to develop a lunar program of relevance to an international community. In this sense, NASA considers human missions to the Moon to be a sixth theme of the GES: that of Exploration Preparation**.** There are at least two elements to this preparation. First is a focus on the testing of technologies, systems, flight operations and exploration techniques to learn how to survive and operate effectively on another planet. Second is the opportunity to learn how to best support astronaut crews living far from home in harsh environments with little direct contact with Earth and limited opportunities for help from Earth in case of emergency. Human lunar exploration will reduce the risks and increase the productivity of future Solar System exploration, and in doing so will be a direct "stepping stone" to the eventual human exploration of Mars.

In summary, NASA believes that establishing a sustained human presence on the Moon has both intrinsic value and importance as a step toward Mars. Enabling the scientific advancements described above will lead to new knowledge and insights into how our own planet was formed. Sustained human presence on the Moon will enable us to develop and maintain the technological capability necessary to send humans to Mars, or other destinations which are farther away from the planet Earth. In order to extend human reach and fulfill the rich scientific promise of Mars, humans will need to master the capability to live for an extended period of time on another planetary surface, and develop systems and techniques to use in-situ resources to increase the robustness of mission plans.

4. Current ESA Exploration Activities

4.1 ESA Objectives and the Architecture for Exploration Study

In 2001, ESA initiated the Aurora program, and within the framework of this program has developed a long-term roadmap for space exploration.[3] In the context of the Aurora program and in light of the development of the GES, ESA has analyzed the potential role of Europe in an international space exploration program. Referred to as the Architecture for Exploration Study (AES), ESA considered long-term scenarios and supporting architectures that enable a significant European role in international space exploration. This study is part of ESA's strategic planning, and is performed in order to identify European strategic interests and priorities, define technology roadmaps, and to inform discussions at an international level on future exploration architectures and associated needs and opportunities for international coordination and collaboration.

Both for the specific analyses ESA conducted for the AES and for the analyses conducted for the CAA, high-level objectives for European involvement in human and robotic exploration activities have been identified. Outlined below, these objectives have to be met by any potential scenario in order to ensure merit to the European community. In particular, any European contribution to an international exploration framework should:

- Support European exploration interests and objectives[4] – address the implementation of European lunar exploration objectives as well as foster technological innovation and Mars-forward preparation.
- Enhance European autonomy - develop new strategic human spaceflight capabilities and enable the implementation of autonomous European human exploration scenarios.
- Foster stakeholder engagement - create opportunities for international cooperation and broad stakeholder engagement.
- Ensure programmatic coherence - build on European heritage; enable synergies with other ESA space programs and support European coordination towards a targeted role in a global space exploration architecture.

With these objectives identified, the AES concentrated on defining the contributions that ESA could make to international space exploration architectures addressing:

1. Human transportation, cargo transportation, or both, to planetary orbits and surfaces, including supporting orbital infrastructures;
2. planetary surface operations, including surface habitation capabilities or mobility systems; and,
3. communication and navigation support services.

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[3] The first European-led mission of this roadmap, ExoMars, has been approved for implementation.

[4] Specific lunar exploration objectives and requirements for the AES have been defined through consultation with representatives of the relevant European stakeholder communities, including industry, government, the scientific community, and relevant ESA advisory bodies.

ESA has determined that any contribution it makes must be relevant to both Moon and Mars exploration, and therefore particular emphasis on synergies between Moon and Mars exploration have been identified and assessed at both the architecture and system level.

4.2 ESA's View on The Long-Term International Scenario for Space Exploration

In order to define and analyze potential European contributions to global exploration initiatives, ESA has developed a long-term, international space exploration roadmap, based on a current understanding of international space exploration plans. The roadmap assumes development of exploration architectures in a phased approach, leading ultimately to the implementation of the first international human mission to Mars. The phased approach allows for the incremental development of technologies and systems over time, and is mindful of both political constraints and financial budgets. The four phases are:

- **Phase 1**, through 2016 and perhaps through 2020: This period will see the advancement of human operations in LEO based on extensive utilization of the International Space Station (ISS), or potential new orbital infrastructures. At the same time, the development of a new generation of crew space transportation systems, designed for access to both LEO and low lunar orbit (LLO), will secure human access and frequent flight opportunities to space. Early robotic preparatory missions towards the Moon (e.g. the International Lunar Network) and Mars will pave the way for future human exploration and demonstrate key capabilities such as planetary descent and landing, surface mobility, in-situ resource utilization (ISRU), and perform valuable in-situ science.

- **Phase 2**, early-to-mid 2020s: This period could see extended human operations in LEO based on the transition to new orbital infrastructures replacing ISS, while first human missions to the Moon commence. During this period, further orbital infrastructures beyond LEO (e.g. in LLO or at the Earth-Moon libration points) might be constructed as an element of a transportation architecture. Such infrastructure could facilitate the assembly of vehicles, crew exchange, docking operations, lunar landings and sustained surface operations, while also enabling research for interplanetary mission preparation. The first Mars Sample Return mission would be implemented during this phase and its findings will drive further Mars exploration.

- **Phase 3**, late 2020's or early 2030s: Phase 3 would introduce extended lunar surface installations for fixed and mobile habitation and research. ESA assumes that during this phase lunar exploration would move forward as a coordinated international endeavor. Initial activities towards the preparation of an international human mission to Mars may commence.

- **Phase 4**, mid-to-late 2030s: Based on the essential knowledge gained from and capabilities developed for continued lunar surface activities, Phase 4 will see the implementation of the first human Mission to Mars. Continuation of lunar surface activities will depend on the long-term exploitation objectives of institutional and private actors.

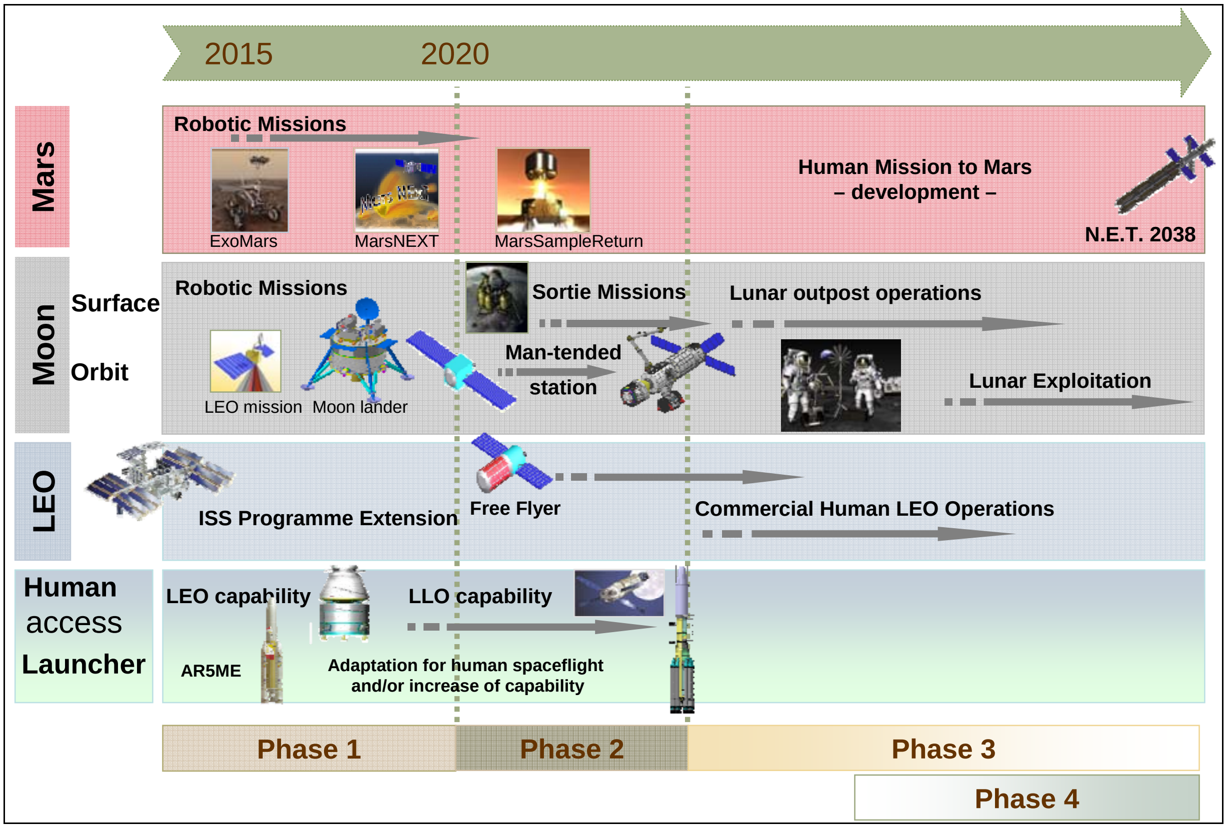

Figure 4.1: ESA Long Term Scenario for International Space Exploration

4.3 ESA Contribution Scenarios

Based on ESA's projection of a long-term international space exploration roadmap, ESA has identified potential European contributions to space exploration that are of particular strategic relevance for Europe. They build on European heritage and strengthen European autonomy, while also providing high potential for synergy and cooperation in an international exploration architecture. Scenarios for a European contribution to space exploration fall into three, non-mutually exclusive categories. Described below, these categories address contributions to robotic and human exploration of the Moon.

- **Scenario 1: ESA Provision of Stand-Alone Capabilities**
  - Autonomous Lunar Exploration based on a lunar landing system and supporting communication/ navigation systems. Applicable to Phases 1 and 2, a wide range of medium mass payloads for lunar human surface operations and exploration activities can be delivered by an Ariane 5 based lunar landing system that could be available as early as 2016. In preparation of extensive science data acquisition as well as human mission preparation, an initial demonstration of a communication relay systems at high data-rates could be implemented in combination with a mission of the lander to the lunar far side.

- **Scenario 2: ESA Development of Crew Transportation Architecture Elements**
  - Participation in an international human transportation architecture, applicable to Phases 2 and 3 is based on the European development of a human-rated Ariane 5 launch vehicle, a crew space transportation vehicle, and supporting orbital infrastructures (incorporating Ariane 5 and ATV heritage). A certain level of international redundancy in critical enabling capabilities for lunar exploration will be required to ensure broad international and commercial engagement over the long-term of human space exploration. ESA has in particular studied transportation architectures offering dissimilar redundancy to the defined NASA human transportation architecture, and analyzed possible European contributions to such a transportation architecture. Important elements of these transportation architecture are orbital infrastructures located in either LEO, at an Earth-Moon Lagrange point (perhaps L1) or in LLO, to support assembly and docking operations, crew exchange, sustained surface operations and act as safe haven in contingency scenarios. The realization of redundancy in human transportation beyond LEO would certainly depend on international cooperation.

- **Scenario 3: ESA Development of Dedicated Lunar Surface Exploration Elements**
  - Participation in Human Lunar Surface Operations and Exploration, the primary focus of Phases 2 and 3, would be based on the provision of fixed or mobile habitats and other exploration equipments. Being a pre-requisite for long-term surface exploration, fixed or mobile habitation assets on the lunar surface can significantly contribute to an international scenario, build on a strong European heritage from Columbus, and strengthen the European role in early human activities on the Moon. Particular emphasis has been given to small lunar habitats which could enable the extension of early lunar sortie missions. Pre-requite for the implementation of this scenario is clarity on the international cooperation framework and international lunar exploration architecture.

5. The Comparative Architecture Assessment

5.1 Overview

As outlined in Sections 3 and 4, NASA and ESA are both independently performing studies on lunar exploration architectures. In January 2008, NASA and ESA agreed to pursue a cooperative study to determine if specific lunar exploration capabilities, currently considered for independent development by each, can complement, augment, or enhance the exploration plans of the other.

From January through April the agencies engaged in Phase 1 of the CAA, involving a joint review of each agency's progress on lunar architecture studies with the intent of identifying potential synergies between ESA and NASA concepts. Elements of the lunar architecture considered in Phase 1 include:

- cis-lunar transportation and lunar surface capabilities,
- potential orbiting platforms (be they in low-Earth orbit, lunar orbit, or at Earth-Moon Lagrange points), and,
- communications systems.

These elements are generally considered to be the basic elements necessary to explore the Moon with both robots and humans, and are the major capabilities being studied independently by both NASA and ESA.

In a series of joint meetings, the potential ESA contributions to an international space exploration architecture defined in Section 4.3 were qualitatively assessed with respect to their synergies with NASA's transportation architecture and preliminary analyses for lunar surface exploration. This assessment was guided by the lunar exploration objectives identified by NASA as a result of LAT-1 and LAT-2, as well as the Themes and Objectives of the GES Framework Document. In addition, NASA and ESA considered the requirements for interoperability and interfaces for implementation.

It is important to note the difference between NASA's key capabilities and the three categories of potential ESA contributions to space exploration. For NASA, the key capabilities identified in Section 3.1 are elements of the Constellation Program that NASA is committed to developing; they are part of NASA's mandate to explore, as expressed in both the 2004 U.S. Space Exploration Policy and 2005 NASA Authorization Act. For ESA, future contributions to human space exploration are similar to NASA's key capabilities in that they address areas of high strategic interest to the agency and to Europe as a whole, but final decisions on their development and implementation have yet to be made, and likely will not be made final until 2011. In this respect any particular ESA contribution is more like the surface exploration elements NASA has examined during its LAT exercises, which will not receive funding for development until 2011. An important goal of this phase of the CAA therefore is to provide the reader an early perspective on opportunities for long-term collaboration between NASA and ESA; a perspective which can be valuable in the near-term as programmatic and funding decisions are being made.

5.2 Method of Assessment and Evaluation

Based on the NASA architecture and the ESA contribution scenarios, a number of potential cooperation opportunities were identified and evaluated. Cooperation in an NASA-ESA partnership could include the utilization of the other's capability for specific or one-time mission objectives, implementing a joint mission utilizing independent contributions from each partner, or explicitly directing the development of a technical capability for shared utilization by each partner. While early robotic systems are expected to simply utilize the partner's independent capability with only limited need for coordination of requirements and development, later and technically more complex human exploration scenarios may include joint missions or shared utilization of capabilities for achieving common mission objectives. These latter missions would be, characterized by a high level of interoperability between systems and significant coordination of requirements. .

The CAA has been particularly focused on a technical assessment of how ESA contributions can be used to complement, augment, or enhance the transportation and initial surface exploration capabilities of NASA. For this purpose, the CAA was guided by the use of several qualitative questions that addressed the opportunities for and benefits from NASA-ESA collaboration under any of the Scenarios in Section 4.3. From the perspective of NASA's architecture and the priorities NASA has identified in Section 3.2, questions about the benefit of collaboration between NASA and ESA included:

- Are ESA capabilities critical elements to any human exploration endeavor at the Moon or elsewhere beyond LEO?
- Do ESA capabilities provide critical, dissimilar redundancy to NASA systems?
- Do collaboration opportunities increase mission assurance or mission safety?
- Will collaboration opportunities accelerate mission operations?
- Can collaboration opportunities facilitate global access for the Moon?
- Will collaboration opportunities extend surface habitation duration, extend the range of surface mobility operations, or enhance the logistics supply and resupply chain?

The CAA also considered more broadly the value of cooperation between NASA and ESA in terms of opportunities for science and technology development, addressing questions such as:

- Will cooperation between NASA and ESA provide opportunities to improve understanding of the lunar environment?

- Will cooperation between NASA and ESA enable technology risk reduction for in-situ resource utilization or other long-term needs?
- Will cooperation between NASA and ESA enable more crew and scientific payloads to be delivered to the surface?

These questions are not comprehensive, but represent the nature of the dialogue ESA and NASA were engaged in during the course of the CAA. These questions were an effective means for each agency to gain insight into the priorities and objectives of the architecture plans of the other and lay an important foundation for any detailed technical or quantitative analysis that may follow. An overarching finding of the CAA is that a clear strategic benefit exists for both ESA and NASA in finding ways to cooperate in the development of a lunar exploration architecture. In addition, it should be noted that there are several synergies in the exploration objectives, study approach, and design concepts between ESA and NASA. The identified opportunities and exchange within Phase 1 of this CAA have encouraged both agencies to continue the cooperative discussions into Phase 2 and potential follow-ups.

5.3 Findings for ESA Scenario 1, ESA Provision of Contributory Capabilities

Within ESA's phased approach for exploration, Phase 1 extends until about 2020 and includes dedicated robotic science and technology demonstration missions in preparation of a human return to the Moon. Within this timeframe and activity, two key capabilities have been identified and assessed with respect to their synergy with NASA's lunar architecture planning:

- a flexible Ariane 5 based lunar landing system, and,
- communications and navigation support systems.

These systems can contribute to many aspects of lunar exploration. They can play a role in the early robotic exploration of the Moon for science and in preparation of human missions, and they can be valuable assets to astronaut crews living on and exploring the lunar surface.

Any lunar exploration endeavor obviously requires some means of access to the lunar surface for crew and cargo in order to enable surface exploration. While a large payload performance is a pre-requisite for crew access and initial outpost build-up, this is not always necessary for a variety of missions or mission options. Therefore a logistics lander system, as envisioned by ESA as capable of transporting between one and two metric tons of payload to the lunar surface, can be a key element of a lunar exploration architecture. As it is currently being studied in ESA, this lander is based on Ariane 5 delivery capabilities. At such an estimated payload performance, various opportunities for NASA utilization of this capability have been identified during the course of the CAA. These include:

- Science utilization, technology demonstration and potential human landing preparation in an early lunar robotic exploration program.
- Delivery of regular logistics to a lunar base.
- Provision of consumables for extended surface exploration range and duration.
- Delivery of surface assets, be they stationary or with mobility, in order to support and accelerate lunar outpost build-up or for science and technology demonstration in sustained human operations.

The automated lander could be available as early as 2016 or 2017 to support automatic lunar exploration activities. If used in support of extended lunar sortie missions, it would be adequate to provide a crew of four astronauts with consumables that would last for approximately one month. A pre-deployed logistics lander can thus significantly increase both exploration range and astronaut time on the surface for any surface activity, especially when involving crew mobility systems.

To a lunar outpost at a fixed location, currently foreseen to be set up in the early 2020s, an automated lunar lander can enable the acceleration of outpost build-up through the early deployment of smaller systems such as power supply and distribution, communications and navigation aids, EVA support and surface mobility elements, as well as through extending early surface stay duration through the deployment of life support and crew consumables.

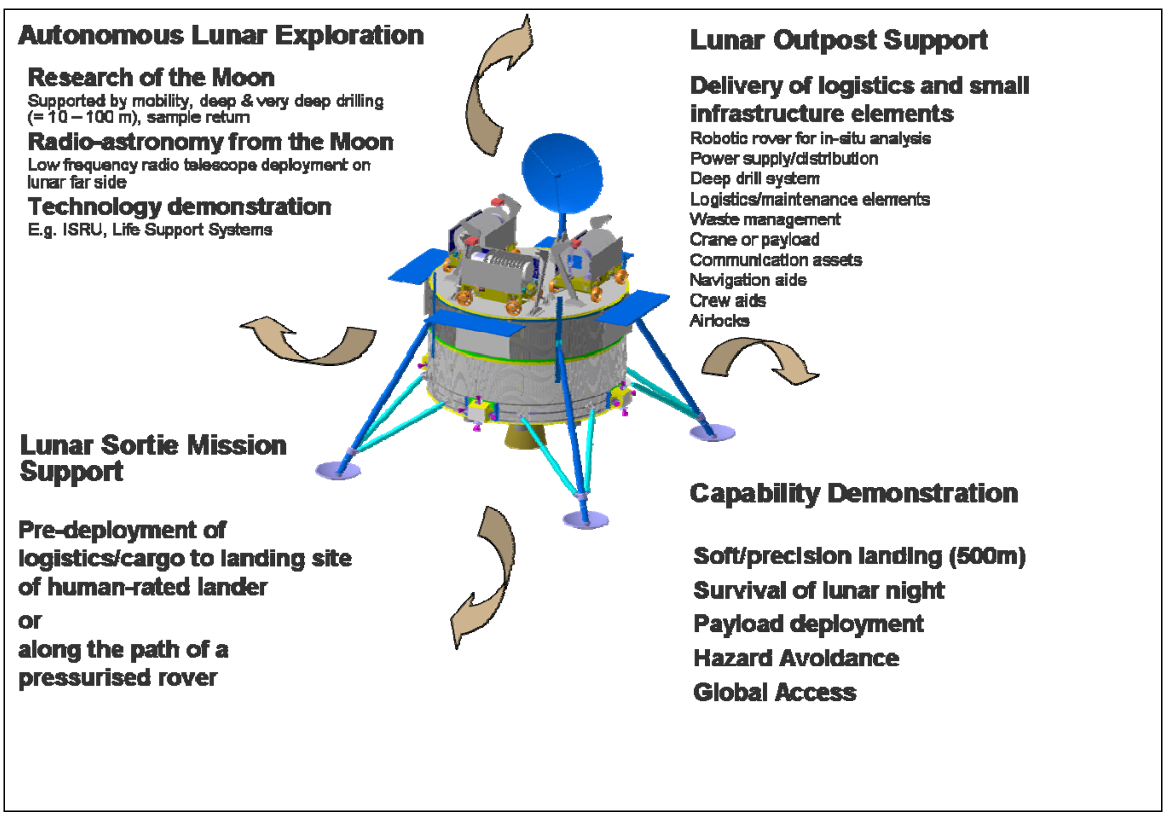

Figure 5.1: The ESA Lunar Lander Concept

Through its potential scientific application the lunar lander could help understanding better the lunar environment prior to human missions. The demonstration of critical technologies and operational aspects for soft precision landing together with the improved knowledge of the lunar surface environment could reduce the technology risk for a crew lander (such as the Altair) depending on the timeframe of the first foreseen flight. Indeed, the availability of such a logistic vehicle would simplify the Altair operations and extend crew surface activities by providing a dissimilar redundancy in the critical delivery of supplies to the crew and thus improving the overall mission assurance. In case the need for services by the ESA lander, and thus its launch frequency, increases with the progress of lunar surface activities, compatibility of the landing system with other U.S. and international launchers of comparable performance to Ariane 5 could be envisioned.

A second key requirement in early lunar operations is the provision of adequate communications and navigation support at high data-rates, not only as a pre-requisite for human surface coverage, but also for large amounts of science data produced by observatories on the Moon. The NASA basic capability for communication envisioned within the frame of the Constellation Program might therefore reach its limit at a very early stage of the lunar activities.

Europe has a strong heritage in communications systems, incorporating not only “classic” systems, but also developing and demonstrating new solutions such as optical communication links. At the same time, when analyzing extensive robotic and human exploration of the Moon, communication and navigation elements relying on several orbiter systems at medium lunar orbits have been investigated within the ESA architecture study.

The CAA provided the unique possibility to discuss between NASA and ESA the requirements and implementation aspects of these systems in order to analyze joint missions and shared capabilities, increasing support to robotic missions to remote destinations on the Moon as well as to early human operations on the lunar surface. While a combined system of ESA and NASA spacecraft and ground stations can obviously enhance the general capability of the system, it can at the same time provide critical redundancy for communication coverage. Both NASA and ESA systems could be operational in the second half of the next decade.

Obviously, this opportunity requires more in-depth discussion on the involved systems, communication standards and protocols. However, inter-satellite links and data relay support ground stations have been successfully exchanged between both partners in previous activities, thus this is not regarded as a challenging concern in the realization of a cooperative lunar communications system.

Both NASA and ESA have determined that an Ariane 5 lunar lander capability would be one of the most promising contributions to their architecture within this assessment and will continue the dialogue on its utilization and implementation potential. The communication and navigation system has been identified as an interesting area for strong commercial engagement on an international level, by providing these services to all international partners engaging in robotic and lunar activities. This aspect shall particularly be communicated and assessed in the near future.

The ESA lunar logistics lander would significantly extend surface exploration opportunities by enabling enhanced mobility, extended habitation, and new science opportunities. Further quantitative analysis is required to determine how an ESA lander, combined with various mission scenarios could enhance global lunar surface exploration and enable potential joint missions.

Beyond a basic capability for communication to be secured by NASA, ESA systems for enhanced communication and navigation could provide significant mission enhancement for all NASA mission scenarios. There are also opportunities for international commercial engagement for the provision of communications services. In both cases, opportunities for detailed collaboration merit further dialogue.

5.4 Findings for ESA Scenario 2, ESA Development of Crew Transportation Architecture

As explained in Section 2 of this report, human space transportation is considered to be a strategic capability for the United States, and NASA is committed to developing an end-to-end transportation capability for human lunar exploration. However, the experience of the International Space Station demonstrates the need and benefit of redundant transportation systems in any international space exploration program. Similar considerations are also highlighted in section 5.3 regarding the value of a distinct and redundant cargo transportation system. The degree of redundancy and interoperability of transportation systems at international level requires further discussion.

ESA is currently studying the development of a human transportation capability to LEO and beyond. In this context, ESA is studying different options for orbital infrastructures and supporting cis-lunar transportation capabilities. Such infrastructure could support human transportation in cis-lunar space and continue European access to the microgravity environment for scientific research following the retirement of the ISS. Options for an ESA orbital platform vary in size and utilization capabilities depending on their potential location; either in low-Earth orbit (LEO), low-lunar orbit (LLO), or at an

Earth-Moon Lagrange (EML) point. It was difficult in the time available to fully examine the benefits from enabling interoperability between NASA's transportation systems and any of these options, given that a great deal depends on details such as orbit altitude and inclination (details that are not finalized yet). In general, NASA could contribute a heavy lift capability for ESA by providing the Ares V launch vehicle as a means to lift orbital elements and transport them to their final location. However, beyond this point, there is no synergy between NASA's plans for lunar exploration and ESA's concepts for a LEO or EML station. However, an ESA-developed LLO station may have many synergies, and these are explored further below.

One means to provide increased mission assurance (specifically, decreasing the probability of a loss of crew or loss of mission) is to provide safe-haven capabilities or contingency opportunities for astronauts on the surface. In particular, there are at least four scenarios conceivable wherein NASA utilization of an ESA LLO station as a safe haven could be highly valuable:

- Outpost habitation failure;
- Failure of the uncrewed Orion in lunar orbit;
- Crew injury or health problem; and,
- Radiation event.

The ability of an LLO station to provide this safe haven capability still has to be determined with more thorough technical analysis. Currently ESA indicates that its LLO station in polar orbit could be accessed at anytime by crews at a polar outpost, and once every fourteen days from other locations. Also, ESA's nominal design for a polar orbiting LLO station would enable a return to Earth once every fourteen days. More analysis is required to determine how these parameters can interact with NASA's outpost assumptions and requirements for safe havens or return to Earth.

From an operational point of view, the presence of infrastructure in LLO creates several intriguing opportunities for lunar exploration missions. Crew rotations on the surface could be extended well beyond six months, if the Orion could dock with an LLO station and depend on that station for power, orbital maintenance, and thermal control. Alternatively, such a station could be a cargo-staging location; cargo transported to LLO could be "dropped" to the lunar surface via an automated Altair lander that simply travels to and from an outpost to LLO or a smaller Ariane based landing system as outlined earlier. Advanced mission planning of this sort would require a great deal of pre-coordination and planning between NASA and ESA on physical and communications interfaces and standards, would require agreement between parties on orbital parameters, and would depend on final decisions made by ESA about the size and capability of an LLO station.

> An ESA-developed low lunar orbiting station that can be utilized by NASA has the potential to enhance mission safety and performance, and could enable different mission profiles. To fully understand the benefits of this station would require further dialogue.
>
> ESA analysis on redundant transportation systems in cis-lunar space has led to other ESA orbital infrastructure concepts (LEO, Lagrange points), which do not have synergy with NASA's architecture at the current stage.

5.5 Findings for ESA Scenario 3: ESA Development of Dedicated Lunar Surface Exploration Elements

As part of the LAT-2 exercise NASA identified the basic constituents of a lunar outpost at one of the poles. At a minimum these consist of a module (or modules) for habitation, a pressurized rover to support long-distance excursions by astronauts away from the outpost, unpressurized rovers for logistics support, a power infrastructure, and communications capabilities. Once these elements are in place astronaut crews can begin utilizing additional tools and equipment for exploration, science objectives, and for testing new methods of operation like in-situ resource utilization (ISRU).

As a complement to the mobility desired from an outpost location, NASA determined that in order to improve the quality of science on the Moon it will be beneficial to have global access to the Moon's surface – either by direct landing of sortie missions or by extended mobility from an outpost, or by some combination of direct landing and extended mobility. Therefore, pressurized rovers should be able to traverse several hundred kilometers, and designs for surface systems should consider how to combine functions for long-duration habitability (several weeks) with mobility and EVA functionality. Given NASA's broad objectives for lunar exploration, and given the budget profile NASA has been asked to assume for the next decade, it is valuable to consider how systems can utilize modularity in their design. For example, pressurized and unpressurized rovers can share a chassis, or pressurized rovers and habitation modules can share environmental control and life support systems (if not in fact be identical modules in many respects).

In doing its own architecture planning ESA has developed conceptual designs for both a lunar surface habitat and a pressurized rover. Both ESA and NASA concepts for pressurized rovers:

- Support two astronauts for excursions of more than 100km;

- Utilize "suitports" so that astronauts can rapidly leave the "shirtsleeve" environment to do work outside;
- Enable multiple (more than 5) EVAs per person per mission;
- Would enable "science on the spot" in support of astronaut EVAs; and,
- Have studied concepts of small habitats that are mobile – either autonomously via astronaut control, or by "towing."

An evaluation of these systems with respect to NASA's exploration concepts and key capabilities is not possible if one only utilizes terms like "enhance." These systems are not meant to enhance a lunar surface architecture; they are the *sine qua non* of a lunar surface architecture. These surface systems, if developed by ESA, would have to be developed in a coordinated fashion with NASA and other space agencies as appropriate, with detailed attention paid to requirements and interfaces and development schedules at an early stage. It is feasible to consider a scenario wherein NASA may forego the development of either a pressurized rover or perhaps a small habitation module if ESA were to undertake this task. This would only serve to quicken the pace of exploration on the surface, enable the development of more advanced technology in other critical areas like surface power or ISRU, and ensure joint European-U.S. exploration missions to the Moon. However, it should be noted that any significant ESA investments in such high-value surface assets would require as a prerequisite the establishment of a framework for international lunar exploration addressing subjects such as responsibilities for the deployment of the surface asset as well as access and utilization opportunities for European astronauts.

Both NASA and ESA have determined that these surface exploration systems are two promising contributions to their architecture within this assessment and will continue the work of identifying and refining their utilization potential and implementation effort.

> Both a pressurized rover and a surface habitation module are fundamental, enabling components of any surface architecture. These capabilities merit further quantitative analysis to determine how they may enable joint lunar exploration missions or enhance total mission capabilities. Any final decision on the part of ESA to develop such systems will require a more thorough assessment of international lunar exploration architectures and a framework for cooperation.

6. Next Steps

The in-depth discussion between NASA and ESA within the Comparative Architecture Assessment has been very fruitful and lead to a better understanding of the respective architecture work, objectives and current status on both sides. A particular item of interest to both parties has been the degree to which identifying even the simplest means of cooperation or collaboration immediately leads to a set of new possibilities, which grow in added value and benefit as the cooperative involvement increases.

Following completion of this report, and for the remainder of calendar year 2008, NASA and ESA will continue further dialogue and technical discussion for selected cooperative scenarios, dedicated to three specific meetings addressing the scenarios outlined in Section 4.3. Such discussions will be geared primarily towards a clarification of the various capability options described in this report. Following NASA's Lunar Capabilities Concept Review, which is intended to refine lunar architecture concepts in support of the transportation elements, NASA will consider participation in ESA's architecture review meetings, currently scheduled for early July, 2008.

NASA and ESA recognize the potential for further discussions leading to proposals for specific areas of cooperation that could materialize following decisions in November 2008 on ESA's programmatic priorities for the coming years. NASA and ESA are each prepared to pursue continued discussions, and understand that any specific proposals for cooperation will require coordination through the normal domestic review and documentation procedures related to the processing of international agreements.