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Analysis of Synthesis Group Architectures: Summary & Recommendations

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NASA

ANALYSIS OF SYNTHESIS GROUP ARCHITECTURES: SUMMARY AND RECOMMENDATIONS

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Douglas R. Cooke
Manager
Exploration Programs Office

Dwayne P. Weary
Manager, Mission Analysis and System Engineering Office
Exploration Programs Office

David I. Kaplan
Architecture Analysis Lead
Exploration Programs Office

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LIST OF ACRONYMS

ATDRSS	Advanced Tracking and Data Relay Satellite System	kg	kilograms
		KSC	Kennedy Space Center
DIPS	Dynamic Isotope Power System	LEO	Low Earth Orbit
DSN	Deep Space Network	mt	metric tonnes
ETO	Earth-to-Orbit	NEP	Nuclear Electric Propulsion
EVA	Extravehicular Activities	NLS	National Launch System
ExPO	Exploration Programs Office	NTP	Nuclear Thermal Propulsion
HLLV	Heavy Lift Launch Vehicle	RTG	Radioisotope Thermal Generator
ISRU	In-Situ Resource Utilization	SEI	Space Exploration Initiative

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1. Executive Summary

The Synthesis Group was formed to assess the innovative ideas about the Space Exploration Initiative (SEI) received through the Outreach Program. Over a ten-month period, the Group sifted through the many submissions and listened to a variety of presentations. As a result, they developed four architectures, or paths, for pursuing exploration. *These Synthesis Group architectures provide the framework for defining the scope and scale of the SEI.* The methodology used by the Group characterizes the architectures in terms of operational capabilities, such that decisions are assumed at key milestones to formulate the architecture path. This original concept of decision flexibility based on knowledge gained has been adopted by NASA for SEI mission planning. Thus, as early missions are defined and realized, our long-term objectives remain true to the Synthesis Group template.

The present document provides a **collective assessment** of the Synthesis Group architectures. NASA has now completed its analysis of these architectures; four documents have been printed, each discussing in detail an individual architecture. The purpose of the current document is to look across all the architectures and to capture the knowledge gained from our analysis activity. This document (1) summarizes key features of the Synthesis Group architectures that are attractive, (2) identifies features for which we would offer alternative approaches, and (3) suggests recommendations to guide the next, near-term steps for SEI .

Strengthening Features

The Synthesis Group specified several important features common among the four architectures. As NASA examined each of the architectures in detail, we concluded these particular features enhance the quality of each architecture. Specifically, features strengthening the architectures are:

- key decision points (waypoints) that formulate an architectural path
- split mission strategy (where cargo and crew fly on seperate missions),
- predeployed and verified ("turn key") habitats,
- robotic, precursor missions to the Moon and Mars in support of human missions,
- nuclear surface power,
- relatively large heavy lift launch vehicles (HLLV),
- nuclear thermal propulsion for transportation to Mars,
- use of the Moon to help prepare for Mars missions,
- life science and human factors research, and
- identification of the overlapping architectural themes.

Concerns

Our analyses also revealed some common features of the architectures that caused us concern. . . . features that could have important repercussions throughout the implementation of architectures. These key, high-leverage concerns involve:

- large crew size specification,
- adequacy of heavy lift launch vehicle (HLLV) size,
- adequacy of surface operations experience prior to long-stay Mars mission,
- scope of Mars dress rehearsal on the Moon, and
- one crew member in lunar orbit.

Recommendations

Lastly, reflecting back upon the completed analyses of the four architectures (and considering the budgetary environment in which the SEI finds itself today), there arise several recommendations that we offer in order to best advance the SEI. These recommendations include:

- initially, do not overemphasize any single architectural theme;
- focus upon the near-term missions (within the overall architectural context);
- advocate robotic, precursor missions to the Moon and Mars in support of human missions;
- follow a campsite approach for the first human lunar missions;
- fly minimum crew size on initial lunar missions; and
- determine the most effective heavy lift launch vehicle (HLLV) capability for the approach chosen by SEI.

2. Background

The Space Exploration Initiative is a great challenge first verbalized by President George Bush in July of 1989 that extends into the 21st century. NASA's *90-Day Study Report* and an internal set of four White Papers provided some initial, alternative approaches to meeting the SEI challenge. The Synthesis Group was created as an independent team to address the SEI challenge from a broader perspective. In May 1991, the Synthesis Group issued its report titled ***America at the Threshold: Report of the Synthesis Group on America's Space Exploration Initiative*** to serve as a navigation chart for implementing SEI.

America at the Threshold presents four potential SEI architectures. (An architecture is defined as "a set of objectives ordered to achieve an overall capability and the sequential series of missions – including specific technical activities – to implement those objectives."[1]) Each is distinguished in terms of its approach, scope, emphasis, purpose, and balance between activities on the Moon and Mars.

1. **Mars Exploration**: This set of missions returns humans to the Moon by 2005, but the primary objective is Mars science and exploration. The lunar capability is established to serve as a testbed of systems, equipment, operations, and experiments for later trips to Mars.

2. **Science Emphasis For The Moon and Mars**: This architecture envisions "balanced" scientific return and exploration activities at both locations. A total of 13 human missions to the Moon and Mars are slated between 2003 and 2020.

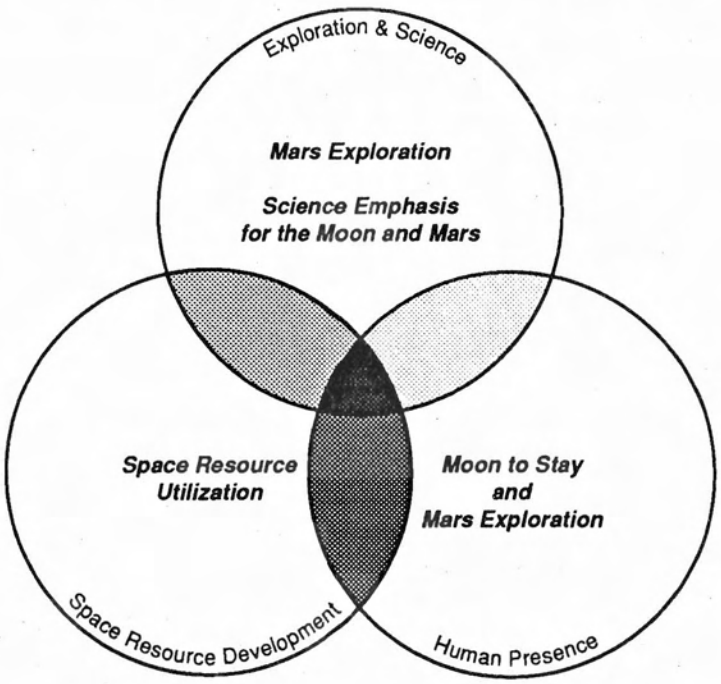

Figure 1. Architecture areas of emphasis

1 *America at the Threshold: Report of the Synthesis Group on America's Space Exploration Initiative*, May, 1991, page 16.

3. **Moon To Stay and Mars Exploration**: This set of missions establishes a human presence on the Moon in 2004, and, by 2007, 18 crew members live and work on one-year assignments. In addition to founding a lunar base, the crews conduct preparatory work for Mars journeys that begin in 2014.

4. **Space Resource Utilization**: These missions concentrate on turning the resources of space into usable, exploration-support products, with the potential toward export. The architecture promotes self-sufficiency with plans to convert Moon and Mars resources into materials for habitation and propellants for transportation.

Shortly after the release of ***America at the Threshold***, NASA began an agency-wide effort to assess the technical and strategic details required to actually implement each of the four architectures. The Exploration Programs Office (ExPO) led this architecture analysis activity, coordinating and integrating the efforts of the participating NASA centers. ExPO has published an analysis document for each of the four Synthesis Group architectures (see the insert below).

By analyzing these architectures *individually*, NASA has developed an understanding of the implications of pursuing those particular themes and approaches. The current document, however, provides a *collective view* of the architectures, resulting in the recognition of important, cross-cutting ideas.

There are four Architecture Analysis documents — one for each of the Synthesis Group architectures. These Architecture Analysis documents have the same format. Section 1 of each documents is a standard introduction. Section 2 outlines the architecture objectives, the key milestones and accomplishments, the technology/advanced development and human support strategies, and the end-to-end mission description. Section 3 provides detailed descriptions of the various systems defined for the architecture implementation, the reasoning behind the selections of the systems employed, and an overview of how the particular system is operated during the various phases of development within an architecture. Section 4 of each document lists possible issues as submitted by members of the NASA community; these issues are printed without screening or evaluation.

The documents are:

Analysis of the Synthesis Group's *Mars Exploration* Architecture, ExPO Document XE-91-001, October, 1991.

Analysis of the Synthesis Group's Science Emphasis for the Moon and Mars Architecture, ExPO Document XE-92-003, March, 1992.

Analysis of the Synthesis Group's *Moon to Stay and Mars Exploration* Architecture, ExPO Document XE-92-001, January, 1992.

Analysis of the Synthesis Group's *Space Resource Utilization* Architecture, ExPO Document XE-92-002, February, 1992.

The sequence of events leading up to the NASA analysis of the Synthesis Group architectures is shown in Figure 2. More importantly, the figure also points to the next step in defining the SEI. Given the excellent template of possible architectures defined by the Synthesis Group, the need to study multiple, grand architectures has diminished. The current ExPO course of action focuses on specific, near-term missions, including robotic, precursor missions and the first human outpost on the Moon. Exploration program planning places these near-term missions in the context of the broader exploration agenda captured by the architectures. Input to that planning comes from this document (in the recommended features) and the other four architecture analysis documents. ExPO is applying the knowledge gained from this Synthesis Group architecture analysis activity to shape the precursor missions and the first lunar outpost. The Synthesis Group architectures will remain as guidelines for our long-term objectives while we define the early steps.

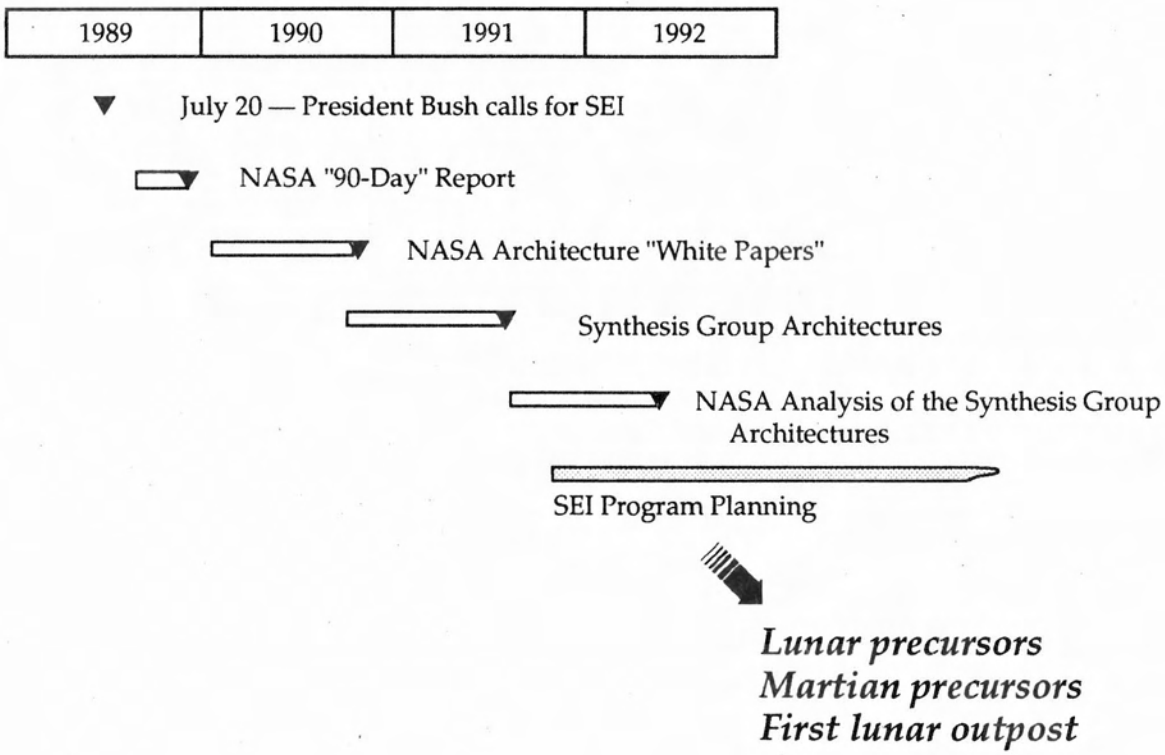

Figure 2. Key planning activities for SEI

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3. Architecture Analysis Process

A consistent analysis process was applied to the four Synthesis Group architectures. The purpose of the analysis effort was to develop a thorough understanding of the implications of pursuing the architectures as well as to provide example implementations. A discussion of this process provides insight into the common features, concerns, and recommendations published in this document.

The analysis process began with understanding the Synthesis Group objectives for the architecture under consideration. These objectives were specified most notably in terms of three themes — exploration and science, human presence, and space resource development. The NASA analysis team then translated the objectives into mission strategies for every operational capability in the architecture. (For example, with the Space Resource Utilization architecture, NASA charted the development of space resources from the demonstration phase to the local-usage phase to the export phase.)

Also dictating the strategic flow of the architecture were the groundrules stated in the Synthesis Group report. Groundrules were interpreted as strategic or implementation constraints, either specific to the architecture or common across all architectures. Specific constraints included the mission milestone schedule plus the key accomplishments to be met at each milestone. Whereas the specific constraints tended to influence the strategy, the common constraints impacted the architecture implementation. The following list specifies some of the most significant common constraints:

- crew size of six (or increments of six),
- lunar heavy lift launch vehicle (HLLV) capability of 150 mt,
- martian HLLV capability of 250 mt,
- nuclear propulsion systems for Mars transit,
- mission design to reduce exposure to zero-gravity during Mars transits,
- short-duration mission class for first piloted mission to Mars, and
- long-duration mission class for second piloted mission to Mars.

The resultant mission strategy formed the basis for pursuing a particular mission design and implementation for that architecture. The implementations, as defined by the NASA analysis team, applied to the precursor missions; science payloads; planetary surface systems; space transportation systems; Earth-to-orbit systems; and telecommunications, navigation, and information management systems. A payload manifest was derived to accommodate the mission strategy. This manifest dictated the vehicle configurations, particularly the lander size and the number of HLLV launches per mission (given the HLLV capability constraint). The implementations for each system were described in terms of a hardware configuration and an operational profile.

In addition to the higher-level architecture objectives, the Synthesis Group architecture descriptions contained a number of specific system-level recommendations. These recommendations were followed, whenever possible, while conducting the architecture analysis in

order to be true to the Synthesis Group's intentions. (For example, the Science Emphasis for the Moon and Mars architecture specified a 4-meter optical telescope on the Moon by 2007. This science instrument was included in the manifest with the appropriate surface accommodations and operations analysis.) Thus, the resulting architecture analyses presented only one of many possible implementations for each of the Synthesis Group architectures.

4. Key Features Common Among Architectures

The Synthesis Group specified several important features that were common among the four architectures. As NASA examined each of the architectures in detail, we concluded that these particular features enhance the quality of the architectures. Specifically, these key features include:

- decision points (waypoints) that formulate an architectural path,
- split mission strategy (where cargo and crew fly on separate missions),
- predeployed and verified ("turn key") habitats,
- robotic, precursor missions to the Moon and Mars in support of human missions,
- nuclear surface power,
- relatively large heavy lift launch vehicles (HLLV),
- nuclear thermal propulsion for transportation to Mars,
- use of the Moon to help prepare for Mars missions,
- life science and human factors research, and
- identification of the overlapping architectural themes:
  - → exploration and science,
  - → human presence,
  - → space resource development.

Decision points (waypoints) that formulate an architectural path

The Synthesis Group expresses their architectures in terms of *waypoints* (or ". . . major topical activities to be performed on the planetary surface"[2]) that define significant levels of capability and identify key decision points. Waypoints ". . . provide a point at which accomplishments to date can be meaningfully evaluated; . . .provide decision points at which a given program can be continued, modified, or stopped; and . . . let each mission contribute to the capability required to meet the next operating level in the sequence."[3]

This general approach of providing key decision points will afford the greatest flexibility (1) to redirect the initiative due to unexpected events or changes in available funding , and (2) to introduce new systems or hardware that measurably improve the pre-existing infrastructure.

It is the sum of the key decisions that formulate an architectural path. The four Synthesis Group architectures are each an *assumed pathway* through these decision points. Each of the architectures is designed to capture a practical range of scope and achievement within its own boundaries. While the actual SEI architecture that eventually will be implemented is unknowable, its scope and scale will be compared back to the Synthesis architectures.

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2 ibid, page 11.
3 ibid, page 16.

Split mission strategy

The split mission strategy separates the flight of the cargo going to the planetary surface from the flight of the crew. This strategy is effective because the habitats and other facilities can be remotely verified as operational on the planetary surface before the crew departs from Earth. In addition, for the Mars missions: (1) the cargo can be sent on a relatively slow, low-energy trajectory in order to maximize the quantity of equipment being transported; and (2) without the burden of heavy cargo, the crew can travel on a faster, high-energy trajectory, thereby minimizing their exposure to the zero-gravity and radiation environment of interplanetary space.

Predeployed and verified ("turn key") habitats

"Turn key" habitats require minimal activation operations by the crew prior to occupation. Since the habitats are predeployed to the surface and verified before the crew begins their part of the mission, the crew will have high confidence that only a nominal set of EVA operations will need to be conducted before they can occupy the habitat.

The advantages of a "turn key" habitat design include: (1) a high degree of confidence in the habitat integrity due to predeployment and verification; (2) a majority of crew time devoted to conducting the mission rather than to preparation of the outpost; and (3) a less complex piloted lander (otherwise the crew would have to rely on the lander as a backup habitat for the entire duration of the surface mission).

Robotic, precursor missions to the Moon and Mars in support of human missions

The Synthesis Group subscribed to the basic philosophy of preceding human landings with robotic, precursor missions. Specific implementations for the Moon and Mars include Site Reconnaissance Orbiters (SRO) and Rovers. The SRO's obtain high-resolution, global images of the planet. The objectives of the SRO are to identify areas of scientific interest, to locate potentially useful raw material concentrations, and to identify sites suitably safe for landing. Specific landing sites are then selected for further investigation by rovers. The objectives of the rover missions are to certify a safe human landing site and to collect, analyze, and verify materials identified remotely. The Mars rover missions are also responsible for determining possible toxic agents in the environment that might be damaging to crew health. As needed on the Moon or Mars, the rovers may emplace infrastructure, such as navigation aids, for subsequent human missions.

Nuclear surface power

The NASA team concurs with the Synthesis Group's utilization of nuclear power systems for all but the first lunar missions. The recommendation to use nuclear power systems is principally based on the reliability and mass savings over photovoltaics with energy storage. As the Synthesis Group Report states:

> Moon and Mars represent different power system challenges. For daytime stays on the Moon, lightweight, easily deployed photovoltaic panels are the minimum mass option over nuclear or energy storage.
>
> For one full-day stay (28 Earth days) on the lunar surface, photovoltaic power systems with energy storage and nuclear systems are the prime candidates. For a 25 kW habitat load, nuclear systems will weigh one-fifth as much and save 8,000 kg on the lunar surface. Continuous base power that can increase to 1 MW will weigh about 12,500 kg using nuclear power, versus 330,000 kg using photovoltaics with energy storage.[4]

The initial nuclear unit development is for the lunar outpost where deployment and safe, reliable operations are validated. For Mars, nuclear power is recommended over photovoltaics as part of a technology investment strategy. Furthermore, the performance of photovoltaics on Mars may be reduced due to dust storms and a solar flux less than half that at Earth. Nuclear surface power systems are capable of providing Mars base power to a megawatt level with reliable, long lifetimes.

Relatively large heavy lift launch vehicles (HLLV)

The Synthesis Group unequivocally stated that a heavy lift launch capability of 150 mt for lunar missions with designed growth to 250 mt for martian missions enabled all of the architectures.

> [T]he Synthesis Group finds that America's ability to return to the Moon and begin the exploration of Mars depends on two fundamental technologies: the restoration of a heavy lift launch capability and the redevelopment of a nuclear propulsion capability.[5]

Relatively small Earth-to-orbit capability requires more complex orbital operations to assemble the many pieces into lunar or martian transportation vehicles. While on-orbit operations cannot be fully eliminated, the use of heavy lift launch vehicles allows: (1) simplifying the complexity of those on-orbit operations towards rendezvous and docking maneuvers, and (2) reducing the launch-rate operational constraints at the launch site. For interplanetary missions, which require departing from Earth during precise "windows," simpler launch and orbital operations increase the likelihood of making those windows.

Nuclear thermal propulsion for transportation to Mars

In addition to the heavy lift launch vehicle, the other technology enabling the Synthesis Group's architectures is nuclear thermal propulsion for both human and cargo transportation to Mars.

With its higher specific impulse, nuclear systems promise high performance with significant savings in propellant mass as compared to chemical systems. Since launch rates are heavily

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4 ibid, page 71.
5 ibid, page 83.

dependent upon the initial mass to low-Earth-orbit, the nuclear systems with their commensurate smaller propellant needs involve lower overall launch demands.

Furthermore, for a given mass of propellant, any technology — such as nuclear propulsion — providing improved efficiency enables the reduction of trip times between Earth and Mars. And, as the Synthesis Group Report states: "Biomedical and psychological concerns relative to the effects of prolonged zero gravity, space radiation, and confinement during Mars missions are strong incentives to reduce transit times."[6]

Use of the Moon to help prepare for Mars missions

It is clear that equipment and procedures for the Mars mission must be properly certified before humans travel to that distant planet. The Moon provides an important test environment for many facets of the Mars mission. Most fundamentally, the relatively accessible Moon affords valuable experience in living on a hostile planetary surface while still maintaining the option to return quickly to Earth in an emergency. In a manner analogous to the role of Mercury and Gemini to pave the way for Apollo, lunar activities lead to essential experience — and confidence building — for the ambitious voyage to Mars.

Life science and human factors research

The Synthesis Group clearly recognized — and called out at several points in their report — the need to conduct significant life science and human factors research. Indeed, one of the Group's top ten recommendations (number 8) is: *Conduct focused life science experiments*[7]. Even so, there is sizeable variance between the four architectures as to how much resources are devoted to life science and human factors research. We will need to identify this research as it applies to both the planetary surface and interplanetary travel arenas. And we will need to insure that the research is performed.

Identification of the overlapping architectural themes

At a fundamental level, the chief variations among the four Synthesis Group architectures lie in each's relative emphasis of "the degree of human presence in space, the level to which exploration and science are pursued, [and] the extent to which space resources are developed."[8]

Another possible thematic distinction between architectures is the relative focus between lunar and martian activities. The four Synthesis Group architectures, however, all present a similar set of Mars missions.

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6 ibid, page 22.
7 ibid, page 9.
8 ibid, page 17.

The NASA team concurs that the fundamental theme of any architecture may be expressed as a relative mixture of:

- exploration and science
- human presence
- space resource development
- Moon versus Mars focus

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5. Concerns

NASA's assignment was to review and analyze the Synthesis Group's architectures. We fully recognize that is it always easier to find faults or flaws in another's work than it is to create that work originally. The Synthesis Group produced a seminal report capturing many excellent ideas. There are, however, some concerns that the NASA review team has. We offer these concerns not to denigrate the work of the Synthesis Group, but rather in the spirit of contribution.

By our definition, a **concern** addresses a groundrule imposed on all the architectures by the Synthesis Group. It has major repercussions throughout the architecture. The key, high-leverage concerns involve:

- large crew size specification,
- adequacy of heavy lift launch vehicle (HLLV) size,
- adequacy of surface operations experience prior to long-stay Mars mission,
- scope of Mars dress rehearsal on the Moon, and
- one crew member in lunar orbit.

[Section 6 discusses **issues**; issues are focused upon specific choices between implementation options within an architecture.]

Large crew size specification

The initial crew size specified in all four Synthesis Group architectures is six persons. Growth in crew size follows in increments of six as well. The report states, "a crew of six was selected for both the Moon and Mars missions to achieve maximum commonality for equipment, crew tasks and procedures."[9] This statement explains why the crew size remains the same between the lunar missions and the Mars missions; however, it does not provide a rationale for that particular number of people. The choice of six crew members seems not to be predicated on the mission responsibilities and proposed activities.

While it is appropriate for the Synthesis Group to establish a size for planning purposes, it is too early to commit to a specific number. Any increase in crew size above the minimum could significantly expand the scale of systems and infrastructure (and ultimately, cost), and therefore such an increase must be founded on either requirements to conduct the mission, human factors considerations, and/or operational efficiency goals. The crew size should be variable based on the content and timing of surface activities for that particular architecture. For example, the Mars Exploration architecture maintains an austere, minimum approach, while the Space Resource Utilization architecture stresses using the Moon as a platform for in situ resource application with the intent toward base self sufficiency; these two diverse objectives could result in two crew sizes.

9 ibid, page 16.

Adequacy of heavy lift launch vehicle (HLLV) size

The Synthesis Group Report advocates a heavy lift launch vehicle as the basic capability needed to support any lunar and martian architecture. As stated in the report, "the mass to low Earth orbit requirements range from a minimum of 150 metric tons up to 250 metric tons per launch."[10] The 150 mt HLLV configuration is specified for the lunar missions, while the growth configuration, 250 mt, is intended for the Mars missions.

Addressing NASA's first human return missions to the Moon, it appears to be desirable to deliver large, integrated payloads to the lunar surface in order to minimize the construction required for an initial outpost. Our preliminary studies indicate this requires on the order of 200 to 220 metric tonnes in low Earth orbit. Using a dual-launch scenario, two 100 mt class vehicles must be processed and launched from KSC within a short period of time. This will add the penalty of on-orbit power, cryogenic boiloff, and system lifetime extensions to the first element launched. In addition, the trans-lunar injection window must be closely synchronized with the second launch; a launch delay may force a one-month-long mission delay and may result in loss of the initial payload. Finally, an autonomous rendezvous and docking system is required. A single launch of a 200 mt class HLLV directly to the Moon greatly simplifies the orbit operations of this type of mission. Preliminary analysis has shown that such a vehicle can be processed within existing KSC facilities, and, when matched with the piloted mission requirements, can reduce demands on launch operations.

The actual payload-to-orbit capability should be an output of analysis taking into account the surface payload requirements, operational constraints, and programmatics. Deriving the most effective approach to launch vehicle size will necessitate an evaluation based on life cycle cost, schedule availability, ground and on-orbit operations, and mission flight rates.

One of the key considerations in determining a viable launch vehicle size is the impact of launch rates. As previously mentioned, the Synthesis Group architectures follow a split mission strategy for both the Moon and Mars (i.e., piloted and cargo missions launched separately). The cargo launch frequency is dependent upon the amount of infrastructure required on the Moon and Mars to implement the goals of the architecture. The specific implementations, as developed by NASA, result in launch rates for the Moon of 2 to 10 per year. The MOON TO STAY AND MARS EXPLORATION architecture poses the most demanding lunar launch schedule, with launches peaking at 10 per year. With respect to the Mars missions, the SCIENCE EMPHASIS FOR THE MOON AND MARS architecture maintains the heaviest schedule with approximately 8 launches every other year (each Mars opportunity), peaking at 10.

The main concern regarding these launch rates involves ground processing feasibility. The Synthesis Group made the implied assumption that there would be a launch facility with access as needed. Current Kennedy Space Center facilities are not sufficient for handling up to 10 launches per year of a 150 mt HLLV or 8 launches per year of a 250 mt HLLV. During the timeframe of these architectures, post 2003, KSC facilities will be accommodating STS and possibly NLS missions plus any additional expendable-class launch vehicles. Ground processing

10 ibid, page 31.

requirements for the Space Exploration Initiative place exceeding demands on KSC's current capabilities, including integrating large payloads, processing and storing nuclear reactor systems, and maintaining large amounts of propellant. The complexity of ground operations for launch processing increases tremendously as the architectures evolve through the lunar and martian phases.

Adequacy of surface operations experience prior to long-stay Mars mission

What total experience — human, systems, and operations — on a planetary surface is sufficient preparation for a 600-day-surface-stay Mars mission? Certainly, the first time humans stay on the martian surface for 600 days will be a true milestone. Each Synthesis Group architecture establishes a human capability on the Moon prior to piloted Mars missions. In addition to its own inherent value, this lunar activity provides some measure of experience towards eventual long-term stays in the martian partial-gravity environment. But will this experience be truly adequate?

The total amount of time spent on the Moon prior to the 600-day-surface-stay Mars mission varies from architecture to architecture. Three of the four architectures (MOON TO STAY AND MARS EXPLORATION excluded) do not provide lunar surface stays anywhere near to a 600 day comparable duration. (For example, the MARS EXPLORATION architecture has a total amount of only approximately 300 days spent on both the Moon and Mars prior to the 600-day-surface-stay Mars mission.)

Are we implying that at least 600 days must be spent on the Moon prior to the 600-day-surface-stay Mars mission? No, not necessarily. We do not know today what will be required in order to ensure confidence that long-duration surface stays are feasible. Our concern is that the needed experience to prepare for such a 600-day surface stay could prove to be quite significant.

Scope of Mars dress rehearsal on the Moon

Each Synthesis Group architecture includes a complete dress rehearsal for the first human mission to Mars, conducted in lunar orbit and on the lunar surface. The purpose of the dress rehearsal is to test human adaptation to zero-gravity and partial-gravity environments as well as to test and verify Mars prototype equipment. The sequence for the dress rehearsal progresses as follows: 1) delivery and remote operation of Mars-configured surface systems, 2) rehearsal crew orbits the Moon in the Mars transfer habitat for the Mars transit duration, 3) rehearsal crew practices the Mars mission at the rehearsal site on the Moon for 30 days, and (optionally) 4) rehearsal crew remains in lunar orbit to simulate the Earth-return transit. This approach emphasizes practicing with the same equipment to be used at Mars "to the extent practical."[11]

11 ibid, page 37.

One of our concerns resides with the fact that the lunar and martian environments are so dissimilar. Hardware such as landers, habitats, and rovers may claim functional similarity, yet the characteristics of the environments demand very different system designs (particularly the thermal control and power systems). The one-sixth Earth gravity plus the lunar dust problem also pose some operational impediments for using the Moon to simulate Mars crew operations.

Another concern regarding the complete Mars dress rehearsal on the Moon is whether such a strategy is cost effective. Many of the features of the dress rehearsal *appear* "costly" at first glance, including duplication of surface systems at a simulation site for full-up verification, the launch and delivery of the Mars transfer habitat to lunar orbit, and the aggressive schedule required to fly Mars hardware six years prior to the actual Mars departure.

Alternatives to the complete Mars dress rehearsal exist. With respect to the concern over environment disparity, information from the robotic, precursor missions about Mars could be used to enhance fidelity of simulations conducted in Earth-based test facilities for certain aspects of the Mars mission. Furthermore, the Moon should be continually used throughout the outpost development as a testbed for operations concept development, subsystems development, and life sciences research for later Mars missions.

In terms of cost effectiveness, the orbital portion of the rehearsal could be performed in low-Earth orbit. Low-Earth orbit facilities could be utilized early to provide valuable life sciences research and zero-gravity systems verification for piloted Mars missions. Furthermore, a life sciences "dress rehearsal" could be conducted from low-Earth orbit in conjunction with the lunar outpost to simulate the zero-g/partial-g/zero-g profile of a Mars mission. (Later, when the actual Mars transit habitat has been constructed, it could be tested in low Earth orbit for a duration similar to the Mars transit period.) As previously recommended, integrating the testbed strategy throughout the lunar scenario and testing Mars equipment on Earth — if that is the most practical location — may reduce the cost of building a separate simulation site on the Moon. Such an approach could also relieve an aggressive Mars-hardware production schedule required to satisfy a full-up dress rehearsal of the first piloted Mars mission.

One crew member in lunar orbit

Each Synthesis Group architecture requires a single crew member to remain in lunar orbit during the Initial Operational Capability. The orbiting crew member resides in the transportation crew module for 14 Earth days, while a five-person team performs the specified surface activities at the designated operational site. The MOON TO STAY AND MARS EXPLORATION architecture extends this requirement into the Next Operational Capability and has a single crew member in lunar orbit for 40 days.

The concern over this mission strategy involves engineering design considerations. The orbiting crew member requirement most significantly impacts the design of the transportation crew module. Throughout the lunar mission phase, the crew module's standard mission includes transporting six people for a total of approximately six days. A severe mass penalty would be incurred in order to sustain one crew member, whether the duration is 14 days or 40 days. The additional mass to the crew module would be designed in systems such as power,

thermal control, and life support. A rather costly alternative would be to build a separate crew module for the orbiting crew member flight, i.e., an additional vehicle to the one meeting the standard requirement of six people for six days.

The Synthesis Group rationale for this mission approach follows:

> For the first two piloted missions to the Moon, one crew member remains in orbit to perform inflight experiments and to monitor the orbiting vehicle while the other five descend to the surface. All six go to the lunar surface after sufficient confidence is gained that the orbiting vehicle remains in an acceptable status while unattended.[12]

Since these formulated architectures describe a *return* to the Moon, not an initial visit, we are confident that automated systems on-board the orbiting vehicle are sufficient. A crew member in orbit is not required for rendezvous and docking procedures between the lander and the space transportation vehicle. (Indeed, if a contingency piloted rendezvous was needed, it could be flown by one of the ascending crew.) Automated orbital activities would be required after the Initial Operational Capability; therefore, they should be designed into the mission from the beginning. To ensure confidence and reduce the risk of failure, the automated procedures could be verified in Earth orbit prior to the return-to-the-Moon mission.

12 ibid, page 16.

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6. Issues and Alternatives

The implementations developed by NASA for the Synthesis Group's architectures are fully consistent with the Synthesis Group's assumptions, groundrules, and intent. However, in creating those specific implementations, other ideas and options arose. Throughout the architecture analysis activity, participants were encouraged to identify potential issues and to construct alternative approaches.[13] *Issues that were judged to be valid, important, timely, and appropriate for further technical evaluation are identified in this section.*

Several submitted issues focused upon specific implementation choices. The submitters believed that another implementation approach would be more effective. An analysis is needed to compare the proposed alternative with the nominal Synthesis Group approach. Examples of this category of studies are:

- Assess the application of nuclear thermal propulsion for the *lunar* transfer stage for initial or follow-on capability.
- Investigate radioisotope systems to power surface transportation vehicles.
- Examine how National Launch System (NLS) evolution/derivatives should be traded against "clean sheet" approaches in support of SEI.
- Study the use of the Advanced Tracking and Data Relay Satellite System (ATDRSS) for supporting lunar communications [as a backup augmentation or replacement for the Deep Space Network (DSN)].
- Identify radiation abatement guidelines to determine the lunar surface stay time at which radiation protection of the habitat with regolith is required.

A second category of issues deals with focused research needs. In several instances, the implementations assumed by the Synthesis Group rely on certain knowledge or hardware availablity. Issues were submitted where current funding or direction of research programs was perceived to be inadequate to produce the required knowledge or hardware. Examples of studies associated with focused research issues are:

- Identify firm requirements for crew safety on Mars as well as martian material back-contamination at Earth in order to determine whether in-situ instruments or a Mars sample return is necessary as a robotic, precursor mission.
- Study the requirements for a space suit that can be used in the lunar and martian environments.
- Perform a study to identify the major contingency scenarios, including abort scenarios.
- Study methods to reduce radiation exposure through mission and vehicle design.
- Assess the technological readiness of nuclear power for use on the surface.
- Study power-generation integration and distribution options.

13 All issues that were submitted by study participants have been printed previously in the appropriate Architecture Analysis document.

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7. Recommendations

Key common features that enhance the quality of the architectures have been described previously in SECTION 4. *Those key common features should be retained in future SEI planning.* In addition — and, in some cases, in amplification — NASA has derivedthe following list of recommendations from performing the architecture analysis activity:

- initially, do not overemphasize any single architectural theme;
- focus upon the near-term missions (within the overall architectural context);
- advocate robotic, precursor missions to the Moon and Mars in support of human missions;
- follow a campsite approach for the first human lunar missions;
- fly minimum crew size on initial lunar missions; and
- determine the most effective heavy lift launch vehicle (HLLV) capability for the approach chosen by SEI.

Initially, do not overemphasize any single architectural theme

Each Synthesis Group architecture is defined according to a particular theme or area of emphasis. Again, the thematic aspect refers to "the degree of human presence in space, the level to which exploration and science are pursued, the extent to which space resources are developed, and the relative emphasis between lunar and martian activity."[14] For each architecture, the scope and scale attributed to one theme's activities appear very ambitious. This overemphasis of a particular theme was designed by the Synthesis Group in order to force differences and distinctions to the surface.

The eventual SEI architecture should initially strive to provide a *realistic* blend of themes. In order to maintain multiple themes, each one must be of a reasonable scope and scale so as not to overwhelm the others nor break the proverbial bank.

We cannot know today which theme (if any) will eventually emerge as the dominant focus for Moon and Mars exploration. (For example, if lunar resources prove to be readily extractable and abundant, then mission activities may be directed to capitalize on this viable capability.) We must strategically plan our program to insure that no theme is prematurely emphasized until its "payoffs" are proven. Thus, we leave open options for the decision-makers of the future.

Focus upon the near-term missions (within the overall architectural context)

The Synthesis Group promulgated a philosophy whereby the eventual architectural path is formulated by decisions made at key milestones. This philosophy insures flexibility to

14 ibid, page 17.

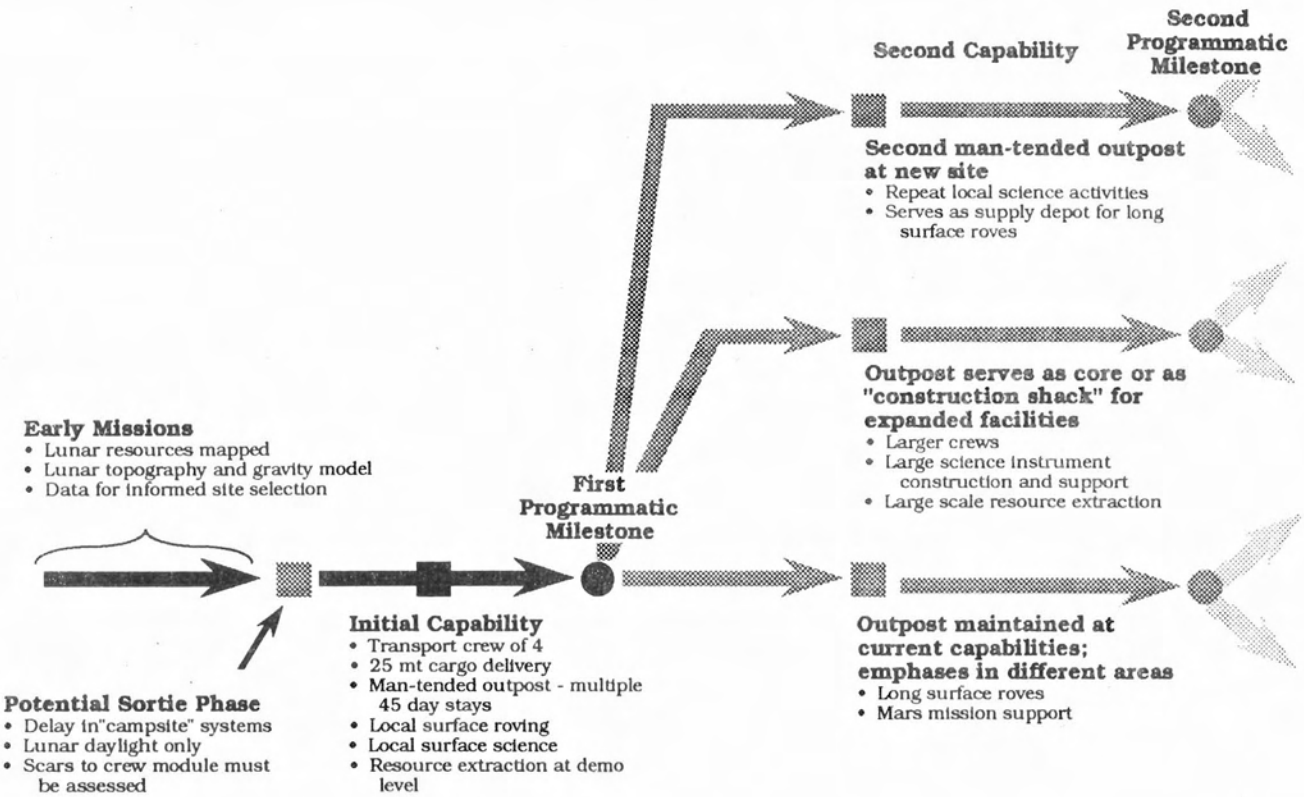

Figure 3. Key decision points for evolution of initial lunar outpost

incorporate advantageous techniques and approaches as they are proven. (Figure 3 is representative of the Synthesis philosophy of allowing the eventual architectural path to evolve from down-range decisions, representedure as the programmatic milestones. In particular, this figure illustrates the approach that has been laid out by ExPO for definition of the first lunar outpost.)

Although the four Synthesis Group architectures each achieve very distinct long-term capabilities, their initial missions are reasonably similar. It is therefore possible to focus upon these near-term missions without knowing *a priori* the specific long-range architectural growth. Clearly, the value in knowing the potential long-range growth of an architecture is to insure that early decisions do not preclude evolutionary paths. However, even if the long-range growth of an architecture is not known, prudent design of the early missions can insure accommodation of future possibilities.

Given the similarity of the near-term missions among the architectures, we recommend that SEI activities now shift their major (though certainly not exclusive) emphasis to planning for lunar precursor, martian precursor, and first lunar outpost missions.

Advocate robotic, precursor missions to the Moon and Mars in support of human missions

Lunar and martian precursor missions completed in the near-term will provide excellent information to help direct the next steps of the SEI. These robotic missions will produce both fundamental science data as well as significant environmental data about the Moon and Mars. These data, such as resource concentrations and terrain features, will prove valuable in preparing for successful human missions. In addition, precursor missions will provide invaluable information to support operations in such areas as site selection, safe landing, in-situ resource utilization, and surface operations planning. (The precursor missions will also provide demonstrated successes for the SEI during the years preceding the journeys of human explorers.) We should therefore aggressively move forward with precursor missions to the Moon and Mars.

*Follow a **campsite** approach for the first human lunar missions*

The SCIENCE EMPHASIS FOR THE MOON AND MARS proposes three initial missions to different locations on the Moon. For each, an expendable habitat is autonomously landed and verified prior to crew arrival. The crew subsequently lands nearby, walks or drives to the habitat, activates the habitat, and spends 14 Earth-days on the Moon. Minimal crew effort is spent preparing the habitat for occupancy. The habitat is not covered with lunar regolith because a fourteen day stay is brief enough not to require enhanced radiation protection for the crew. Maximum crew time is devoted to science, exploration, and resource utilization objectives. This approach is labeled a "campsite" philosophy.

The NASA team believes the "campsite" concept is the most reasonable way to return initially to the Moon.

Parenthetically, NASA's Exploration Programs Office has already accepted this recommendation and is currently studying lunar campsite options. These studies have already begun to provide new details and new decisions. For example, the human return missions to the Moon will be designed to stay for 45 Earth-days in a campsite mode. (Initial sorties using only the piloted vehicle could stay for shorter periods on the lunar surface and might precede the 45-day-stay missions.) Unlike the SCIENCE EMPHASIS FOR THE MOON AND MARS architecture, the habitat will be reusable; therefore, the option exists to return to the campsite. Hence, evolution options to the initial campsite include establishing alternative campsites or enhancing the campsite for longer duration missions (see Figure 3).

Fly minimum crew size on initial lunar missions

With the campsite approach, crew resources are not spent for habitat construction, long-term infrastructure emplacement, surface-clearing preparation for future missions, etc. It might therefore be possible to accomplish science, exploration, and resource utilization objectives of the initial Synthesis Group lunar missions with a somewhat smaller crew size. Since it is clear that vehicle sizing — and therefore cost — is positively related to number of crew, the cost of

a campsite mission would be reduced if a lesser number of people were flown.

We are not in a position today to know an exact crew size due to unclear, specific tasks and workloads. The point, however, is not to arbitrarily accept six as the proper crew size for the initial campsite missions.

Determine the most effective heavy lift launch vehicle (HLLV) capability for the approach chosen by SEI

Through our analysis, we agree with the Synthesis Group's belief that America's ability to return to the Moon and explore Mars fundamentally depends on a heavy lift launch capability. We recommend a robust launch infrastructure designed to meet mission requirements. The specific launch vehicle size should be determined based on analysis, as mentioned in section 5. CONCERNS. Our preliminary belief — based on a desire to reduce complexity of the lunar missions, of on-orbit operations, and of ground facilities — is that the HLLV vehicle will be at the upper end of the range recommended by the Synthesis Group. Arriving at the most effective launch vehicle size will necessitate studies of:

- system evolution,
- development cost,
- life cycle cost,
- funding constraints,
- schedule availability,
- payload requirements,
- vehicle processing, facilities, and operations on the ground,
- on-orbit operations,
- mission flight rates, and
- environmental impacts.

In conclusion . . . .

The Synthesis Group architectures collectively help to define the envelope of potential scope and scale. They provide four assumed paths through the matrix of key decision points. And they have given us an important metric for comparison.

The eventual SEI architecture to emerge will most probably not be any of those currently documented. It will, however, be an architecture to emerge out of the philosophy of the Synthesis Group . . . . a flexible, responsive series of accomplishments evolving anew at each key decision point. This waypoint philosophy may be one of the greatest legacies of the Synthesis Group.